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Contents

CORROSION PROTECTION OF UNBONDED TENDONS

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Abridged version of a report prepared by the Netherlands Committee for Corrosion Protection of Unbonded Tendons (Committee C 26A) for the Netherlands Committee for Research, Codes and Specifications for Concrete (CUR-VB)

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Preface

In 1974 the CUR-VB Committee "Corrosion protection of unbonded tendons" was set up with the object of conducting research on the coating to be applied to unbonded prestressing tendons with reference to the properties of the coating itself, the manner of application and how this can be checked, and the protection of the anchorage zone. On the basis of STUVO Report 18 prepared by STUVO Study Cell 16 it was decided to make a closer study of the protective grease and the end anchorage in order to arrive at recommendations which ensure that unbonded tendons will be sufficiently protected against any corrosive influences liable to be encountered in practice.

At the time of completion of the research the Committee was constituted as follows:

Ing. D. C. Binnekamp, Chairman
Ir. C. F. Etienne, Secretary
Ir. W. J. Copier
Dr. W. Enterman
Ir. R. Hendrickx
Ing. C. L. Smit
Ing. C. D. de Waal
Ir. H. van Tongeren, Mentor

In 1981 the Committee suffered a grievous loss from the death of Dr. J. W. Boon, who made a major contribution more particularly to the study of protective greases. From the outset, Ir. F. Blekkenhorst participated in the Committee's work. He was succeeded by Ing. C. D. de Waal in 1978.

The investigations were carried out in the Metal Research Institute TNO (MI-TNO) and in the TNO Institute for Building Materials and Building Structures (IBBC-TNO).

This publication is based on CUR-VB Report 105 "Corrosiebescherming van voorspankabels zonder aanhechting".

CORROSION PROTECTION OF UNBONDED TENDONS

Synopsis

Besides damage due to anchorage failure, faulty design or careless execution, corrosion of the prestressing steel is a potential hazard to prestressed concrete structures built with unbonded tendons. Exclusion of moisture is essential: if no moisture can penetrate to the prestressing steel, no corrosive attack will occur. Neither normal corrosion nor stress corrosion or hydrogen embrittlement can then cause tendon fracture.

With the aid of literature research and its own experimental research, including exposure tests of $4\frac{1}{2}$ years' duration, CUR-VB Committee C26A studied the question of how prestressed concrete construction with unbonded tendons may be carried out in a reliable manner from the corrosion protection point of view. Attention was focussed particularly on the requirements to be fulfilled by the grease applied to the tendons, by the tendon sheathing and by the method of finishing of the anchorages.

Proposals are made for an intermittent immersion test in which the moisture impermeability of greases can be tested with the aid of small steel plate specimens coated with grease, and for a stress corrosion test on a tensioned unbonded tendon with a view to ascertaining that the grease employed does not contain inadmissible amounts of harmful constituents. Both these functional tests are to be considered important for the certification, if subsequently introduced, of unbonded tendon systems.

Corrosion protection of unbonded tendons

1 Introduction

There are important differences between prestressing without bond and prestressing with bond, not only from the structural point of view, but also with regard to protection against corrosion. With bonded tendons the prestressing steel is embedded in grout, i.e., in a chemically basic (cement) environment with a high pH, which, as is well known, provides good protection. On the other hand, with unbonded tendons the steel is in a chemically neutral (grease) environment, which in itself does not provide protection against corrosive attack. Furthermore, unbonded prestressing steel differs from bonded prestressing steel in being much more critically vulnerable to the consequences of local attack, because, in the absence of bond, local fracturing of a tendon will render it incapable of performing its intended function at any point along its entirely length.

In prestressing without bond the prestressing steel (almost invariably in the form of seven-wire strands) is coated with grease and enclosed on plastic sheathing. The tendons are then cut to the required lengths and installed in the concrete structure. Already in an early stage of the development of this technique, however, misgivings were felt as to the durability of the prestressing steel used in this way. This culminated in the questions as to what requirements the protective grease should fulfil and how the steel could be effectively protected more particularly at the anchorages. The object of this concern was to prevent possible damage due to deficient durability of the prestressing tendon as a whole.

As for the grease, in course of time it emerged that the types generally employed did not provide the protection that they were supposed to. Because of this, the function of the enclosing sheath - initially conceived as merely a secondary one, namely, keeping the anti-corrosion grease in position around the steel - was elevated to the status of a primary function: the sheath itself was now required to contribute to protecting the steel from corroding and thus to preserving the durability of the structure.

The need to devote attention to the protection of the anchorages also became apparent when experience in actual practice yielded instances not only of totally unprotected anchorages, but also of reason-well protected ones in which moisture had nevertheless penetrated to the prestressing steel.

More recently, specific solutions to the problem of effectively protecting the prestressing steel, both near the anchorages and along the length of the tendon, have evolved in structural engineering practice. In fact, the CUR-VB Committee C26A has not very much to add to these solutions, except that the incidentally applied methods of protection now need to be embodied in a well and clearly formulated set of requirements.

Within the framework of the Fédération Internationale de la Précontrainte (FIP) a working group of the Commission on Prestressing Steels and Systems has already for some considerable time concerned itself with the durability of unbonded tendons. Good contacts have been maintained with that working group, and results of investigations have been exchanged. It emerged that no appreciable amount of research on the durability of the tendon as a whole had been, or was being, carried out anywhere in the world. The text and conclusions of this report will accordingly form the basis for international recommendations to be drafted by that FIP working group.

Many of the instances of trouble associated with unbonded prestressing tendons were found to be due to trivial causes, including the use of the wrong kind of wedges, inadequate protection of anchorages, etc. If these causes are excluded, however, and if it is presupposed that the correct materials are used in the correct manner and that effective protection is provided, three possible causes of damage are to be distinguished:

1. damage due to failure of the anchorage itself, e.g., because of non-compliance with the requirements of Netherlands Standard NEN 3869*;
2. damage due to failure of the tendon, e.g., caused by corrosion (stress corrosion) attributable to the presence of moisture in the sheath, whether from the outset or due to subsequent penetration;
3. damage due to faulty design of careless execution, e.g., because the actual distribution of the prestressing force in various parts of the structure was not properly taken into account or because of incorrect positioning of the tendons.

It has been found in practice that there has never been an instance of damage due to the first of these causes, and that damage due to the second has rarely occurred. Most cases of damage were attributable to the third cause. At the same time it should, in fairness, be noted that any damage due to the second cause is not likely to manifest itself until some time, possibly even a very long time, has elapsed, whereas damage due to the third cause will soon make its consequences distinctly felt.

The Committee's investigations have been concerned solely with the prevention of damage arising from the second of the above-mentioned causes, namely, attack of prestressing steel in consequence of inadequate protection, so that the durability of the prestressed structure was impaired.

The Committee is of the opinion that the recommendations made in the report will provide a reasonably good safeguard for the durability of prestressed concrete structures with unbonded tendons and the damage due to inadequate durability will be prevented. At the same time, however, the Committee must emphatically point out that the possibility of damage to such structures cannot be ruled out as long as correct design and careful execution are not ensured and indeed as long as it is not quite certain that the willingness and expertise essential to correct design are always available. The possibility that failure to comply with these requirements could bring the technique of prestressed construction as a whole into discredit is certainly not to be ignored.

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* see [28] in Chapter 7 References.

The above cautionary comments are of course not intended as a contribution to discrediting this technique. Quite the contrary. If the special aspects of design and execution are given the necessary attention, sound and durable structures can be built with unbonded tendons, offered both technical and economic advantages. These advantages are enumerated in the Introduction of CUR-VB Report 95.* It may be added that with unbonded tendons it is in general possible to achieve greater slenderness of structural members and therefore to effect savings in materials - cement, sand and gravel - that are becoming increasingly scarce.

After this introductory section, the problems associated with protection against corrosion of unbonded tendons are discussed in Chapter 2. In the study reported here it has been endeavoured to find effective solutions to these problems. Naturally, the primary objective has not been that of finding "the best" solution, but merely those solutions that will adequately safeguard the durability of structures built with unbonded tendons.

The experience gained by other investigators has been utilized as far as possible in this study. Chapter 3 reviews the principal data that have been collected in course of time. Chapter 4 describes the experiments that have been conducted over the years under the auspices of the Committee. An evaluation of the various aspects of protection against corrosion on the basis of data published in the literature, of the results of the Committee's own experimental investigations and of its discussions is presented in Chapter 5. Finally, Chapter 6 summarizes the principal conclusions. References are given in Chapter 7.

2 Characterization of the problems

2.1 *General*

The terms of reference of the Committee were to investigate the protection against corrosion of prestressing tendons installed without bond to the surrounding concrete. As described in the Introduction, the fundamental difference between prestressing with bond (bonded tendons) and prestressing without bond (unbonded tendons) consists, from the corrosion point of view, in the difference in chemical environment in the prestressing steel:

- with bonded tendons the environment formed by the cement of the embedding grout or concrete is strongly basic (pH = 12 to 13), which provides excellent protection against corrosion of the steel;
- with unbonded tendons the environment is neutral (grease coating) and does not in itself protect the steel against corrosion.

With regard to the protection of unbonded tendons against corrosion there are two aspects to consider:

- the materials (more particularly: grease) which come into direct contact with the pre-

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* see [29] in Chapter 7 References.

stressing steel must not cause any direct or indirect attack of the steel;
- the protection must be so effective as to ensure that any moisture penetrating from the outside will not get to the prestressing steel.

In principle, the first of these two requirements is the simpler to fulfil. The prestressing steel is coated with oil products or asphalt products which in general contain no substances deleterious to steel. Thus, various greases are generally used for preventing the corrosion of steel components, while asphalt-based products are used in cases where a dense waterproof layer is needed that will not itself attack the steel.

Yet it is by no means self-evident that such products are harmless to steel. Corrosive attack occurs as the result of a combination of moisture and unfavourable environmental conditions. If no moisture is present, no attack can develop. In the case of prestressing systems, however, there are ample possibilities for the presence of moisture:

- water that penetrates through the concrete to the steel;
- water that may make its way into the sheaths of the unbonded tendons during storage, transport, etc. (the ends of the sheaths then being open and therefore as yet unprotected);
- water that may enter at points where the sheath has locally been removed (at the end anchorages or intermediate anchorages).

If moisture penetrates to the steel and if oxygen is also present, corrosive attack of the steel will occur, accompanied by the formation of corrosion products, mainly iron oxides. This attack becomes more dangerous if hydrogen is locally evolved which can be absorbed into the steel. This may result in hydrogen embrittlement, causing sudden formation of cracks which propagate very rapidly resulting in fracture of the prestressing steel.

This phenomenon is caused basically by the decohesion of the iron atoms in the lattice as a result of the accumulation of penetrated hydrogen atoms formed during the corrosion process. The various corrosion processes that may be involved in prestressed concrete have been described in detail in CUR Report 49 [1]; see also [2]. The principal processes associated with cracking due to stress corrosion/hydrogen embrittlement are schematically shown in Fig. 1 (adopted from [3]).

Therefore the most important problem in connection with the corrosion protection of unbonded prestressing steel is the exclusion of moisture. In other words: how can any moisture that penetrates from the outside, whether with or without corrosion-promoting substances such as chlorides or sulphides, be prevented from getting to the steel?

Possible paths by which moisture can penetrate to the prestressing steel are indicated in Figs. 2 and 3. Thus, moisture may makes its way by diffusion through the concrete slab from above, possibly also from the underside, to the tendon (path 1). The obstacles encountered by the moisture on this path (i.e., the water barriers or waterproofing) are: the concrete surrounding the tendon sheath, the sheath, and the grease. Alternatively,

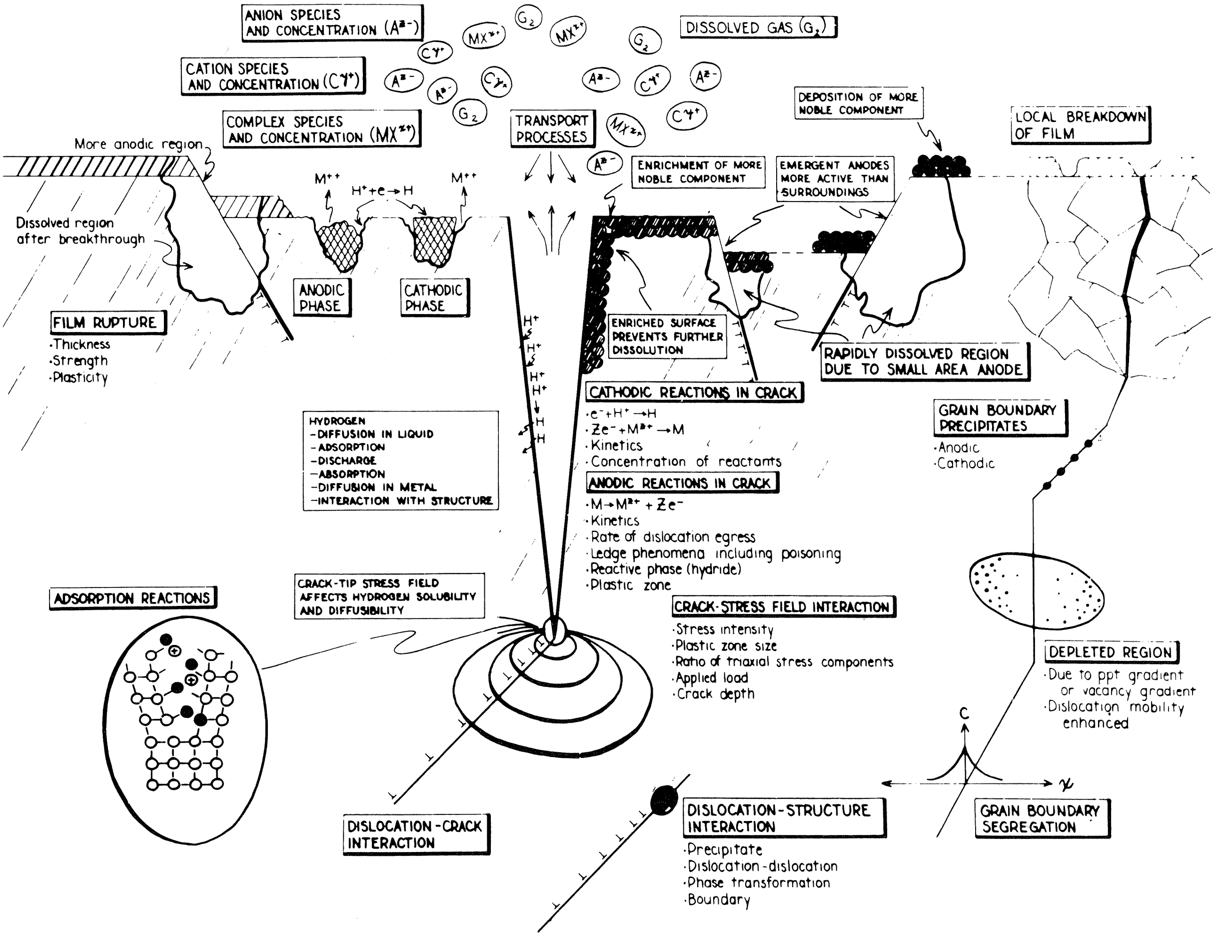


Fig. 1. Schematic representation of the principal processes affecting stress corrosion cracking (from [3]).

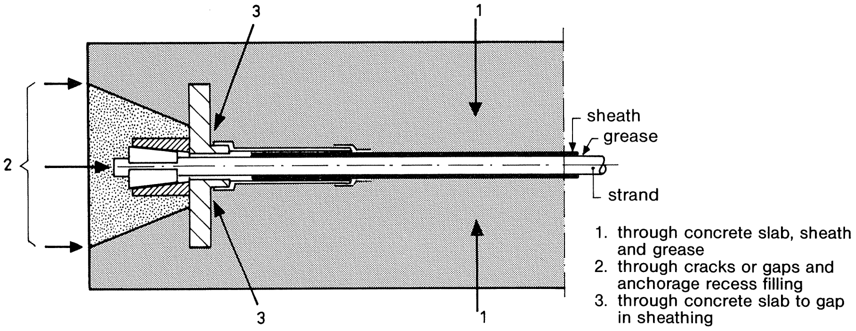
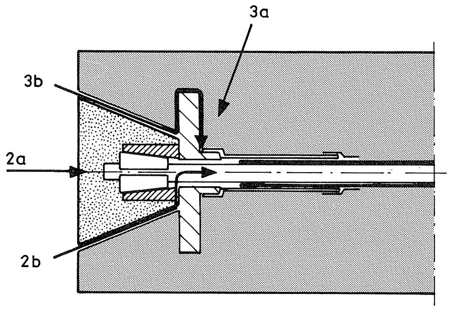


Fig. 2. Possible moisture penetration paths to the prestressing steel.



2a. through anchorage recess filling to end of strand
2b. through shrinkage gaps to strand
3a. through concrete slab to gap in sheathing
3b. through shrinkage gaps around anchor plate to gap in sheathing

Fig. 3. Details of moisture penetration paths to the prestressing steel.

moisture may penetrate from the end of the slab, making its way through the mortar filling of the anchorage recess and through the anchorage itself, thus reaching the prestressing strand (path 2a). If there is a shrinkage crack between the mortar filling and the surrounding concrete, moisture ingress will be even easier (path 2b). Both these effects are promoted by "breathing" of the structure. Thirdly, moisture can enter through gaps in the sheath: either direct through the concrete slab to the gap at the anchorage (path 3a) or via a shrinkage crack between the anchorage recess filling and the concrete and around the anchor plate (path 3b).

In assessing the corrosion protection it is necessary to distinguish between the *grease* with which the steel is coated, the *sheath* enclosing the steel with the grease, and the situation at the *anchorage*. The desired protective effects for unbonded tendons are indicated in Fig. 4 and will be examined in more detail below.

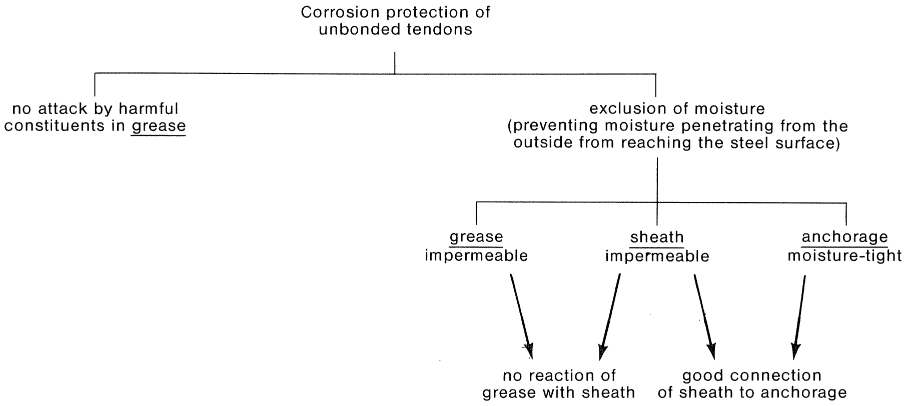


Fig. 4. Desired corrosion protection effects for unbonded tendons.

2.2 *Characterization of the problems associated with grease*

2.2.1 Impermeability to moisture

Existing recommendations or directives nearly always state the requirement that the grease must be impermeable to moisture (see more particularly [4]). If this requirement is fulfilled under all circumstances, any moisture that penetrates from the outside will evidently be prevented by the grease from reaching the steel. No corrosion of the steel will then occur, i.e., corrosion protection will be completely ensured (ordinary corrosion as well as stress corrosion). Most greases, however, can absorb a certain amount of moisture without giving this off at their interface with the steel. Since it is not permissible to presume that concrete is completely watertight and since the presence of an excess of water on the outside of the concrete structure must be reckoned with, the grease should conform to the requirement that it will, even in the long run, completely bar the penetration of an aqueous solution even under a slight overpressure.

2.2.2 Sealing layer

Even if the grease as such provides a complete barrier to moisture penetration of moisture to the steel may nevertheless occur if there are local interruptions or gaps in the layer (e.g., due to local damage) or as a result of "ageing" or "sedimentation" of the grease in course of time. Hence it is necessary to lay down requirements not only for the properties of the grease, but also with regard to its mode of application.

2.2.3 Deleterious action of grease

Grease is generally made from natural substances. It may contain numerous constituents, some of which may in themselves give rise to corrosion of steel: moisture and certain ions. Here, too, the governing principle is that corrosive attack can occur only if moisture and oxygen are present. Since it can never be guaranteed that both of these will be completely absent from the grease, it must instead be considered what guarantees can be given that the grease is free from constituents which, in the presence of moisture and/or oxygen (though in small amounts), could give rise to corrosion. The complex phenomena involved, and the fact that the substances concerned are mainly organic in character, make it very difficult to establish really meaningful and effective requirements for grease.

2.2.4 Summary of the problems associated with grease

The principal questions with which the Committee was faced with regard to corrosion protection by grease were:
- are the usual greases used for unbonded tendons sufficiently impermeable to moisture?
- if not: are there economically viable greases which are indeed impermeable to moisture?
- what requirements should be applied to the grease in order to ensure that, even if

small amounts of moisture and oxygen are present, corrosion of the steel will not occur?

2.3 *Characterization of the problems associated with the sheath*

From the point of view of corrosion protection of unbonded tendons the function of the sheath is, primarily, to ensure that the grease will always entirely enclose the steel. This means that the sheath must more particularly ensure:

- that the grease is not scraped off during handling and storage, nor at the time of installing the tendons and placing the concrete;
- that the grease will not - even in the long run - so react with the sheath that the grease or the sheath may cease to perform its function.

To prevent the grease being scraped off the prestressing steel, the sheath should possess such strength and wear-resisting properties that it will not split open, become punctured, wear through, etc. as a result of normal or unintended actions (placing the sheath around the tendon, friction during handling, abrasive wear, etc.) in the various stages of preparing and installing the tendon.

By applying functional requirements as to the wear resistance and other properties it can be ensured that the sheath will at all times remain intact over its entire length.

In those cases where the grease is not completely impermeable to moisture the sheath has a second function to perform, namely, that of preventing any ambient moisture from penetrating to the grease and the steel. To cope with such conditions, the sheath must fulfil more stringent requirements, such as:

- in placing the sheath around the tendon it is necessary to apply a process which will rule out any possibility that holes or thin areas in the wall of the sheath will be formed;
- the sheath must be sufficiently thick and watertight to obviate moisture penetration even where local damage occurs.

If these and other such requirements are fulfilled, a "second line of defence" is obtained, with better protective value of the grease/sheath combination.

The connection of the sheath to the anchorage calls for special care and attention and will be further considered in dealing with the problems associated with the anchorages in Section 2.4.2.

The problems to which the sheath gives rise can be summarized as follows:

- how can it be ensured that the sheath will be intact over its entire length?
- how is a good moisture-tight connection of the sheath to the anchorage to be achieved?
- what functional requirements should be imposed on the sheath so that what are to be regarded as normal actions during handling, storage and installation of the tendon

will not damage, puncture or cause any discontinuity to the sheath?
- of what material should the sheath be made in order to make quite certain that the grease will not react with it?
- what minimum thickness is needed for the sheath wall, in conjunction with the choice of material, to fulfil the above requirements?

2.4 *Characterization of the problems associated with anchorages*

2.4.1 General

In the anchorage zone the sheath and grease are removed for connecting the tendon to the anchorage. In this zone the exclusion of moisture must therefore be achieved by other means. The usual method is to fill the recesses formed in the concrete at the anchorages (anchorage recesses) completely with cement mortar. Quite often a preliminary treatment is applied before this sealing mortar is applied.

The following questions arise in connection with moisture exclusion at tendon anchorages:
- how can it be guaranteed that all the anchorage recesses have indeed been filled with mortar?
- what type of mortar is suitable for this?
- how can effective bonding of the mortar to the concrete be achieved?
- how can shrinkage cracking be avoided?
- how can the steel be pre-treated for extra protection?
- may the pre-treatment compound also be applied to the walls of the anchorage recesses?
- can tendons be so cut to length that there is sufficient concrete cover also to the protruding tendon end?
- how can tendons be cut in such a way that the grease coating or the sheath is not damaged?
- etc.

If satisfactory answers cannot be given to the above questions, other methods of sealing at the anchorages may have to be sought. The following are some alternative possibilities:
- applying a protective treatment to the end faces of the slabs (e.g., epoxy coal tar, bonding-on of plastic sheet with adhesive, etc.);
- filling the anchorage recesses by means of prefabricated plugs bonded in with adhesive (plugs of cement-based plastic composition, fixed in the recesses with a suitable adhesive);
- enclosing the whole anchorage in a plastic sealing unit (a sort of box around all the metal parts, which is connected to the sheath);
- etc.

In view of what has been said above, it will be evident that the *method of finishing* of the anchorages of the tendons must be done with considerable care. In practice these operations after leave much to be desired. Thus, it has been found in a number of instances that the mortar fillings of the anchorage recesses had been omitted altogether. Obviously, penetration of moisture is bound to occur under such circumstances.

It is also sometimes supposed that if the recesses are filled at all, there will be adequate protection. But it is not difficult to see that, say, a porous filling or a filling in which cracks develop or which (locally) detaches itself from the wall of the recess by shrinkage will also allow water to penetrate. Indeed, it is not inconceivable that this situation may be even more hazardous than a recess containing no filling at all, because moisture that seeps in through cracks or narrow (shrinkage) gaps will hardly be able subsequently to escape by evaporation. This problem will be examined in the following chapters.

In practice it is sometimes asked why moisture in an anchorage recess is not something that can be tolerated anyway. This is an understandable question, for it is rightly considered that the projecting end of the tendon is not tensioned and that corrosion thereof will not result in tendon fracture due to stress corrosion. Besides, it is argued, the other metal parts (anchor plate, wedges, etc.) are of such stout construction that some corrosion of these will surely not cause anchorage failure.

This may indeed be so, but that line of reasoning overlooks two important aspects. For one thing, the corrosive attack of the anchorage wedges may in the long run become so serious that their teeth are “eaten away”, so that the strand is no longer securely gripped and slips through the now defective anchorage. Furthermore - and this may result in serious corrosion in unbonded tendons - moisture may penetrate by diffusion between the individual wires of the strand (and in these internal spaces within the tendon there is moreover often little or no grease), so that the tensioned part of the strand is attacked, possibly giving rise to hydrogen embrittlement and sudden fracture. This hazard exists more particularly because there is no “concrete environment” at the steel surface to prevent a hydrogen evolution.

From the above considerations it will be evident that moisture penetration through the anchorage recess will in the long run be deleterious to the tensioned tendon. Also, very good sealing of the recess will obviously be needed to prevent moisture ingress via this path.

2.4.2 Connection of sheath to anchorage

An additional problem associated with the anchorage consists in efficiently connecting it to the tendon sheath. If cutting the sheath to the required length involves the removal of so much material as to leave insufficient for forming a proper connection, some alternative material will have to be used to replace it. Sometimes waterproof tape is used for the purpose, but it will readily be seen that it is rather difficult to obtain a watertight seal in this way. The resulting situation is liable to be unsatisfactory in that moisture may penetrate to the steel: rainwater (in the interval between installing the tendons and placing the concrete), cleaning water (from hosing the formwork just before concreting) or mixing water (from within the concrete while it is still in the plastic condition).

If in general concern is felt about the access of moisture to the steel at any point in a concrete slab where, as a rule, the steel is enclosed in its grease and sheath, then most certainly the zone just behind the anchorage - where the sheath is likely not to be connected in a watertight manner and where the grease may have to some extent been removed - must particularly deserve close attention in this respect.

2.4.3 Dead-end anchorages

The considerations relating to the problems at the anchorages have so far been confined essentially to the anchorages from where the tendons are tensioned (jacking anchorages). In the case of dead-end anchorages (non-jacking anchorages) the situation is in principle more favourable: when the concrete has hardened, the risk of moisture penetration at these anchorages is less serious, at least if a sufficient depth of good-quality concrete cover is provided (in accordance with the requirements stated in the VB '74 code of practice [27]).

Yet there are two reasons why protective measures are essential also at dead-end anchorages:

- The dead-end anchorage differs from the jacking anchorage in that hardly any tendon movement occurs during tensioning. Any moisture that has penetrated into the tendon or the grease between the time of installing the tendon and the hardening of the concrete will remain there. (In the case of a jacking anchorage it can reasonably be anticipated that the moist zone will, after tensioning of the tendon, have been pulled outside the anchorage and will then be cut off).
- At a dead-end anchorage the concrete cover provides the only protection against moisture penetration. Within the anchorage the sheath has been at least partly removed from the tendon, as well as most of the grease coating. Besides, it is very doubtful whether a sufficiently alkaline "concrete environment" does indeed exist in the immediate proximity of the surface of the steel.

For these reasons it is important to obtain a proper connection of the sheath to the anchorage in the case of dead-end anchorages as well.

2.4.4 Summary of the problems associated with the anchorages

From the point of view of corrosion prevention the problems associated with the anchorages can be summarized as follows:

- is the usual method of filling (sealing) the anchorage recesses effective?
- if not, are better methods available?

- is the application of a covering to the end faces of the slabs a meaningful protective measure?
- is enclosure of the anchorage in a plastic unit a suitable possibility?
- how can good connection of the sheath to the anchorage be achieved?
- what requirements are to be applied to the protection of a dead-end anchorage?

3 Literature research

3.1 *Introduction*

Much of the existing information on experience with prestressing without bond and on the types of grease to be used for the protection of unbonded tendons is recorded in merely a fragmentary way in reports which the Committee was able to obtain only through personal contacts. Very little has been published on these matters in the generally-accessible technical literature. All the same, the Committee feels that it has indeed succeeded in collecting all the most important information currently available, comprising details given by the suppliers of greases, by manufacturers of unbonded tendons, by some study groups (more particularly the working group "Durability of unbonded tendons" of the FIP Commission on Prestressing Steel and Systems) and a few publications, chiefly from the United States.

Unfortunately, it must be said that the available information is insufficient to allow definite conclusions solely on the basis thereof. This is more particularly because the information suffers from the following shortcomings:
- lack of clarity: especially with regard to anti-corrosion additives there is a good deal of obscurity;
- limited value: most of the tests reported were of too short a duration to enable unambiguous conclusions to be drawn;
- conflicting: many of the results are contradictory; the results that the Committee obtained in its own research was found to be at variance in many ways with the commonly accepted views.

In an attempt to make good this lack of reliable information, the Committee conducted a number of exposure tests that lasted for several years (in one instance: as much as $4\frac{1}{2}$ years). The results of those tests are reported in Chapter 4.
The information collected by the Committee from other sources is embodied in a separate report [5]. Here only the principal information from the "open" literature will be referred to.

3.2 *Initial situation*

Not long after the introduction of prestressed concrete construction with unbonded tendons in the Netherlands the Stuvo organization published a "state-of-the-art" report on corrosion protection for such tendons [6]. Even before the publication of that report there had been provisional recommendations - drawn up by ACI-ASCE Committee 423 - in use in the United States, where prestressing without bond had indeed been applied for some considerable time already [4].

Both in [4] and in [6] it is stated that the grease should possess the following properties:

1. remain free from cracks and not become brittle or fluid anywhere in the specified temperature range (usually extending from −20 °C to +70 °C);
2. be chemically stable throughout the service life of the structure;
3. not react with the surrounding materials such as prestressing steel, sheathing and concrete;
4. not be corrosive and preferably be corrosion-preventive by virtue of an added inhibitor;
5. be impermeable to moisture and chlorides;
6. be sufficiently viscous and adhere to the steel so as to resist the abrading action of the sheath or tube into which the greased tendon is inserted.

In order to prevent loss of grease and penetration of water, the greased strands were, in America, initially wrapped in nylon-reinforced paper. Other materials were sometimes used for the purpose, such as glass-fibre-reinforced kraft paper and sheet metal. At a later stage a polyethylene sheath formed with a longitudinal glued joint was similarly employed.

Under practical conditions in the Netherlands the thin sheathing material on tendons imported from America proved unsatisfactory on account of frequent mechanical damage (incurred during handling and transport) and splitting at the seams. Partly for this reason, the only material that has been used for the purpose in this country since the early 1970s is polyethylene sheathing - initially in the form of prefabricated tubing into which the greased tendon was slid, later in the form of a sheath extruded with the grease to enclose the tendon [7].

In the Stuvo report [6] it was indicated where doubts as to the correctness of the provisional recommendations existed and where it might be possible, by further research, to obtain greater certainty both with regard to the grease and with regard to the finishing of the anchorages. The CUR Committee C26A was set up, at the end of 1974, for carrying out such research.

3.3 *Principal literature*

The usual greases for unbonded tendons have a soap structure (preferably based on lithium stearate, but sometimes with calcium stearate) filled with mineral oil. Such greases are not impermeable to moisture, even though this is frequently claimed to be the case. At best, as result of the addition of corrosion inhibitors and substances that improve the adhesion of the grease to the prestressing steel (wetting agents), the corrosive action of any penetrating moisture is reduced. It was not till 1977–1978 that the Committee recognized indications in the literature that suggested that oil and grease are not impermeable to moisture [8, 9, 10].

Greases based on a microcrystalline wax with mineral oil are far less permeable to moisture. Viscosity Oil Cy. [11] has succeeded in producing a grease of this type which possesses good workability and which, thanks to a range of special additives it contains, virtually prevents any moisture reaching the surface of the steel coated with this grease. Although even this grease is not in fact completely impermeable to moisture, its corrosion-preventive action is to be rated as excellent. The firm of Shinko Wire also uses special greases for which a degree of corrosion prevention far superior to that of the usual greases is claimed. The results of research up to 1978 have been described by Tanaka et al. in a three-part report [12].

Griess and Naus [13], at the Oak Ridge National Laboratory, carried out tests on prestressing tendons for use in prestressed concrete pressure vessels. Those investigators report that corrosion can be practically obviated by applying correct storage, treatment, construction and corrosion protection. They performed tests in various environments with specimens of cold-drawn prestressing steel, with or without coating. Some of the specimens were subjected to a tensile test at low strain rate, whereas others were first exposed to a certain environment and were then subjected to a normal tensile test with constant (low) speed of crosshead movement in the testing machine. (Exposure was either 6 days in environment at 60% of tensile strength or 150 days in environment under zero tension). When coatings were used (two types of commercially available grease, petroleum-based with additives; also injected portland cement grout), it was found that no detectable effect due to the environment occurred during 6 days' or 150 days' exposure, provided that the coating or covering layer was intact during that period. Small cracks in the grease coatings employed were indeed harmful, especially in sulphide solutions. As for the grouted tendons, it was only when the grout layer contained cracks 0.8 to 1.0 mm or more in width that harmful consequences occurred, these being more severe according as the crack width was greater. With narrower cracks there was a self-healing action due to chemically basic liquid that was exuded from the cement grout and completely filled the cracks.

From the results of their tests Griess and Naus conclude that, if there is an intact and properly applied coating or covering of a suitable kind, there will be no direct danger to prestressing steel in the event of unexpected penetration of aggressive salts in low concentrations into the tendon ducts.

On the basis of the results of its own investigations the Committee cannot endorse that conclusion. A period of 6 days is evidently too short for attack of the steel – and therefore certainly for hydrogen embrittlement – to occur even if greases with relatively high permeability to water are used. During an exposure period of 150 days there will be penetration of liquid through the grease, but for untensioned test specimens this will only result in corrosive attack, but not necessarily as yet cause impairment of the properties of the prestressing steel.

The relatively large number of publications concerning the application of unbonded tendons in prestressed concrete pressure vessels for nuclear reactors is notable: besides Griess and Naus of ORNL [13], there are Blackie of CEGB [10, 14], Rotz of Bechtel [15], Hildebrand of General Atomic [16], and FIP [17]. The reason for this may have to be sought in the high degree of reliability required for nuclear engineering structures, so that financial resources for research are more readily made available for such purposes. In this sphere of application, circumstances of an unusual character may moreover play a part:

- in one instance, stray electric currents from welding equipment caused sodium sulphonate, which had been added to the grease as a corrosion inhibitor, to be converted into sulphide or free sulphur [14];
- at the Wylfa nuclear reactor the tendon ducts sometimes remained open for long periods, so that moisture got into then and easily penetrated through the grease coating, with pitting corrosion as the consequence of this [10];
- in another case, periodic blowing of warm air into the ducts caused condensation, thus temporarily producing very high relative humidity [13].

In [15] and [16] some special arrangements are described which were applied for checking the state of corrosion of unbonded tendons in nuclear reactor pressure vessels. The FIP Commission on Concrete Pressure and Storage Vessels conducted an inquiry into the corrosion protection of tendons in nuclear reactor structures [17].

The above-mentioned cases do not relate to the normal application of unbonded tendons, for which the risk of moisture penetration is much less. They do show, however, that the grease is unable to provide effective protection for the steel of moisture can get to the tendons.

That good connection of the sheath to the anchorage is very important is shown in [18], although this particular instance did not involve unbonded tendons. In a bridge near Hamburg, Germany, all the suspension cables (enclosed in a plastic protective covering) had to be renewed after only five years because of poor workmanship in the execution of the job (the covering did not continue into the cable attachment); thus there was inadequate protection against access by moisture and salt, so that corrosion and cracks in the covering occurred. It was not possible reliably to assess the actual condition of the cables, and for this reason it was decided to undertake their complete renewal.

So far as is known, no instances of damage affecting normal unbonded tendon systems in consequence of corrosion of the steel have been described in the literature. The Committee feels justified in inferring from this that the occurrence of such damage can be prevented if careful execution is applied. Those cases where corrosion damage affected unbonded tendons in actual practice - and which have not been included in the present review of the subject because they have not been described in the literature - were almost invariably due to defects of execution which could have been prevented if the (provisional) codes and recommendations had been more carefully complied with.

Many attempts have been made to establish a set of requirements for the grease as regards its corrosion-preventive action, purity and workability. So far, however, these efforts have not yielded a consensus of opinion. The most advanced treatment of the subject has been given by Tanaka [12]. The FIP working group [19] has also devoted much attention to these matters. The suppliers of grease will - on request, anyway - indeed give information on how their products behave with regard to various functional requirements. The subject has been comprehensively discussed in the report previously prepared by the Committee [5]. For the present purpose it will suffice to note the following:

- the most important functional test in use for corrosion resistance is a salt spray test;
- for the sake of ensuring freedom from impurities, requirements are sometimes imposed as to the maximum permissible amounts of chlorides, sulphides and nitrates;
- the consistency or viscosity of the grease is very important with regard to workability.

What quantitative requirements should be applied to these tests is still uncertain, but Tanaka [12] at any rate has put forward proposals which appear to have been adopted by the Posttensioning Institute of Japan.

For the sake of completeness it is to be noted that the Committee published its provisional findings at an earlier stage in 1978, in the journal "Cement" [20, 21].

4 Experimental research

4.1 *General*

The great difficulty in connection with research on corrosion and corrosion protection is the long duration of the experiments that have to be carried out. This is even more relevant in a case where the durability of a system already successfully applied in practice has to be assessed with a view to making proposals for enhancing the durability, if possible. In such a case an experiment under practical conditions can indeed hardly be expected to lead quickly to surprising results. Results on short-term can be expected only if the test conditions are made considerably more severe. But then the question of whether and how the accelerated test results are "translatable" into results for normal conditions will always be debatable.

This being so, the Committee was faced with a choice from three possibilities:

a. base itself on the experience reported by other investigators, i.e., not carry out any experimental research of its own;
b. carry out tests of very long duration under practical conditions;
c. carry out tests of short(er) duration under more severe conditions.

From the literature research already reported in the preceding chapter it had emerged - certainly in the early years of the Committee's investigations - that the findings of other researchers were unlikely to provide the basis for sufficiently reliable conclusions.

Since therefore the first of the three above-mentioned possibilities had to be discarded, the choice between the other alternatives (b) and (c) had to be considered. However, the Committee felt that it could avoid having to make this choice – for in either case it would still entail the risk of yielding inadequate conclusions – by exposing a number of normal prestressed concrete slabs with unbonded tendons to (more or less) normal environmental conditions as encountered in practice and, furthermore, by investigating a number of special aspects under more severe test conditions.

With this approach the whole system of prestressing with unbonded tendons was studied with a large number of variables by means of exposure tests of 4½ years' duration in all. Subsequently, various supplementary tests were carried out over a two-year period, some of which were performed under conditions of increased severity.

The experimental research conducted by the Committee will be described – though not in great detail – in this chapter.

4.2 *Exposure tests on two slabs with unbonded tendons*

4.2.1 Introduction and description of the slabs

In order to obtain some idea of the possible occurrence of corrosion affecting strand tendons and their anchorages, exposure tests were carried out on two prestressed concrete slabs. The anchorage recesses were pre-treated in different ways and were then filled with different types of mortar, except for one tendon in slab II, where the recesses were not filled. The object of this research was to find out what pre-treatment and what type of filling of the anchorage recesses are most effective in preventing corrosion on exposure to the outdoor atmosphere. The exposure time for slab I was 2 years + 3 months,

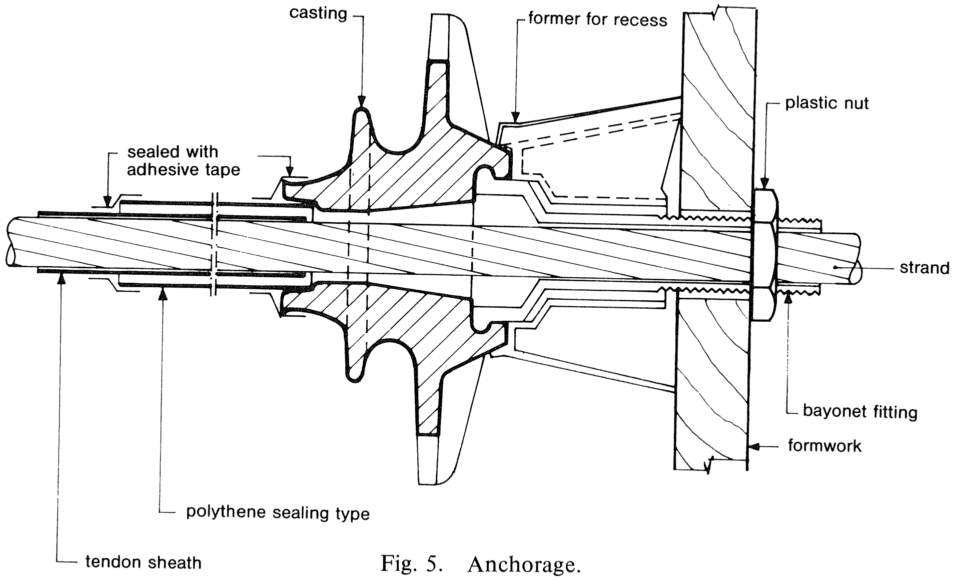


Fig. 5. Anchorage.

and that for slab II was 4 years + 6 months. In all, the slabs comprised 28 anchorages. The two slabs were made, at the request of CUR-VB Committee C26, for the purpose of strength tests. On completion of those tests the slabs were made available to CUR-VB Committee C26A.

The significant data of the slabs are listed in Table 1. The tendon anchorages were of the CCL type for strand. Details of this anchorage system are shown in Fig. 5. For forming the connection of the tendon sheath to the anchorage a short polythene sealing tube was employed, sealed with adhesive tape at both ends.

This procedure was adopted in order to prevent ingress of water while the surrounding concrete was still in the plastic state.

It is to be noted that the coils in which the unbonded tendons were supplied to the IBBC-TNO (Institute for Building Materials and Building Structures) were stored under favourable laboratory conditions. The tendons were installed in the formwork under the same favourable conditions.

Table 1. Data of the test slabs with unbonded tendons

Dimensions of the slabs: $l \times b \times h = 6.52\ \text{m} \times 1.80\ \text{m} \times 0.143\ \text{m}$

Unbonded tendons:
diameter - 12.5 mm
steel grade - FeP 1860
maximum sag - 30.0 mm slab I
- 22.5 mm slab II
number of tendons - 6 in slab I
- 8 in slab II
prestressing force - 100 kN
grease - Castrol Grippa 83
sheath - polyethylene, thickness 0.8–1.0 mm

After curtailment of the tendons (by grinding) and pre-treatment, if any, the anchorage recesses were filled with:
non-shrink mortar
rich mortar
normal mortar
lean mortar
The recesses of one tendon in slab II were not filled.

Materials used for mortar and pre-treatment:

	masonry sand :	cement :	water
rich mortar	1.8 :	1 :	0.35
normal mortar	3.4 :	1 :	0.55
lean mortar	4.8 :	1 :	0.75

non-shrink mortar - Betec grouting mortar with 6 litres of water/50 kg of dry substance
bonding agent - Cicol two-component epoxy glue
anti-corrosive agent - Rust-oleum 678 rapid-drying red priming paint

Table 2. Coding of anchorage recess fillings

tendon	direction of slab				
No.	north	south	mortar used	pre-treatment	slab
1	d_{41}	d_{42}	rich	anti-corrosive on steel parts	I
2	d_{51}	d_{52}	normal		I
3	d_{61}	d_{62}	lean		I
4	e_{11}	e_{12}	rich	anti-corrosive in entire anchorage recess	I
5	e_{21}	e_{22}	normal		I
6	e_{31}	e_{32}	lean		I
1	a_{12}	a_{11}	no mortar	-	II
2	b_{12}	b_{11}	non-shrink	-	II
3	c_{12}	c_{11}	rich	-	II
4	c_{22}	c_{21}	normal	-	II
5	c_{32}	c_{31}	lean	-	II
6	d_{12}	d_{11}	rich	bonding agent in entire anchorage recess	II
7	d_{22}	d_{21}	normal		II
8	d_{32}	d_{31}	lean		II

After being fully tensioned, the tendons were curtailed (by grinding) at a distance of 15 mm inwards from the slab end faces. The anchorage recesses were then filled with various kinds of mortar. The materials employed are indicated in Table 1.* In all, fourteen different types of seal were applied (in duplicate) in the recesses. The sealing methods are subdivided into five categories (a to e). This coding of the respective anchorage recess fillings is given in Table 2.

The anchorages in slab I were treated with an anti-corrosive agent, more particularly a type of paint (Rust-oleum), as this was recommended in the working instructions issued with the CCL anchorage system. In slab II the bonding agent called Cicol was, inter alia, applied because favourable experience had been gained with it as regards sealing function and bond strength.

At the time of filling the anchorage recesses the two slabs were 44 days old. Because the fillings were applied in a dry environment, the end faces of the slabs were covered with plastic sheet immediately after the filling operation. When the fillings had hardened, the slabs were transported to an outdoor site of the IBBC-TNO at Rijswijk, near The Hague. The position of the slabs during the exposure tests was as shown in Fig. 6. Slab II was horizontal, whereas slab I was sloped longitudinally at an angle of 15°.

* As stated in Table 1, the two slabs subjected to the exposure tests were constructed with unbonded tendons coated with Castrol Grippa 83, a strongly adherent lubricating grease containing added bitumen and graphite. At the start of the exposure tests (September 1975) this grease was extensively used for the protection of unbonded tendons in actual constructional applications. For practical reasons, however, other greases were subsequently adopted. It should therefore be noted that, with regard to the corrosion protection of unbonded tendons, the greases now in current use may yield different results from those obtained with the grease investigated.

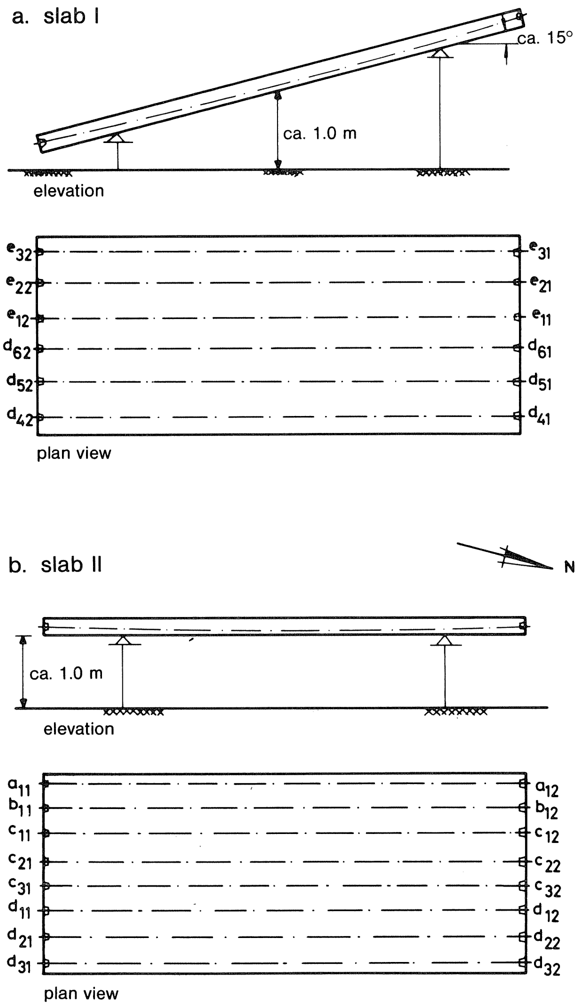


Fig. 6. Positions of the slabs during exposure test.

A more detailed description of these slabs, the procedure employed, etc. is contained in [22].

4.2.2 Inspection

Slab I was subjected to an inspection in January 1978 (exposure time = 2 years + 3 months), slab II in March 1980 (exposure time = 4 years + 6 months). In these inspections the following checks were carried out:

- Check for shrinkage gaps or cracks around the anchorage recess fillings. The width of the gaps detected between the concrete and the filling mortar (Fig. 7) was measured to the nearest 0.01 mm with a measuring magnifier.

- Check for bonding of the anchorage recess fillings. For this purpose tensile tests were performed for measuring the force needed for pulling the plugs of sealing mortar out of the recesses. In slab I the bond in all cases was ruptured at the interface of the mortar and the concrete, whereas in slab II fracturing within the mortar was the predominant form of failure in these tests. Both types of failure are shown in Fig. 8.
- Visual inspection of anchorages and wedges for corrosion. For this purpose the prestressing force in the tendons was released and the anchorages with the tendons were removed from the slab. The degree of rusting was subdivided into six rating classes: no rusting; very light rusting; light rusting; light/heavy rusting; heavy rusting; pitting. If the rust was removable with simple means, it was rated as "light/heavy". With "heavy rusting" it was not possible to get rid of it simply, and some slight change in surface structure had occurred. Fig. 9 shows some anchorages with wedges after removal from slab II.
- Visual inspection of the tendon sheath for damage. Radial pressure acting at curves in the tendon profile could have caused damage in the form of crushing or scuffing. This was checked by hacking out a strip of concrete in the middle of the slab and inspecting the sheath taken from this strip.
- Visual inspection of the strand tendons for corrosion. For this purpose the grease was first removed and then the appearance of all the wires was examined.

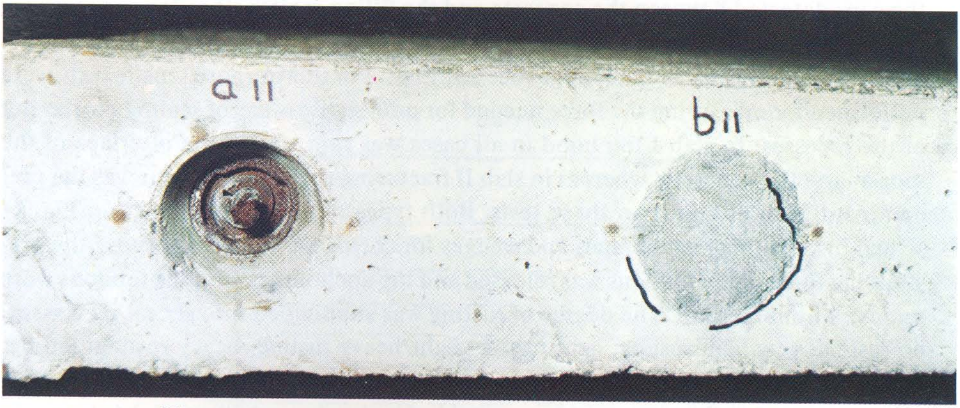
4.2.3 Results

The principal results of the inspection are given in Table 3 for slab I and in Table 4 for slab II.

4.2.3.1 Shrinkage gaps between mortar and concrete

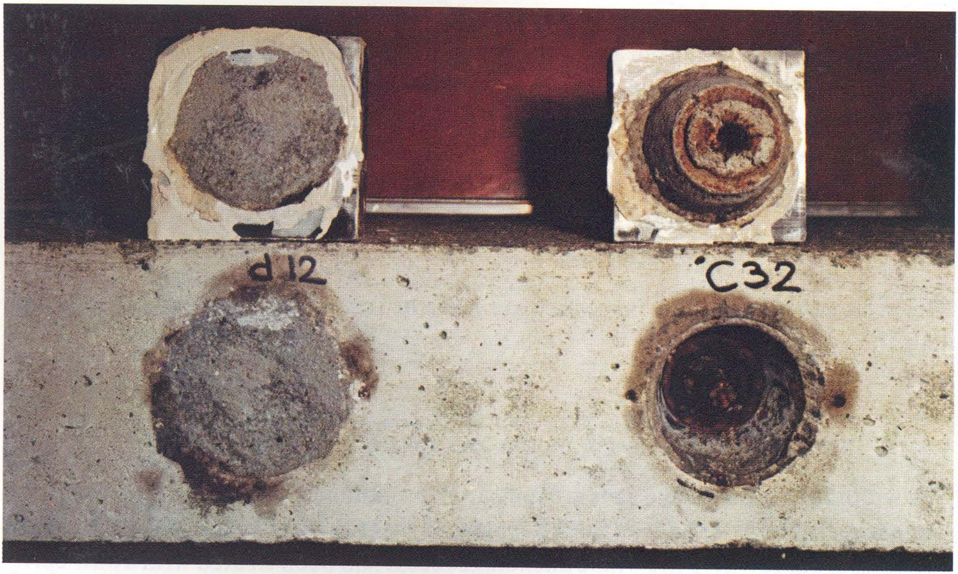
The widths of the shrinkage gaps are indicated in columns 2 and 8 of Table 3 and 4. On comparing columns 2 and 8 in Table 3 it appears that the width of these gaps was greatest in those cases where the whole anchorage recess had been treated with a anti-corrosive agent (rust-preventive paint). This was as expected, because the bond of mortar to concrete is in general adversely affected by an interposed paint-type coating. The sequence of widths listed in column 8 is in accordance with the general rule "the richer the mortar, the greater the shrinkage".

Comparison of the positions of the anchorage recess fillings in slab I reveals that the width of the gaps on the south side (= lower end of slab) was smaller than on the north side (= upper end). This would mean that the drying shrinkage on the north side was greater on account of longer drying periods (more wind and less dripping moisture). In slab II (Table 4) there is no distinctly discernible trend associated with the positions of the recess fillings.



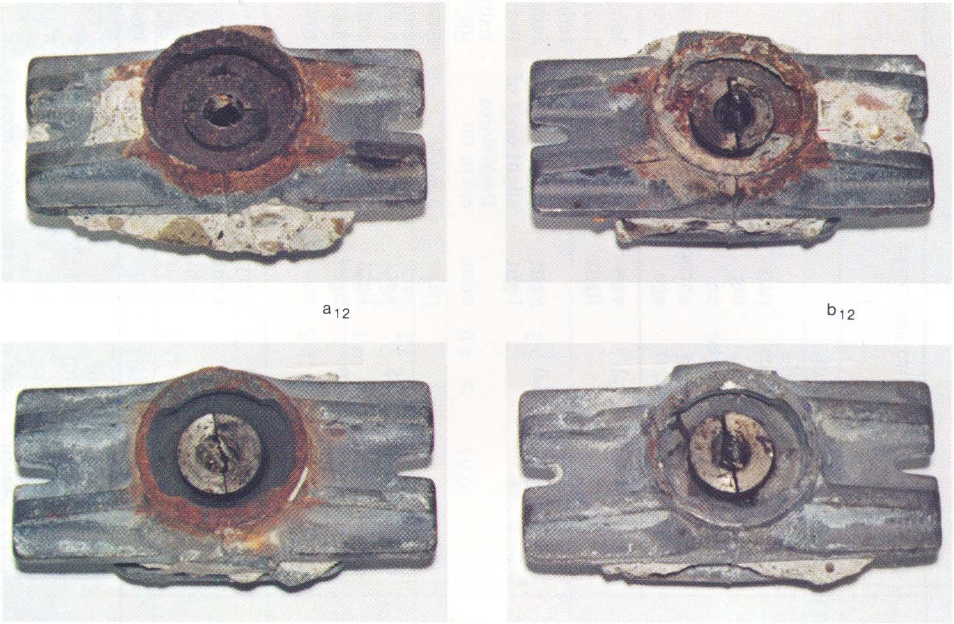
a_{11} recess not filled
b_{11} recess filled with non-shrink mortar; shrinkage cracks marked in black

Fig. 7. South end face of slab II after exposure, showing the recesses.



d_{12} fracture within mortar (pre-treatment: bonding agent in entire recess)
c_{32} rupture of mortar/concrete bond (no pre-treatment)

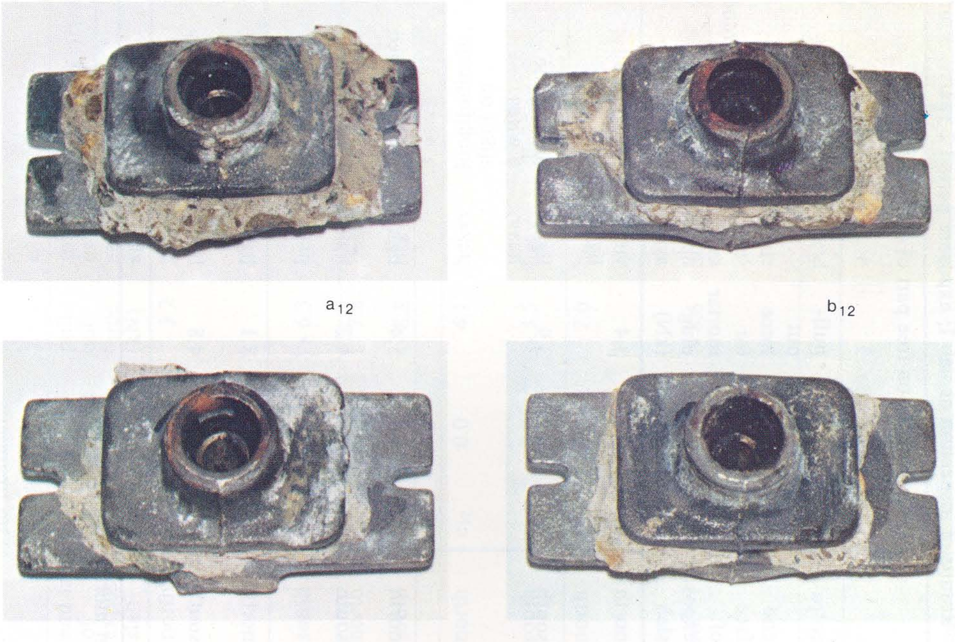
Fig. 8. North end face of slab II after exposure and after pull-out of mortar plugs, showing pulled-out plugs in the upper part and recesses in the lower part.



a_{12} b_{12}

c_{22} d_{12}

a. front view of anchorages



a_{12} b_{12}

c_{22} d_{12}

b. rear view of anchorages

Fig. 9. View of anchorages from north end face of slab II after removal.

Table 3. Results of inspection of slab I; exposure period 2 years + 3 months

		anti-corrosive on free part of anchorage						anti-corrosive in entire anchorage recess					
		1	2	3	4	5	6	7	8	9	10	11	12
						rusting on strands						rusting on strands	
mortar used in recess	end face of exposed slab	coding	crack width (mm)*	pull-out force for mortar plug (kN)	rusting on anchorage	outer wires	core wire	coding	crack width (mm)*	pull-out force for mortar plug (kN)	rusting on anchorage	outer wires	core wire
rich mortar	north	d$_{41}$	0.1	3.4	very light	hardly at all	slight trace	e$_{11}$	0.4	2.2	very light	longitudinally on 1 wire	longitudinally
	south	d$_{42}$	0.0	3.9	light/ heavy	on 4 of the 6 wires	distinct	e$_{12}$	0.2	2.0	very light	longitudinally slight on 4 of the 6 wires	longitudinally distinct
normal mortar	north	d$_{51}$	0.1	5.4	light	not examined	not examined	e$_{21}$	0.3	2.5	very light	present	present
	south	d$_{52}$	0.0	4.2	light	longitudinally slight on 1 wire	slight	e$_{22}$	0.1	4.0	light	distinct	distinct
lean mortar	north	d$_{61}$	0.1	8.1	light	slight	slight	e$_{31}$	0.1	1.4	very light	longitudinally on 3 wires	distinct
	south	d$_{62}$	0.0	4.8	light/ heavy	longitudinally slight on 1 wire	slight	e$_{32}$	0.0	1.9	light	not examined	not examined

* between mortar and concrete

Table 4. Results of inspection of slab II; exposure period 4 years + 6 months

		no treatment						epoxy bonding agent in entire anchorage recess					
		1	2	3	4	5	6	7	8	9	10	11	12
mortar used in recess	end face of exposed slab	coding	crack width (mm)*	pull-out force (kN)	rusting on anchorage	rusting on strands outer wires	core wire	coding	crack width (mm)*	pull-out force (kN)	rusting on anchorage	rusting on strands outer wires	core wire
rich mortar	north	c_{12}	0.2	3.2	heavy	slight on 5 wires, up to 50–100 mm behind the wedges, in one case 250 mm	none	d_{12}	0.0	> 15.0	light	longitudinally slight on 2 wires	slight
	south	c_{11}	0.1	> 6.3	heavy	slight on 4 wires	slight	d_{11}	0.0	> 18.5	none	slight	slight
normal mortar	north	c_{22}	0.05	7.8	heavy	slight on 3 wires	longitudinally distinct	d_{22}	0.0	> 9.1	very light	none	none
	south	c_{21}	0.1	> 8.8	heavy	slight on 3 wires	slight	d_{21}	0.0	> 7.7	very light	present on 5 wires	longitudinally
lean mortar	north	c_{32}	0.0	4.1	heavy	longitudinally slight on 1 wire	none	d_{32}	0.05	> 4.0	none	slight on 2 wires	none
	south	c_{31}	0.05	> 3.5	heavy	slight on 3 wires	slight	d_{31}	0.0	> 5.2	none	none	none
non-shrink mortar	north	b_{12}	0.5	7.0	heavy	slight on 1 wire at 100 mm behind the wedges	none						
	south	b_{11}	0.3	> 8.6	heavy	slight on 3 wires directly behind the wedges	none						
no mortar	north	a_{12}			pitting	heavy outside the wedges, slight at 50–100 mm behind the wedges	heavy outside the wedges; remainder none/slight						
	south	a_{11}			pitting	heavy outside the wedges, slight at 250 mm behind the wedges	heavy outside the wedges; remainder none/slight						

* between mortar and concrete

The widest shrinkage gaps were formed when a non-shrink mortar was employed (column 2 of Table 4). When an epoxy bonding agent was applied to all parts of the recess (column 8), virtually no shrinkage gaps occurred.

4.2.3.2 Bonding of the recess fillings

The pull-out forces for removing the mortar sealing plugs (recess fillings) are indicated in columns 3 and 9 of Tables 3 and 4. On comparing these forces for slab I (Table 3) it appears that the application of an anti-corrosive agent to the whole anchorage recess resulted in bond impairment. For slab II (fracturing predominantly in the mortar!) it can be stated that in most cases the pull-out force for the mortar plug as a whole would have been larger than the values listed in Table 4. In those cases the pull-out force is preceded by the sign $>$.

4.2.3.3 Corrosion of anchorages and wedges

After the pull-out tests on the mortar sealing plugs had been performed, visual inspection of the anchorages was carried out. Only on the anchorages of series d in slab I – where an anti-corrosive agent had been applied to the free part of the anchorage – were some traces of rusting found. After the anchorages had been hacked out of the concrete, there was found to be some rusting on their undersides, this being presumably due to sedimentation of the fresh concrete, causing a minute gap to form there.

In slab II the anchorages did not display any preferred zones of rusting. After pull-out of the mortar sealing plugs from the recesses of the series b and c anchorages in slab II there was seen to be rusting on those anchorages while still embedded in the concrete.

In the case of the unprotected anchors (no recess fillings) which had been exposed to the weather for 4 years + 6 months there was pitting of the anchorages and wedges. The wedges of the other anchorages were not, or only lightly, attacked by corrosion.

From a comparison of the ratings of rust formation of series b and c in slab II it appears that in this test there was no advantage in using a non-shrinkage mortar. The best results were obtained when an epoxy bonding agent was applied to the whole anchorage recess. In that case there was light to very light rusting on three of the anchorages; the others were found to be quite intact on removal from the concrete.

Comparison of series d in slab I with series c in slab II shows that rusting had approximately doubled in consequence of increasing the exposure time from 2 years + 3 months to 4 years + 6 months.

4.2.3.4 Corrosion on the strands

The data are listed in columns 5, 6, 11 and 12 of Tables 3 and 4. Most of the rusting on the strands behind the wedges was observed in slab I, which, as already stated, was exposed for 2 years + 3 months and was sloped longitudinally at an angle of 15° during that time. Distinctly less rusting was observed in slab II, with an exposure period of 4 years + 6 months, during which time the slab was horizontal. Many of the wires in slab II were found to have a black deposit on them (see Table 4), which must be regarded as incipient rusting.

In general, rusting proceeds in the longitudinal direction and occurs on the core wire as well as on the other wires of the strand. This is due to the penetration of moisture, which largely progresses by capillary action. The heaviest rusting occurred in slab I at the tendon ends which were located on the south side (lower end) of the tilted slab. There is no clearly ascertainable reason for this. Probably the lower part dries more slowly after rain, so that capillary penetration of moisture may occur there with greater intensity.

The application of an anti-corrosive agent to the concrete surfaces failed to achieve the anticipated result because the adhesion between the mortar and this paint was not good enough to prevent a shrinkage gap from forming. The relatively favourable result that was obtained in slab II with the tendon without mortar-filled anchorage recesses must, in the Committee's opinion, be regarded as a "maverick", for in actual practice such a manner of construction is found rather frequently to have disappointing consequences.

The use of a so-called non-shrink mortar should, the Committee feels, not be overrated. This view is also supported by the findings of investigations carried out elsewhere and brought to the Committee's attention.

4.3 *Moisture penetration via the anchorage*

4.3.1 Introduction; description of test set-up

As described in Section 4.2, one of the exposed slabs contained a tendon whose anchorage recesses had not been filled with protective sealing mortar. After an exposure period of 4 years + 6 months, at and behind the wedges the tendon was found to have remained almost unaffeced by corrosion. From this it can be inferred that little or no moisture had managed to get to the tendon in these zones. On the other hand, heavy rusting had indeed occurred on the part of the tendon (end of the strand) that projected beyond and outside the wedges. However, the Committee is acquainted with instances of tendon fracture where no filling of the anchorage recesses had been provided either. This fact is therefore at variance with the result of the exposure test. For this reason, a test series consisting of six test pieces was arranged with a view to investigating whether moisture penetration from the outside, via the anchorage, into unbonded tendons is indeed possible. For this purpose, a varying lower temperature in relation to the ambient temperature was produced in the unbonded tendons under investigation. The climatic conditions in which these specimens were tested are, however, not directly comparable with those encountered in actual practice.

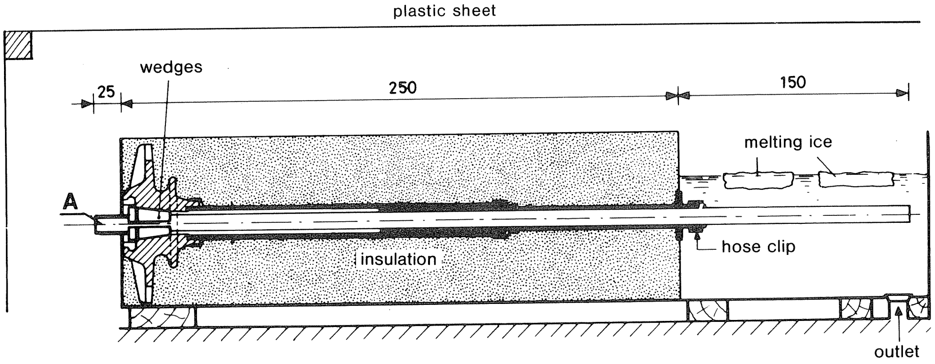


Fig. 10. Set-up for preliminary test for moisture penetration in air-conditioned room. (dimensions in mm)

The test set-up is shown in Fig. 10. The anchorage used here is of the same kind as that in the exposure tests decribed in Section 4.2. The wedges were pushed in with a force of about 120 kN. The transition from the tendon anchorage to the short sealing tube and from this tube to the tendon sheath was sealed with waterproof adhesive tape. The sheath had been removed from the end of the tendon (strand) over a length of 150 mm. This bared portion of the tendon was placed in a small tank which, during alternate periods, was either empty or contained water with melting ice. In order to obtain an appreciable lowering of the temperature in the short piece of tendon protruding beyond the anchoring wedges (see A in Fig. 10), thermal insulation was applied around the unbonded tendon and the anchorage. In all, six test specimens were placed in an air-conditioned room in which 98% relative humidity and 20 °C temperature were maintained. The whole group of specimens was covered with plastic sheet.

For comparison, six specimens were placed in an outdoor location (under a pentroof): see Fig. 11. In these specimens there were no differences between the temperature of the tendon and the ambient temperature. It should, finally, be noted that in all twelve specimens the tendon was horizontal.

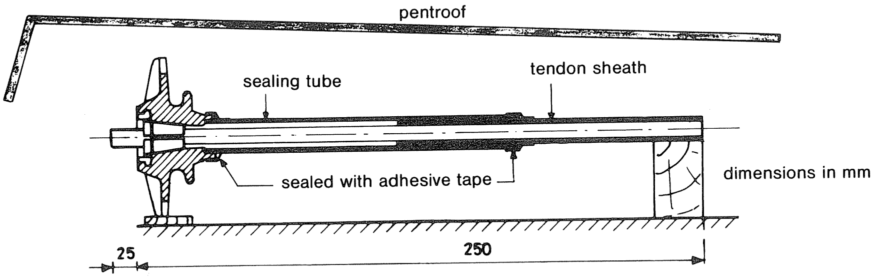


Fig. 11. Set-up for preliminary test for moisture penetration in outdoor location.

4.3.2 Results

After successive intervals of several weeks, two tendons – one from the air-conditioned room and one from outdoor storage – were each time inspected for corrosion. The principal results of these inspections are given in table 5. A more detailed description of these tests is presented in [23].

For the specimens which had been exposed to temperature variations the following conclusions were thus drawn:

- in principle, penetration of moisture is possible through the anchorage and then through the space between the sheath and the tendon;
- corrosion of the core wire of the strand in many cases extended less far than that of the outer wires;
- the moisture penetration distance is not a function of time, but would appear to depend on chance circumstances (perhaps whether there happens to be more or less grease on the strand); see Table 5.

As corrosion of the tendon behind the anchorage had occurred already after a short time (6 weeks), it can be inferred on the evidence of these test results, too, that good sealing of the anchorages is absolutely necessary.

For the specimens that had been stored in the open air under a pentroof the following conclusion was drawn:

- no rusting was found to have occurred on the tendon even after 45 weeks; the Committee considers, however, that this observation does not justify the conclusion that rusting will never occur under similar conditions.

Table 5. Results of visual inspection for corrosion of strands from the moisture penetration tests

		specimens from air-conditioned room		specimens from outdoor exposure
test	duration of tests (weeks)	length of strand corroded behind the wedges (mm)	corrosion on remainder of strand length	corrosion on the strand
I1	6	70	none	none
I2	15	100	very light	none
I3	25	150	light	none
I4	32	20	light	none
I5	39	60	light	none
I6	45	60	light	none

4.4 *Exposure of greases*

4.4.1 Introduction; types of grease investigated

In view of the conflicting statements in the literature on the corrosion protection provided by greases, the Committee carried out three series of experiments in which various greases were exposed to wet environmental conditions for long periods of time. The purpose of the exposure tests can be characterized as follows:

- in the first series various greases were exposed in order to obtain some idea of moisture penetration (see Section 4.4.2);
- in the second series various amounts of impurities (chlorides and sulphides) were added to a particular grease that is used in unbonded tendons, the object of these tests being to find out whether such impurities cause more rapid corrosive attack; if so, stringent requirements to ensure the exclusion of these impurities would have to be specified (see Section 4.4.3);
- in the third series various types of grease were applied to small mild steel plates and then exposed for considerable lengths of time in various environments in order to find out to what extent rusting occurs; also, it was thus possible to ascertain whether there are major differences in corrosion protection between different types of grease (see Section 4.4.4).

The investigation was more particularly concerned with establishing by the use of which greases and which additional measures the corrosion of the steel could be avoided. In order to ascertain whether the chlorides and sulphides present in the grease give rise to hydrogen embrittlement, an additional series of tests would have to be performed in which tensioned prestressing steel coated with grease containing impurities is exposed to the test conditions. Such tests were not performed, however, because the Committee bases itself on the view that, as soon as corrosion due to chlorides and sulphides occurs, there is *by definition* a hazard of stress corrosion/hydrogen embrittlement. In practice such a “system test” procedure would nevertheless provide a good indication of the stress corrosive or hydrogen embrittling action of any chlorides, sulphides and nitrates that may be present. A test procedure of that kind could be as follows:

- the sheath enclosing a portion of unbonded tendon is locally removed or pierced;
- the tendon is tensioned to 80% of the characteristic tensile strength;
- the portion of tendon where the sheath has been removed or pierced is immersed in distilled water;
- the test conditions are maintained for 6 months or until fracture of the tendon occurs.

The various greases employed in the three series of tests are indicated in Table 6. The designation A relates to a grease that is used for normal unbonded tendons. Chemically it has a soap structure (lithium stearate) filled with mineral oil to which certain substances (inhibitors) have been added. At the request of one of the Committee members, the supplier artificially added chlorides and/or sulphides to this grease (A1, A2, A3).

Table 6. Types of grease investigated

type of grease	designation	application in: series 1 (4.4.2)	series 2 (4.4.3)	series 3 (4.4.4)
A	normal unbonded tendon grease	x	x	x
A1	A + 100 ppm chlorides		x	
A2	A + 100 ppm sulphides		x	
A3	A + 50 ppm chlorides + 50 ppm sulphides		x	
B	grease resistant to sea water			x
C	improved unbonded tendon grease	x		x
D	specially developed grease	x		x

B is a comparable product with added inhibitors for increasing its resistance to sea water.

C is an improved grease for unbonded tendons which has occasionally been used for nuclear reactor structures in America. It contains other and more highly active inhibitors.

D is a grease specially developed for tendons in nuclear reactor structures. It does not possess a soap structure, but consists of pure hydrocarbons (petrolatum with mineral oils) to which various active inhibitors have been added. This grease is characterized by increased alkalinity due to the addition of, among other substances, calcium carbonate; it is considerably more expensive than the other greases. Its manufacturer guarantees high purity (max. 2 ppm of chlorides, sulphides and nitrates), while substantially better performance with regard to water penetration and corrosion protection is claimed for it. On account of its price it is not used for ordinary applications of unbonded tendons. It has been included in the tests in order to serve as a basis for comparison.

4.4.2 Tests for water penetration into grease

The greases were each placed in a 10 mm thick layer in a round glass dish. The dishes were then immersed in demineralized water or in water with a 3.5% content of NaCl. The exposure test was of 622 days' duration. Inspections were carried out after 19 days, after 333 days and after 622 days. The extent to which the grease becomes turbid provides a good measure of the extent to which water (possibly containing chlorides) has penetrated into the grease.

Thanks to certain arrangements in the experimental set-up, no penetration along the wall of the dish occurred. This was confirmed by the absence of premature turbidity at the bottom of the grease layer due to such penetration.

The results are summarized in Table 7 for exposure of the grease specimens in demineralized water, and in Table 8 for their exposure in 3.5% NaCl solution. Fig. 12 schematically shows the increase in turbidity that occurred in the specimens exposed to demineralized water.

Table 7. Water penetration into grease; environment: demineralized water

type of grease	appearance after an exposure period of 19 days	333 days	622 days
A	turbidity at interface with environment	grease is entirely white	grease is entirely chalk-white
C	as grease A after 19 days, but less pronounced	turbid layer about 3 mm thick	grease is turbid throughout, with 3 mm thick chalk-white layer at interface
D	unchanged	unchanged	turbid

The following conclusions can be drawn from the results of the tests:

- None of the three greases investigated was found to be completely resistant to water penetration throughout the whole period of exposure.
- Grease of type A, which is extensively used in unbonded tendons for normal purposes, has so low a resistance to water penetration that this is of little practical value.
- Water penetrates at a distinctly slower rate into grease of type C than into grease of type A. Even so, the length of time during which the grease offers good resistance to penetration must be rated as short.
- Grease of type D is completely resistant to water penetration for a reasonably long time (more than 1 year). At the end of that period, however, water slowly penetrates, possibly as a result of gradual leaching of the water-repellent substance out of the grease.

Table 8. Water penetration into grease; environment: water with 3.5% NaCl

type of grease	appearance after an exposure period of 19 days	333 days	622 days
A	turbidity at interface with environment	grease is turbid throughout	grease is turbid throughout, with a chalk-white layer of 3 mm thickness at interface with the environment
C	as grease A after 19 days, but less pronounced	turbid layer about 1 mm thick	as grease A after 622 days
D	unchanged	unchanged	turbid

Note: A grease sample of type A which had become turbid at the interface after about 50 days' exposure became quite clear again after storage in air for some weeks. Turbidity in this case is therefore a reversible process caused by water penetration.

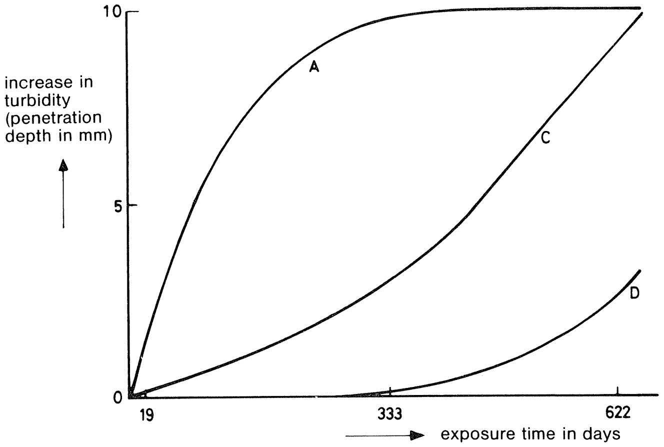


Fig. 12. Increase in turbidity of greases A, C and D in demineralized water.

- In grease specimens immersed in pure (demineralized) water the penetration proceeds a litte more rapidly than in those immersed in brine (water with 3.5% NaCl). The difference between these penetration rates is not of great significance, however.
- The penetrated water slowly evaporates on exposure to the air. The salt contained in any brine that penetrated into the grease remains behind on evaporation of the water.

The test results show that the unbonded tendon greases employed under normal conditions offer only limited or very little resistance to the penetration of water. Greases that do resist water penetration for a reasonable length of time are available, but are expensive, and even their resistance does not last indefinitely.

4.4.3 Tests with contaminated greases

This series of tests was carried out with the object of investigating the corrosive influence, if any, of impurities or additives in unbonded tendon greases. In order to keep the investigation simple, the tests were performed with small greased steel plates which were intermittently immersed in various liquid environments. It was ascertained to what extent corrosion phenomena occurred in consequence thereof. The test procedure is indicated in Table 9.

In these tests only one type of grease (A) was used, which in some cases was intentionally contaminated with certain quantities of chloride and/or sulphide (A1 through A3). These quantities of impurities were moreover intentionally large in comparison with those which could be encountered in normal practice, the object being to establish clearly their effect, if any, in causing corrosion phenomena. The environment to which the greased plates were exposed was distilled water for some of these specimens, and water with 3.5% NaCl for the others.

Table 9. Immersion tests with greased steel plates (second series, Section 4.4.3)

Mild steel test plates (grade Fe 360), 50 mm × 40 mm, degreased in acetone, edges lacquered
Grease applied to bare surface area (30 mm × 40 mm) with spatula
Thickness of grease coating 0.4 mm and 0.8 mm respectively
Greases used: A
A1 = A + 100 ppm chloride
(mixed uniformly into the grease by two different methods)
A2 = A + 100 ppm sulphide
A3 = A + 50 ppm chloride + 50 ppm sulphide
Greased plates intermittently immersed: 6 hours in liquid, 6 hours out of liquid, etc.
Liquid:
- distilled water
- aqueous solution of 3.5% NaCl

Duration of test: 190 days

At the end of the test period (after 190 days) the grease had not noticeably changed on the specimens that had been immersed in distilled water, but had in general become very turbid on those in the salt solution. Also, the first-mentioned specimens were free from rust at the end of the test, whereas those exposed to the action of the salt solution had distinctly rusted: plates coated with a 0.4 mm thick layer of grease were covered with rust over their entire surface; those with 0.8 mm of grease coating had rusted over a proportion of their surface area ranging from 45 to 75% after 190 days.

There were only minor differences between the various specimens in each category, i.e., the deliberate contamination with chlorides or sulphides was found to have no significant effect on the corrosive attack. This is not really very surprising, because the high concentration of NaCl (more than 200 times the concentration of the added chloride contamination) could indeed be expected to have largely blotted out the effect of these impurities.

The presence of sulphide undoubtedly increases the hazard of hydrogen embrittlement of tensioned prestressing steel, but this is something that could not be detected by means of these simple immersion tests.

From the results of this series of tests it can likewise be concluded that water is able to penetrate through the grease. So long as the water is pure, however, it will not cause any rapid corrosion; on the other hand, this will occur if the water contains salts. How much salt the water must contain in order to initiate early corrosive attack is a question that could not be answered by these investigations; the test solution employed had too high a salt content for that. "Exaggerated" purity requirements for the grease are certainly unwarranted. Quite probably the normally attainable purity is adequate, certainly in so far as the content of *chlorides* is concerned.

4.4.4 Comparative tests on corrosion protection of greases

In these tests the protective effect of four unbonded tendon greases in the as-supplied condition, i.e., without intentionally added impurities, was investigated on a comparative basis. In this test series, too, greased steel plates were used, which were intermettently immersed in aqueous solutions respectively containing 3.5% NaCl (artificial sea water) and 0.35% NaCl (diluted sea water). Details of the tests are given in Table 10. As such tests would certainly have had to be of long duration if carried out under practical conditions, it was attempted to find ways and means of accelerating them, preferably of such a kind as to link up with particular cases encountered in actual practice. This was achieved by the application of intermittent immersion and by using water containing 3.5% NaCl. Alternations of wetting and drying are indeed quite possible in practice. In view of the strong effect that 3.5% NaCl could be expected to produce, tests with a concentration of only 0.35% NaCl were performed for comparison.

The leaching action of the salt solutions employed in the intermittent testing procedure was, however, an effect very different from what occurs in practice. Repeated immersion is bound to have a more strongly leaching effect than is encountered under normal practical conditions, where in most cases the penetration of water, or indeed sea water, to the steel as a result of a fault or irregularity of execution will be only local and probably be confined to a small or relatively small amount; besides, such water in contact with the steel will not be repeatedly replaced by fresh supplies of water. The strongly leaching action associated with the test conditions can be expected to occur in actual structures only in a disaster situation. It is not certain that the difference in leaching action between the test conditions and normal practical conditions is indeed important with regard to the comparative results. However, if any particular grease to be investigated claims to have special properties and if these are due to the presence of a substance liable to be leached out (such as possibly the inhibitor in grease B), the abovementioned difference may indeed be of importance. This aspect should be taken into account in making an assessment of the greases.

Table 10. Immersion tests with greased steel plates (third series, Section 4.4.4)

Mild steel test plates (grade Fe 360), 50 mm × 40 mm, degreased in acetone, edges lacquered
Grease applied to bare surface area (30 mm × 40 mm) with spatula
Amount of grease: in 1 coat 0.26 ± 0.03 g
in 2 coats 0.55 ± 0.06 g
Average coating thickness: 0.23 mm and 0.48 mm
Greases used: A-B-C-D
Greased plates intermittently immersed: 6 hours in liquid, 6 hours out of liquid, etc.
Liquid: aqueous solution of 3.5% NaCl
aqueous solution of 0.35% NaCl
Number of greased plates: 9 plates per coating thickness, per type of grease and per test solution, total $9 \times 2 \times 4 \times 2 = 144$ plates
Inspection for rusting:
- at regular intervals
- at each inspection, some plates cleaned for judging actual rusting
- criterion: percentage of surface area that had rusted

Duration of test: up to 279 days

The following emerges from the results of this series of tests:

- Grease D provided complete protection during the test, even when applied in just one coat. There was, however, a slight indication that some incipient attack may nevertheless occur in thin coatings. Besides, the result does not of course mean that equally favourable behaviour will be sustained in testing continued over a long period of time. At the same time, however, it is evident that grease D offers much better corrosion protection in (artificial) sea water (whether diluted or not) than the other greases investigated.
- Grease A, applied in two coats, provided nearly 100 days' protection in (artificial) sea water and nearly 200 days' protection in diluted sea water. A thin coating has considerably less protective effect, and there is rapid failure of the grease. In thick coatings there likewise occurs failure in course of time.
- At the end of the test the results obtained with grease B were very similar to those obtained with grease A in terms of rust formation, but it appeared that in both the test solutions rusting of the specimens coated with grease B commenced later. This could indicate the effectiveness of the inhibitor in this grease in the early stage of the test. When the inhibitor has been leached out, incipient rusting then proceeds at an accelerated rate, however.
- Grease C turned brown fairly quickly, so that it was difficult to ascertain clearly just when rusting started. Specimens treated with two coats of grease showed, when cleaned, that no rusting had occurred up to 150 days' sojourn in the test environment, however. Gradual rusting then commenced. Specimens provided with only one coat of grease rusted much more rapidly, so that rust in areas where the coating had developed damage was manifest already at somewhat under 100 days' exposure, even in the diluted solution. At the end of the test the protection provided by this grease was found not to be adequate, certainly not when it was applied in a thin coating. Whether this failure can be attributed to the leaching removal of a protective substance from the grease or a possible intrinsic shortcoming of the grease itself cannot be determined without further research.

To summarize, it can be stated that these test results show the use of grease D under leaching conditions to offer advantages, in terms of corrosion protection, over ordinary grease (as represented by grease A). Against this, the high cost of grease D – between twice and three times that of ordinary grease – tends to rule out its use for normal purposes. Using grease B or grease C in lieu of grease A is of no advantage at all under leaching conditions.

Under non-leaching conditions, such as those associated with the penetration of a small amount of water into a unbonded tendon (in practice this is probably a frequent, if indeed not the most frequent, deviation from the ideal condition, i.e., the completely intact unbonded tendon), the use of grease D is of course, from the corrosion prevention point of view, highly advantageous in comparison with ordinary grease such as A. However, under such conditions grease B or C may likewise offer advantages over grease

A. The available test results give no conclusive indication of this; it would require exposure tests over a longer period of time.

4.5 *Analysis of grease*

4.5.1 Introduction

The greases normally employed for the protection of unbonded tendons are of complex composition. The principal constituent is often a mineral oil containing additives. This being so, the Committee was unable to obtain clear insight into the composition of such greases, the more so as many of their constituents are in themselves quite complex in composition. The known data have been compiled in the literature review [5]. The following description will accordingly confine itself to some general points of information.

4.5.2 Composition; corrosion preventives

The greases mostly used for unbonded tendons are lubricating greases obtained from suppliers of oil products. More particularly, they are greases on a soap basis, frequently a stearate. The type most extensively used in unbonded prestressed concrete construction is a lithium-12 hydroxy-stearate. Sometimes a calcium stearate is employed, but this is more water-absorbent than lithium stearate, and the latter is therefore preferred. The structure of the grease is formed by the soap molecules. The network is filled with mineral oils. In order to improve the corrosion preventive action, various additives called corrosion inhibitors, e.g. sulphonates, are also incorporated. So-called wetting agents are sometimes added as well. Their designation is somewhat confusing in that it could give the impression that these agents assist penetration of moisture to the steel. Actually, these are indeed substances that lower the surface tension, but particularly for the purpose of enabling the grease to adhere better to the steel (this being termed "wetting"), so that may moisture penetrating from the exterior will in fact find it more difficult to reach the steel.

Yet all these greases are really intended only for more or less temporary corrosion protection: none of them is able permanently to exclude moisture. Permanent exclusion of moisture is attainable with certain kinds of silicone grease. These are very expensive, however, and therefore not used for unbonded tendons.

Substantially superior to soap-based greases in respect of moisture resistance are greases based on mineral wax which are known by the general designation of petrolatum (petroleum jelly). The absence of an open soap structure ensures that hardly any moisture can make its way through these microcrystalline wax greases, which are, however, of too hard or stiff a consistency to be used as lubricants. The consistency can be improved in this respect by mixing them with mineral oil. Vasiline is a familiar example of such a product. These greases are not in general used for unbonded tendon systems because of problems associated with workability: at low temperatures they stiffen, so that they are liable to crack. Furthermore, when the tendons are tensioned at fairly low temperature, the grease tends to impede their sliding, and cracks or discontinuities in the grease coating may thus develop. In order to apply this grease to the tendons it should be heated so that it begins to soften. For good workability in unbonded tendon systems it is preferably to employ a grease that does not crack or become brittle even at – 20 °C and which at 70 °C is still not so fluid ("runny") that it could, under unfavourable conditions, trickle away out of the tendon. Since mineral wax melts at about 70 °C, it is obviously not a very suitable basis for unbonded tendon grease. All the same, such petrolatum greases are sometimes used for the purpose in Britain and Japan. The Committee considers this not to be a good practice, however.

The usual lubricating greases, characterized by good workability, have the drawback of only a limited anti-corrosive effect, as already explained. However, this does not apply to some special types of grease which are commercially available from oil companies and a few specialized suppliers. The important feature of these products is not their lubricating, but their corrosion preventive action. The Committee has not, however, managed to obtain much information on the composition of these greases either. It is known that specially developed greases have been used for tendons of prestressed concrete pressure vessels for nuclear energy plants in America. Grease D, which was studied in the tests described in Section 4.4, is an example of such a product. Viscosity Oil Cy. Chicago, has succeeded in producing a grease based on completely saturated hydro carbon greases which possesses the good workability of lubricating greases and yet have excellent moisture-excluding and moisture-repellent properties, thanks to the use of microcrystalline wax [11]. Corrosion inhibitors, including aryl-aryl sulphonate, are present as additives in this product, which moreover has been given a high alkalinity by the addition of, among other substances, calcium carbonate. The drawback of this special grease, however, is that it costs about twice as much as the usual unbonded tendon greases. The cost aspect will be further considered in Section 5.2.2.

4.5.3 Impurities in greases

Besides the composition of the grease and the inhibitors it contains, it is important that grease for use in prestressed concrete constructions must not contain any constituents that may cause hydrogen embrittlement of the prestressing steel. In this respect even very small amounts of chlorides, sulphides and nitrates are harmful. It is therefore desirable that grease intended for use with unbonded tendons should be checked for the absence or presence of such constituents.

From the series of tests described in Section 4.4 it emerged that the presence of chlorides in a amount of 100 ppm causes some slight acceleration of corrosive attack, which is "overshadowed", however, by the action of any chloride-containing water that may penetrate. But if the grease moreover contains sulphides, it must be presumed that hydrogen embrittlement may occur in prestressing steel. On the basis of these results the Committee has formed the opinion that it is not necessary to apply the most stringent requirements as to the grease being free from chlorides, and sulphides, but that an upper limit of 50 ppm should nevertheless appropriately be imposed. The Committee also whishes to adopt a limit of 50 ppm for nitrates, because these may give rise to anodic stress corrosion.

In view of these considerations it would be advisable to check the greases to be employed, in order to ascertain that they do not contain more than 50 ppm of the abovementioned impurities. The difficulty, however, is that the usual methods of determining these impurities quantitatively are rather unreliable. Methods for the purpose are given in some ASTM specifications:

- ASTM D512 for chlorides;
- ASTM D992 for nitrates;
- ASTM D1255 for sulphides.

It has been found that more particularly the sulphide determination procedure yields results that are very poorly reproducible. ASTM D1255 is accordingly considered to be unreliable. Indeed, at least for greases, it is not suitable as a test standard. Yet it has hitherto not proved possible to find other methods offering better reproducibility.

The Committee had hoped that this difficulty could be overcome by determining the total content of sulphur, chlorine and nitrogen. If this content is low enough, it obviously means that the individual values of the sulphide, chloride and nitrate content will not be too high either. A fairly simple analytical method can be used for determining the total content of such elements: the combustion method. Unfortunately, it turned out that good types of grease contain so much sulphur (up to about 1 of 2%) that this analysis is unable to provide guidance as to the suitability of grease. More particularly, this is so because a high proportion of the sulphur in the grease is organically combined in which form it does not give rise to corrosion. It is true that in some unbonded tendon greases in present use the total sulphur content is only about 1/25th of that in other normal unbonded tendon greases, but that does not necessarily mean that the content of free sulphides is also lower.

For nitrogen, too, the analytical determination of the total content is not meaningful, in as much as grease contains so many nitrogen compounds that the combustion method - in which all the nitrogen that is present is burned to nitrate - yields a nitrate content of about 6%, a figure that bears no relation at all to the content of free nitrates normally occurring in grease. A better method would be to determine the water-soluble impurities. In this way only free chlorides, etc. are determined. A result obtained in this way would indeed give some indication of the amount of impurities liable to contribute to corrosive attack of the steel. The snag is that no good and satisfactorily reproducible analytical method for water-soluble impurities in greases is available. This is hardly surprising: although the usual types of grease are permeable to water, the penetration of water into the grease proceeds so slowly that only a fraction of the impurities will dissolve in the water. In fact, in this way the values determined for the impurities would be much lower than the amounts actually present. It is therefore a rather futile effort.

All this goes to show that a reliable method of analysis for correctly determining the content of impurities in grease needs to be developed. This could most suitably be undertaken in a international context, preferably with FIP backing.

The key question for the analysis of grease with regard to the presence of impurities is how the free chlorides, etc. can be liberated from the grease without causing decomposition of the other chlorine compounds, etc. that are bound in the grease. Some possible methods of achieving this are:
- dissolving the chlorides in a acid (HNO_3), and
- dissolving the sulphides in a hot acid (H_3PO_4 at 100 °C), or
- stirring the grease in hot demineralized water for a long time,

and then analysing the solution (acid or water) for the amounts of impurities present in it by means of the usual methods.

That something can indeed be achieved by this approach will be apparent from the results obtained with the greases A and B (the same as those used in the tests described in Section 4.4) after 15 mg of grease was stirred for 2.5 hours at 75 °C in 100 ml of demineralized water:

	grease A	grease B
chloride	1500 ppm ($\pm$ 100)	60 ppm ($\pm$ 10)
sulphide	distinctly present (> 5 ppm)	distinctly present (> 5 ppm)
nitrate	40 ppm $\pm$ 10	20 ppm $\pm$ 5

The pH of the demineralized water was initially 5.0 and became 7.5 for grease A and 6.9 for grease B.

Of course, it would be very helpful to the users of grease if the suppliers would give a guarantee as to the maximum amount of impurities contained in their products, even though it would hardly be practicable for the customer to verify the validity of such a guarantee. In general, however, the oil companies are not prepared to give such a guarantee: in the first place, because the impurities in question are not of real significance in the context of normal applications of lubricating greases; secondly, because they can guarantee their products in this respect only if a reliable and reproducible method of analysis is available. Only specialized grease suppliers are sometimes in a position to give guarantees for their products, and this is possible only because these are manufactured from higher-purity starting materials. For the specially developed greases such as grease D (see Section 4.4) the guaranteed maximum values are 2 ppm or 5 ppm.

4.6 *Exposure tests with unbonded tendons*

Two series of tests were carried out with a view to assessing the moisture-excluding effect of the sheath. The test conditions and the results are summarized in Table 11.

Table 11. Results of exposure tests with unbonded tendons (normal and extreme thicknesses of sheath)

steel	grease	sheath	environment	length	position	end sealing	total duration of exposure	observations	remarks
strand	normal unbonded tendon grease	extruded HDPE ca. 0.8 mm	3.5% NaCl	30 cm	vertical in the solution	none	576 days	- at first inspection corrosion of immersed part - corrosion progressing further inwards in course of time	black corrosion stains on steel, black discoloration of grease
					vertical in the solution	HDPE caps with grease	576 days	no corrosion at all, grease completely free from discoloration	—
					horizontal	none	576 days	corrosion from both ends, corroded over entire length	—
					horizontal	caps with grease	576 days	no corrosion	—
strand	normal unbonded tendon grease	normal ca. 1 mm	3% NaCl and 5M HCl	15 cm	horizontal	caps with grease	1½ years	no corrosion	—
		thick ca. 1.2 mm			horizontal	caps with grease	1½ years	no corrosion	—
		thin ca. 0.6 mm			horizontal	caps with grease	1½ years	puncture in sheath	corrosion at puncture only
		extremely thin 0.3 mm			horizontal	caps with grease	1½ years	several punctures	ditto
		extremely thin 0.2 mm			horizontal	caps with grease	1½ years	several punctures	ditto

Normal unbonded tendons were used in the first series: a strand coated with the usual type of grease and enclosed in an extruded sheath made of high-density polyethylene (HDPE) about 0.8 mm thick. Portions of tendon 30 cm in length, with or without sealing caps, were immersed in 3.5% NaCl solution and stored there for $1\frac{1}{2}$ years (some of the specimens were in the horizontal, others in the vertical position). The tendon specimens which had been sealed with end caps (close-fitting greased caps of HDPE) showed no corrosion of the steel at all at the end of the $1\frac{1}{2}$ years' test period; the grease was then still completely free from discoloration.

On the other hand, the specimens which had not been sealed at the ends were found to have undergone distinct corrosion already at the first inspection (after about 2 months): black corrosion stains on the steel, blackening of the grease. Subsequent inspections showed the corrosive attack to have progressed further and further inwards.

The tendons stored in the horizontal position, with moisture penetration from both ends, were corroded over their entire length within a year. In the case of the vertical tendons the corrosive attack after $1\frac{1}{2}$ years had progressed up to the level of the immersion solution (halfway the length of the specimen). Therefore no further rise of moisture by absorption into the grease occurred.

In the second series of tests, specially made portions of unbonded tendon, 15 cm in length, with sheaths of various thicknesses were employed. Here, too, the actual tendon consisted of strand coated with grease. The thickness of the extruded HDPE sheaths on the respective specimens ranged from 0.2 mm to 1.2 mm. With extremely thin sheaths the occasional formation of a small hole in the sheath wall during manufacture by extrusion can hardly be avoided. The sheaths used in these tests were visually inspected for absence of holes or punctures. Tendon specimens enclosed in these sheaths were kept immersed for up to $1\frac{1}{2}$ years in 3% NaCl and in 5M HCl. These specimens were in the horizontal position and sealed with caps at both ends. Two of the 34 tendons were found to have become corroded, this being due (as was then discovered) to the presence of a small hole in the sheath. As the corrosive attack even after 18 months in 5M HCl was still confined to the immediate vicinity of the hole, this goes to show that the hole must indeed have been a very small one. It does not mean, however, that the corrosion – even if just moisture and not a corrosive solution had penetrated to the steel – must therefore have been harmless. On the contrary, even with only a minor degree of corrosive attack the evolution of hydrogen can cause embrittlement in a tensioned tendon, so that there is a risk of tendon fracture despite the apparent triviality of the primary defect.

The following conclusions can be drawn from these two series of tests:

- grease-filled close-fitting sealing caps can prevent the penetration of moisture (or aggressive environmental agents) into ready-assembled (greased and sheathed) unbonded tendons;
- in the absence of end seals, penetration of moisture into the tendon must be reckoned with;
- the sheath should be of such quality that no punctures or perforations can form in it during manufacture;

- the sheath should be of such thickness that any puncturing thereof due to mechanical actions (knocks, abrasive rubbing, etc.) can virtually be ruled out;
- what sheath thickness is to be considered adequate in this respect is something that cannot be deduced from these tests;
- on the evidence of general practical experience it can reasonably be presumed that the commonly employed sheath thicknesses provide sufficient safeguards.

4.7 *Testing of plastic enclosure of anchorages*

In 1979 an anchorage enclosure made of plastic – high-density polyethylene (HDPE) – for improving the corrosion protection of unbonded prestressing tendons appeared on the market in the Netherlands. This enclosure unit consists of a tube, likewise of plastic, which is slid over the tendon, and the actual "anchorage enclosure" enclosing the anchorage elements (Fig. 13). The anchorage enclosure is closed by a cover, and the remaining space in the recess of the outside of this cover is plugged with mortar.

In order to investigate the behaviour of this anchorage enclosure under practical conditions, the Committee carried out a preliminary test in which attention was focused more particularly on the following points:

- does the anchorage enclosure preserve its sealing function after the prestress has been applied?
- does the part of the strand where the sheath has been removed not come into contact with the material of anchorage enclosure?

Assembly of the various components and placing the concrete for making the test specimen were done in the same way as in normal construction practice. At one end of the specimen the contact face of the anchorage enclosure was coated with unbonded tendon grease; at the other end of the specimen this contact face was free from grease. The prestressing force was applied by means of a 12.9 mm diameter tendon; the stress was 75% of the tensile strength. The compressive stress exerted upon the contact face – be-

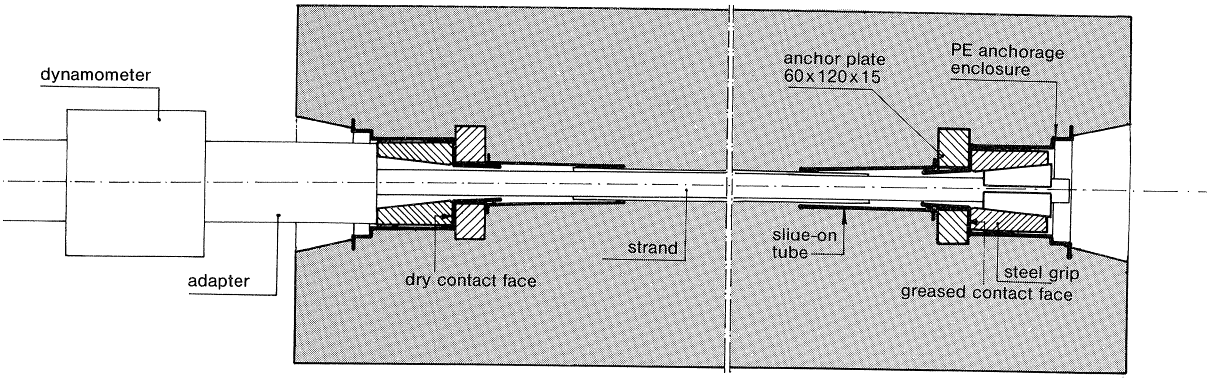


Fig. 13. Creep test on anchorage enclosure.

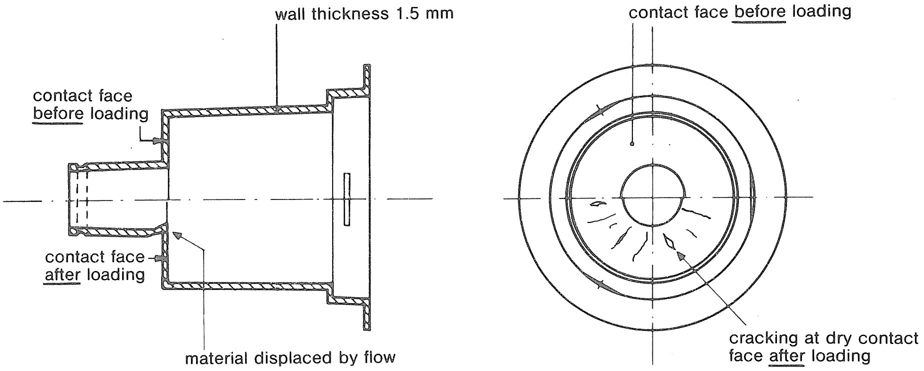


Fig. 14. Anchorage enclosure before and after loading test.

tween the anchor grip and the anchor plate - was about 119 N/mm^2, which was maintained for 98 days.

After the prestressing force had been released, the anchorage enclosure was removed from the concrete and examined. The principal results of this examination are:

a. the contact face the material of the anchorage enclosure had undergone plastic deformation and had flowed towards the strand (Fig. 14);
b. there were small radial cracks in the material at the contact face (Fig. 14).

Re a: As a result of flow of the material of the anchorage enclosure towards the strand, the plastic material could come into contact with the strand, so that, during tensioning, the grease could be scraped off over a certain length. On dismantling it was found that the enclosure could still be slid over the strand, though there was indeed only little clearance between the strand and the anchorage enclosure. It is not certain that the enclosure material that was squeezed and flowed towards the strand did in fact come locally into contact with it.

Re b: After dismantling, there were some very small radial cracks in the greased contact face. They did not penetrate all the way through the material. In the non-greased contact face there were numerous radial cracks, and these did go all the way through. It was not ascertainable whether the cracks had been formed during the tensioning (jacking) of the strand or had occurred later, as a result of local material redistribution on release of the prestressing force. As the cracks were formed between the faces of the anchor plate and the anchor grip, it can be presumed that no moisture can penetrate through these cracks. All the same, it would appear advisable to investigate whether such cracking due to flow of the material can be prevented by greasing the anchorage contact faces.

The test described above was, as already stated, of a preliminary character, so that it is not possible to draw definite conclusions. The test merely provided more insight into the behaviour of the material under high compressive stress at the contact face. The Committee did not carry out any further systemic tests as regards sealing effect, etc., and no pronouncements on these aspects can therefore be made.

5 General review

5.1 *Introduction*

The main aspects of the dicussions that were conducted within the Committee have been brought together in this chapter, for the Committee considers it to be much more important that all those concerned should acquire a clear understanding of the problems involved and of the possible solutions than that the available experience is embodied solely in the form of recommendations or guidelines. The durability of prestressed concrete structures is to a great extent determined by the quality of execution and workmanship, i.e., in the actual construction stage. More particularly in connection with corrosion protection, careful execution is of essential importance to avoiding "accidental" defects in the moisture exclusion arrangements.

5.2 *Grease as a protective substance*

In Section 2.2.4 the problems associated with corrosion protection by grease have been summarized in questions relating to its impermeability to moisture, the application of special kinds of grease, and requirements as to freedom from impurities. In the following, it has been endeavoured to answer these questions - on the basis of data published in the literature, of the results of experimental research and of the discussions within the Committee.

5.2.1 Impermeability to moisture

From the information in the literature [8, 9, 10] it was to be inferred that the usual types of grease are in general not impermeable to moisture. This was confirmed by the grease exposure tests, described in Section 4.4. Although some less commonly used greases are distinctly better in this respect, the length of time for which even these effectively resist water penetration is to be rated as fairly short (possibly a few months). Only some special greases for unbonded tendons offer good or reasonably good resistance to penetration by water.

From the exposure of two slabs and from tests relating to the entry of moisture through the anchorage - described in Sections 4.2 and 4.3 respectively - it emerged that the grease employed was unable to resist penetration. Of course, it might be supposed that if water makes its way through the grease only occasionally, at other times it will disappear again by drying out.

If the water is pure, this will indeed occur; but if water containing chloride penetrates into the grease, the salt will largely remain behind when the water subsequently evaporates in a dry period. In the long run this can only result in an increase in the chloride content (cumulative effect).

To summarize, it can be stated that the greases used for normal applications of unbonded tendons offer very little resistance to moisture penetration. So-called corrosion inhibitors and wetting agents are, however, added to greases in order to improve their anti-corrosive effectiveness (see Section 4.5.2). These additives make it more difficult for moisture entering from the outside to penetrate to the surface of the steel. Thanks to these arrangements, the usual unbonded tendon greases have a reasonably good corrosion preventive effect, despite penetration of moisture into them [24, 12]. If moisture not containing chlorides penetrates to the steel from the outside, corrosive attack will occur only after a very long time; but if the moisture contains chlorides, attack will develop fairly rapidly (see also Section 4.4.4).

Greases not containing corrosion inhibitors were not included in the research reported here. It can, however, be presumed that such greases are unacceptable for use with unbonded tendons. The suppliers of unbonded tendons will undoubtedly use only greases containing inhibitors, and the user of the tendons can put their trust in the suppliers. In connection with the issuing of a certificate for a particular type of unbonded tendon it would, however, be advisable to ascertain, by means of a functional test, whether the grease employed is indeed sufficiently effective in preventing corrosion. At present it is not possible to lay down a standard procedure, with acceptance or rejection criteria, for this purpose. Before that can be done, comparative tests will have to be performed.

In the Committee's opinion a method as described in Section 4.4 (Table 9 and 10) is suitable in principle. Small steel plates are coated with a certain thickness of grease and are then intermettently immersed in a salt solution. The purpose of the salt is merely to shorten the testing time and to enable the occurrence or non-occurrence of rusting within a certain period to be definitely ascertained.

The following tentative procedure is suggested for the purpose:

- apply a 0.2 mm thick coating of grease on steel plates;
- immerse the specimens intermittently: 6 hours in the test solution, 6 hours out of the solution, etc.;
- use a 3.5% solution of NaCl as the immersion liquid;
- continue the test for 28 days;
- at the end of this period, remove the grease from the plates;
- ascertain what percentage of the surface area has rusted.

In a comparative research it will have to be investigated what criterion can be laid down for assessing the suitability of the grease concerned.

5.2.2 Special greases

In the experimental research that the Committee itself conducted, some special types of grease were included. These had been developed in the United States for use in the construction of prestressed concrete presssure vessels for nuclear reactors. Very important work in this field has more particularly been accomplished by Viscosity Oil Cy. [11]. One such grease (Visconorust 2889) completely prevents moisture penetration for a reasonably long time (well in excess of 1 year): see grease D, Section 4.4. Over a longer period of constant exposure to water ingress, the water gradually penetrates into the grease, possibly in consequence of a slow process of leaching-out of the water-repellent substance incorporated in the grease. For use in unbonded tendon systems, in which of course adequate precautions have been taken to reduce the risk of water penetration as low as possible, a grease of this kind would probably provide lasting protection of the steel against corrosion. From subsequently reported results of ORNL [13] it also emerges that such greases do indeed permanently protect the steel, though in the Committee's opinion those tests were not performed in an entirely conclusive manner. *In any case the Committee considers that there are greases which are sufficiently impermeable to moisture.*

The problem of corrosion protection for unbonded tendons with the aid of grease would thus be disposed of, but for the fact that these greases are expensive. Thus, Visconorust 2889 costs about 6.50 guilders per kg, which is about twice the price of the usual unbonded tendon greases. Although this need not in itself be prohibitive - we shall revert to this in due course - there is as yet no tendency among users to change over to such expensive greases. In the Committee's opinion that is not in fact necessary, because the penetration of moisture can be prevented by alternative means, more particularly by the use of adequate sheathing. This will be further considered in Section 5.3.

Both in its discussions and in the investigations it conducted, the Committee wished to confine itself to greases that are applied under normal or under more special conditions. This does not, however, rule out the possibility that other greases, too, are quite suitable for unbonded tendons, and perhaps even cheaper. In the following it will therefore be endeavoured to elucidate the functional behaviour of various types of grease in order thus to optimalize the requirements applicable to a suitable grease for the purpose.

The grease has to fulfil a number of functional requirements, not all of which will be considered here (for more details the literature review [5] should be consulted), but only the following general criteria:
- impermeability to moisture;
- chemical purity;
- workability;
- price.

Impermeability to moisture, i.e., the ability to exclude moisture and keep it away from the prestressing steel, is of course the most important requirement. Chemical purity is important in order to ensure that nothing in the grease itself will attack the steel (see Section 5.2.3). Workability is important as a criterion of how the grease can be used in

Table 12. Principal criteria for some types of "grease"

designation of material	impermeability to moisture	purity	workability	price guilders/kg
a. silicone greases	(very) good	(very) good	moderate/good	50–200
b. special unbonded tendon grease	fair/good	good/fair	good	5–7
c. pure vaseline	fair/moderate	good/moderate	good	ca. 3
d. normal unbonded tendon grease	moderate/ doubtful	fair	good	2–4
e. petrolatum	moderate	fair/moderate	good/moderate	2–3
f. asphalt-based grease	fair/good	doubtful	moderate	1.5–3
g. asphalt	good(subject to adequate deformability)	doubtful	poor (except at sufficiently high temperature)	0.5?

conjunction with the prestressing steel and the sheath to give the finished product, i.e., the assembled (greased and sheathed) unbonded tendon. Although workability is governed by a number of properties (such as viscosity, "self-healing", softening behaviour, embrittlement behaviour, etc.), these can, with a little good will, be combined into one rating factor.

Seven types of grease are qualitatively assessed in respect of the above-mentioned criteria - impermeability, purity, workability and price - in Table 12. Each type of grease listed in the table represents a particular category within which a considerable range of variation is possible.

These various greases call for the following explanatory comment:

- Silicone greases are the only kind not made from oil products. In general, they possess properties ranging from good to very good, but are very expensive.
- Unbonded tendon greases: the special products such as those of Viscosity Oil* and the normal ones are included.
- Vaseline: a well-known product available with considerable variation in purity.
- Petrolatum: a product that may exhibit a fairly wide range of variation in its properties, but which is generally somewhat stiffer in consistency and can be used in a more limited temperature range (0–60 °C) than the normal unbonded tendon greases. Sometimes used in Britain [19].

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* It is of course not the intention to publicize one particular grease obtainable from one supplier. The difficulty with greases is, however, that it is virtually impossible to give a descriptive designation that properly characterizes a certain type. The product mentioned here by name is described by its supplier as a thixotropic self-healing organometallic complex, being a completely saturated cyclic hydrocarbon grease with additions of aryl-aryl sulphonate and sufficient calcium carbonate (to achieve high reserve alkalinity).

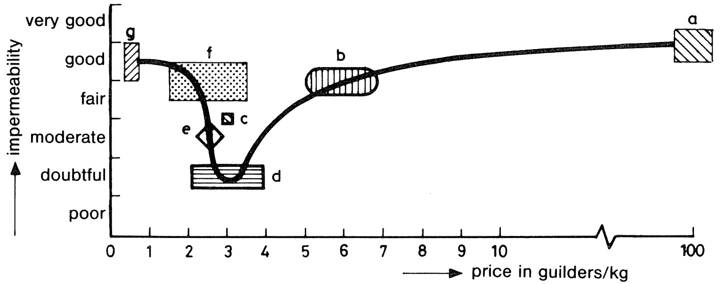
- Asphalt-based greases: somewhat heavier fractions from the distillation process, therefore of even stiffer consistency and with rather more residues.
- Asphalt: the heaviest oil fraction, with as its principal properties: impermeability to water (provided that it does not crack), low cost, but with the highest content of impurities and poor workability. It tends soon to become brittle.

The information given in Table 12 raises the question whether the usual unbonded tendon greases are indeed optimally suitable. The relevance of this question is more strikingly apparent from Fig. 15, where the three diagrams represent impermeability, purity and workability plotted as functions of the price of the greases concerned. To avoid possible misunderstanding, it must be pointed out that this representation is of course merely of a schematic nature and that the curves give approximate guidance only. What is notable, however, is that the relations between these criteria and cost can be schematized in so simple a manner.

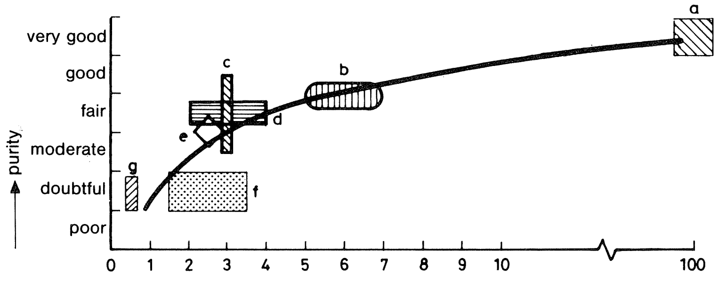
It directly emerges from the diagrams that the usually employed unbonded tendon greases constitute the least favourable choice as regards impermeability to moisture. Cheaper as well as more expensive products are superior to those “normal” greases in this respect. The more expensive products are better also in respect of purity, and their workability is not significantly inferior. The cheaper products are better from the point of view of impermeability, but their purity and workability are likely to be unsatisfactory. Although it is therefore necessary to exercise caution with regard to these aspects, it could nevertheless occur that somewhat heavier fractions from the distillation process come out as the preferred type of grease in an optimalization procedure. In fact, this is precisely the case in some countries. Thus, in Britain there is a slight preference for petrolatum greases among some engineers, and in Japan sometimes asphalt-based greases appear to be used.

The Committee is of the opinion that it should indeed be possible to use the cheaper types of grease to obtain a good product. This does mean, however, the workability will have to be improved by means of additives and that the assembly of the tendon in its sheath may have to be done at a somewhat higher temperature. To achieve this the manufacturers will have to carry out a great deal more research and development, because the completed unbonded tendon must also satisfy other requirements. For example, in the case of asphalt products it may be possible to envelop the tendon in the protective substance at elevated temperature, but it is then unlikely that the tendon can slide easily within its sheath when it subsequently has to be tensioned. Another drawback of these products is that they fail to wet the HDPE sheathing properly. Because of this and also because of the movement of the tendon during tensioning (when the “grease” is brittle), cracks and capillaries are liable to form in the protective coating. Other potentially suitable “greases” likewise involve specific problems.

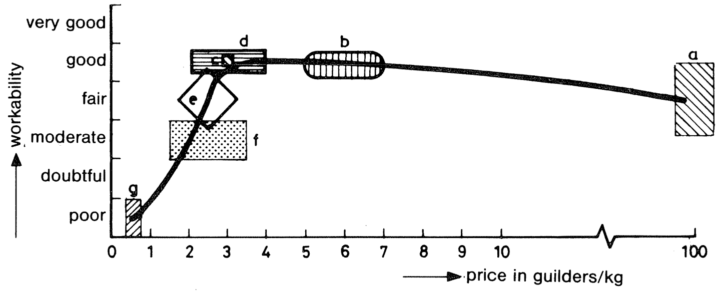
Besides, the advantage gained from the development envisaged above will be only of a relative character, inasmuch greases incorporating heavier distillation fractions will



a. impermeability



b. purity



c. workability

letter	symbol	type of grease
a	▨	silicone greases
b	▥	special unbonded tendon greases
c	▨	pure vaseline
d	▤	normal unbonded tendon greases
e	◇	petrolatum
f	░	asphalt-based greases
g	▨	asphalt

d. key

Fig. 15. Impermeability to moisture, purity and workability of various types of grease in relation to price (schematic).

inevitably involve a lowering of chemical purity. The only way to avoid this is to base their manufacture on "cleaner" oil products, but then the advantage of reduced cost associated with the use of the heavier fractions will soon be wiped out.

It therefore appears relevant, in connection with the optimalization process, to reconsider whether "dearer" products do indeed offer sufficient advantage to justify their higher cost. At the same time, however, it is to be noted that higher-priced products can be really advantageous only if their impermeability to moisture is significantly better than that of the normal unbonded tendon greases. With this in mind, we then soon have to move up-market to products such as Visconorust 2889 already mentioned.

Is the higher price charged for these superior greases really prohibitive? For assessing this, Table 13 gives a cost comparison for the various materials used in the fully assembled (greased and sheathed) unbonded tendon. Basing ourselves on a few assumptions, we find that 85% of the total cost of materials is assignable to the prestressing steel, 8% to the sheathing and 7% to the grease ("normal" grease for unbonded tendons). If a special grease is used (costing about 6.50 guilders per kg), it will account for 13% of the total cost. Unfortunately, in commercial circles there is a tendency to rate the extra cost associated with special greases at "10 cents per metre" rather than at 6% of the total costs of materials. All the same, the Committee considers that a 6% increase in cost, resulting in a 2 to 3% more expensive "as-installed" tendon, ought to be an acceptable price for the additional safety obtained. It cannot, however, assess whether such a cost increase is commercially acceptable in view of the competitive position.

Table 13. Cost comparison for the raw materials of an unbonded tendon (statement of prices in the Netherlands in the middle of 1981)

		prestressing steel	grease		sheath
type		7-wire strand	normal unbonded grease	special unbonded grease	high density polyethylene
thickness	mm	6 × 4.10 + 1 × 4.25			0.8
area	mm^2	94	32–40		±45
quantity per metre of tendon	cm^3	94	32–40		±45
specific gravity	kg/m^3	7800	900–1000		950
weight per metre of tendon	g	730	30–36		42
price per kg	f	1.65	2.8 (2–4)	6.5	3
cost of materials per m of tendon		f 1.25	f 0.10	f 0.20	f 0.12
breakdown of costs:					
- for normal grease		85%	7%	–	8%
- for special grease		80%	–	13%	7%

At any rate, the problem of moisture exclusion from the prestressing steel has not yet been conclusively solved by the greases used in actual practice. For that purpose other arrangements are needed, as will be discussed in Section 5.3.

5.2.3 Requirements as to purity

The American "tentative recommendations" [4] already stated the requirement that the grease must be non-corrosive and preferably have a corrosion-preventive effect with regard to the prestressing steel. Obviously, the grease must not incorporate constituents which could themselves attack the steel if, for whatever reason, even very small amounts of moisture and oxygen are present at the surface of the steel. Such requirements must of course be further specified, otherwise it will not be possible to judge whether they have indeed been fulfilled. More particularly, two sets of requirements have to be considered:
- functional requirements;
- intrinsic requirements.

5.2.3.1 Existing functional requirements

Functional requirements as to "non-attack", i.e., freedom from constituents that may cause or promote corrosion of the steel, make it possible to assess whether this function (non-attack) does indeed exist. For example, a functional requirement of this kind is laid down in the ASTM specification D1743, which is specially concerned with monitoring rust-preventive properties of lubricating greases. According to that specification, the degree of rusting of completely smooth and clean steel ball bearings is measured after they have been coated with the grease in accordance with a standard procedure and are then exposed for a 14 days' period to an atmosphere having a very high relative humidity.

The Committee considers this American specification not suitable as a functional test criterion for the purity of unbonded tendon greases. This consideration is based on the fact that corrosive attack can occur only if moisture and oxygen are present. The commonly employed unbonded tendon greases are, however, sufficiently impermeable to ensure that no moisture will penetrate to the steel within 14 days, so that no rust formation will have developed by the end of that period. Testing would have to be continued over a much longer time to provide a suitable criterion. All the same, most of the unbonded tendon greases have, at one time or another, been tested in accordance with the above-mentioned ASTM specification, with results that invariably were favourable. No classification of such greases is therefore possible on the basis of that test.

Another functional test for corrosive attack is the salt spray test, in which the material for investigation is kept in a "fog" of salt solution for a certain length of time (and usually at a somewhat elevated temperature). This kind of test is advocated by several research groups concerned with the subject: Shinko Wire [12], working group of FIP Commission of Prestressing Steel [19], and others.

Yet the Committee considers this test not to be functionally suitable for unbonded tendon greases either, for here, too, it remains true that attack by any impurities in the grease can occur only if moisture has penetrated to the surface of the steel, which is something that cannot be accomplished in an accelerated test. Besides, the salt spray test introduces some other problems. Thus, if it does give rise to corrosive attack, this will not necessarily be due to constituents of the grease, but may be entirely attributable to the salt solution that has penetrated. This test accordingly cannot serve as a measure of the purity of the grease, though it does provide a meaningful criterion of protection against impurities that enter the grease from the outside.

5.2.3.2 Intrinsic requirements

Intrinsic requirements relate to the composition of the grease, the permissible or desirable additives, the permissible amount of impurities, etc.

With regard to corrosive attack of the steel by the grease the presence of certain ions, such as chlorides, is especially important. In connection with the stress corrosion hazard it is moreover important that certain other ions must not be present, e.g., sulphides and nitrates, since sulphides promote the absorption of hydrogen into steel, while nitrates can act directly in causing so-called nitrate stress corrosion.

In determining the intrinsic requirements relating to the possible attack of the steel by the grease the object is therefore to decide what content of Cl^-, S^{--} and NO_3^- can be allowed. Accordingly certain conditions are stipulated, and certain guarantees are given by the supplier, for some special types of grease used for protecting the unbonded tendons in prestressed concrete pressure vessels for nuclear reactors. More particularly, the following values are applied:

	permissible	guaranteed
chlorides	10 ppm	$\leqslant 2$ ppm
sulphides	10 ppm	$\leqslant 2$ ppm
nitrates	10 ppm	$\leqslant 4$ ppm

These requirements are indeed complied with in the case of special greases. However, from the available information (see Sections 4.4 and 4.5) it emerges that:

- the suppliers of normal greases are mostly not prepared or able to give specific guarantees as to impurities in their products;
- the measuring methods for determining such small amounts of impurities are sometimes inconsistent (at least rather laborious);
- even if suppliers of normal greases give guarantees at all, their products nevertheless sometimes entirely fail to conform to them.

On the basis of the available information it is therefore not possible to arrive at satisfactory and well-founded (functional or intrinsic) requirements that could be applied to the grease. For this reason the Committee decided to carry out some tests of its own in order thus to obtain more insight into the behaviour of grease containing impurities (see Section 4.4).

Although these tests cannot enable any conclusive statement to be made concerning the very long-term behaviour of impurities, they do justify the following conclusions:

- if moisture with chlorides penetrates from the outside to the steel, it makes little difference whether or not there are impurities in the grease;
- with a higher concentration of impurities (an increase from 0.35 to 3.5% NaCl) corrosive attack does indeed start earlier, but in the long run the effect is hardly more severe than that of the lower concentration;
- if moisture not containing chlorides penetrates from the outside to the steel, corrosion will occur only after a very long time.

The general overall conclusion to be drawn from these results is that it is more important to prevent moisture (and certainly moisture with chlorides) from penetrating to the steel than to impose very stringent requirements on the chemical purity of the grease itself. Accordingly, from the corrosion protection point of view it is necessary to choose such a system that:

a. moisture is prevented from penetrating to the steel: with a good polyethylene sheath enclosing the tendon this object can in fact be achieved, as described in Section 5.3;
b. the grease meets requirements which ensure that it will not contain any excessive amount of impurities (a permissible limit of 50 ppm could be adopted).

5.2.3.3 Proposal for a functional test for purity of grease

From what has been stated above it is apparent that there are no suitable methods of assessing the purity (freedom from impurities) of grease. Intrinsic tests are not sufficiently reliable; functional ones cannot be performed in conformity with a standard method. Yet it is desirable to be able to assess the grease as to the absence of excessive harmful constituents.

After due consideration the Committee concluded that a stress corrosion test on a greased tendon (without a sheath) would provide the most suitable means of making such an assessment. A test of this kind cannot, however, be performed in the usual manner. Present-day stress corrosion tests on prestressing steel are carried out in an ammonium rhodanide environment [25]. In this way, hydrogen is evolved at the steel surface under intensified conditions, so that a limited test period is sufficient. On the other hand, for judging the action of any chlorides, nitrates or sulphides that are present in grease it is evidently not possible to operate under such intensified conditions, for these would completely overshadow the effect of any harmful grease constituents. In the present context the object is not, after all, to test the hydrogen sensitivity of the steel, but solely to assess the possible stress corrosion promoting effect of substances in the grease. This can be done only in a neutral moist environment. Since unbonded tendon greases are at any rate so well able to exclude or to absorb moisture that it takes quite a long time (several months) for the moisture to penetrate to the steel, such a test will require about six months to perform. For this reason the Committee did not have an opportunity to conduct its own stress corrosion tests. So far as is known, such tests on greased tendons have been carried out only by ORNL, but almost entirely in aggressive environments [13].

The Committee is of the opinion that experience with stress corrosion tests in a neutral moist environment of distilled water should be gained and that the suppliers of unbonded tendon systems should be encouraged to undertake tests for that purpose. At the same time, however, it must be stated that such tests can never be specified as acceptance tests. They can in due course – when sufficient experience has been gained – be applied only within the framework of a "certification scheme for greased and sheathed prestressing strands".

In view of the importance of functional testing of the purity of the greases employed, the Committee considers that it has a duty to offer a proposal for a stress corrosion testing procedure:

- the tendon sheath should be locally removed so as to enable moisture to enter;
- this can be done by cutting away and removing the sheath over a length of 5–10 cm and coating the cut faces with enough grease to prevent accelerated corrosive attack from occurring there;
- an alternative possibility is to puncture the sheath with 12 small holes (1 mm diameter or more) disposed in a spiral around the sheath over a distance of about 20 cm;
- the specimen tendon prepared in this way is then tensioned to 80% of its characteristic tensile strength (intermediate re-tentioning during the test so as to restore the initial stress is not considered necessary);
- the part of the tendon where the sheath has been locally removed or perforated is immersed in distilled water;
- the test is continued for 6 months.

5.3 *Aspects of the sheath*

5.3.1 Sheathing materials

The tendon sheath should behave neutrally with regard to the steel, the grease and the concrete. It should give reasonably good protection against damage, abrasion and wear, remain stable throughout the life of the structure and yet be flexible enough to allow convenient manipulation.

All kinds of sheathing materials are mentioned in the literature, such as PVC, low-density polyethylene, high-density polyethylene, polypropylene, etc. Only the high-density polyethylene (HDPE) sheathing normally employed in the Netherlands was studied in the testing program. This material possesses a combination of properties that satisfactorily fulfils the requirements. It has good mechanical properties and substantial wear resistance and chemical stability. In these respects HDPE is distinctly preferable to other materials.

The exposure tests (Section 4.6) showed that attack of the steel by corrosive action occurred only at those points where the sheath had been punctured or in test specimens which had not been properly sealed at the ends. This indicates that the HDPE sheath itself gives excellent protection against moisture penetration and is suitably resistant to the action of a salt solution.

For the sake of the desired continuity (freedom from accidental perforations) of the sheath, it should preferably be placed around the tendon by an extrusion process. This technique moreover ensures a high degree of uniformity of the sheath.

In the various tests that were performed there was nothing to indicate the occurrence of chemical reactions between the concrete and the HDPE. This material is also very stable with regard to the usual kinds of grease, and no interaction was detected in the tests.

5.3.2 Thickness of the sheath

In view of the function of the sheath, it is especially important to ascertain what minimum thickness is acceptable to enable it adequately to fulfil all the requirements. In the tests it was found that even a thickness of only 0.2 mm is in itself sufficient to provide an effective sealing barrier. It must at once be added, however, that for practical purposes this thickness is not a realistic value because it is too small to enable uniform quality to be guaranteed and because there is the risk of small holes being locally present in it.

The Committee did not establish a program of tests for studying the wear and abrasion resistance of sheathing, for it is hardly possible to lay down criteria as to what are and what are not acceptable manipulations with the ready-sheathed tendons. However, in the light of some experience as to what happens in actual practice, it is in any case not advisable to employ sheathing with a wall thickness that is very small. The thickness of 0.75 mm commonly used in practice would appear to be a good minimum value. Certainty with regard to wear and abrasion resistance will have to be achieved by proper precautions and instructions for handling, storing, transporting and installing the tendons, especially on the construction sites. More particularly, when mild steel reinforcement is dragged across the tendons installed in position, inadmissible damage of their sheaths may occur.

5.3.3 Enclosure of the tendon by the sheath

The sheath has a dual function to perform. It must effectively seal the tendon against external influences and must also allow tendon movement to occur during tensioning. These requirements could in principle be fulfilled by a sheath that fits very loosely round the tendon. In actual practice, however, it is important to have a closer-fitting sheath which, on cooling, is completely filled with grease. By employing the extrusion technique in sheathing the tendon, air inclusions can be virtually eliminated. This is important because the possibility of moisture inclusions within the sheath is thus also negligible.

From what has been said above it will be evident that only those sheathing methods are suitable which ensure complete and continuous enclosure over the entire length of the tendon. This can be achieved with an extruded sheath; in principle it should also be possible with a sheath sealed by a welding seam, but the methods employed for the purpose in practice have seldom proved completely reliable in producing 100% watertight sheaths. Besides, they cannot prevent local breaks in the continuity of the sheath as a result of forces exerted in handling and transport.

5.3.4 Characterization of the sheathing material

The Committee's investigations did not provide any indications that the composition and properties of HDPE are subject to any considerable variations. Its material and mechanical properties can be characterized with the aid of the tests indicated in Table 14, which also gives approximate guide values for the principal properties of the material.

Mechanical testing can be performed on the HDPE sheath. Values for the yield stress and for the elongation at rupture can be deduced from the results. However, it is essential to carry out these tests at a specific strain rate, because this may considerably affect the results obtained.

Table 14. Guide values for the properties of HDPE

characteristic	value	unit	standard
specific gravity at 23 °C	940–960	kg/m^3	DIN 53.479
melt index under load 5 kg	0.3–1.0	g/10 min	DIN 53.735
softening temperature (10 N) Vicat A	ca. 131	°C	DIN 53.460
mechanical properties at 23 °C; at strain rate 50 mm/min:			DIN 53.455
- yield stress	> 20	N/mm^2	
- elongation at rupture	> 350	%	
IZOD impact strength (notched)	400	J/m	ASTM D256-56 ISO R/180
shore hardness D	ca. 65	-	DIN 53.505
stress corrosion	> 200	h	ASTM D1693-70

5.4 *Aspects of the anchorage*

5.4.1 Introduction

This section is concerned more particularly with the protective measures that can be taken during the constructional phase. But it is important that appropriate precautions should also be taken to ensure that that there is no access of moisture to the prestressing steel during transport of the sheathed tendons to the site and during storage there. As the exposure tests with unbonded tendons (Section 4.6) have shown, moisture penetration in this phase can effectively be prevented by providing the ends of the sheathed tendons with close-fitting grease-filled caps.

The anchorages of the tendons are the most vulnerable accessories of unbonded tendons with regard to corrosion-protection. In the early period of using unbonded tendons some of the solutions adopted for the detailing and finishing treatment of the end anchorage were not in agreement with present-day views. When some cases of damage had occurred it was accordingly asked whether the finishing methods then commonly used were in fact adequate for preventing the entry of moisture at the anchorage. As a result of these misgivings, a process of development was started in which various promotors of proprietary systems brought about some significant improvements in their methods of corrosion protection of the unbonded tendon at the anchorage.

The improvements that have been introduced consist mainly in obtaining a more or less watertight transition from the tendon sheath to the anchorage unit and in better protecting the anchorage elements themselves by the use of e.g. a plastic anchorage unit to enclose them. In cases where a different method of corrosion protection is adopted, the importance of effective pre-treatment of the steel anchorage parts as well as of the concrete in the anchorage recess is increasingly being realized. The Committee considers this to be a good development, as a result of which the application of prestressed concrete construction with unbonded tendons will become more widely acceptable.

The draft Netherlands code of practice for prestressed concrete with unbonded tendons [26] also pays attention to durability. The rules it gives are to be regarded as minimum requirements for structures with unbonded tendons that are not exposed to water. In the present report, too, the Committee has confined its attention to such circumstances (thus, excluding e.g. offshore structures and such).

Some of the possible practical examples that are discussed here have in fact already been applied in actual structures; others are still in an experimental stage.

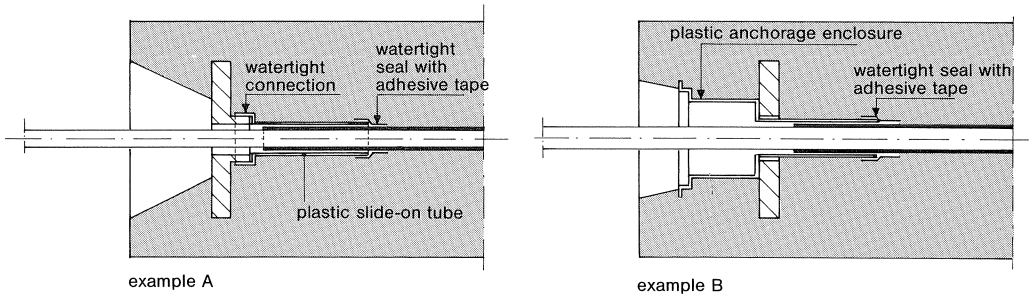
5.4.2 Connection of anchorage unit to sheath

Proper connection of the sheath to the anchorage unit is important both at a jacking anchorage (from which the tendon is tensioned) and at a dead-end (non-jacking) anchorage. The greatest risk of moisture access to the prestressing steel at the anchorages exists during the period of steelfixing – installing the reinforcement and tendons – and subsequently up to the time of hardening of the concrete. If the sheath is not properly joined to the anchorage, water may get in between the sheath and the tendon, e.g., from rainwater or formwork cleaning water prior to concreting or from mixing water within the concrete itself while the latter is still in the plastic state. Despite the grease coating, corrosion of the tendon may occur under such circumstances.

Some possible solutions for forming a satisfactory connection at the jacking end of the strand tendon are shown in Fig. 16. In example A a plastic tube with an enlarged end socket is slid tight-fittingly over a collar on the anchor plate. To facilitate assembly and improve watertightness, this collar may be lightly greased. The other end of the plastic tube is slid over the tendon sheath and the joint made watertight with adhesive tape. The Committee is of the opinion that a good seal can thus be obtained with the commercially available types of tape.

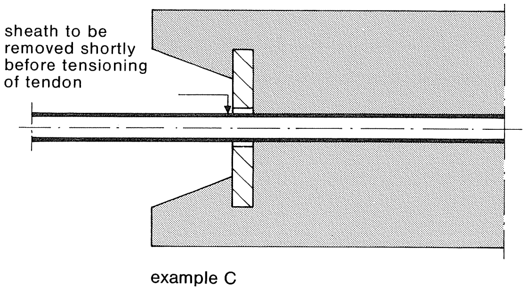
In the solution presented in example B the plastic tube forms an integral part of the anchorage enclosure which will subsequently accommodate the actual anchorage elements for securing the tendon. As in the preceding example, the joint between the plastic tube and the tendon sheath must be sealed with tape. The Committee carried out a long-term load test on an anchorage of this kind, the results of which are reported in Section 4.7.

In example C the end portion of the tendon sheath is removed with the aid of a special cutting device a short time before the tendon is tensioned. As this removal of part of the sheath is done only when the concrete has already hardened, the risk of moisture ingress during the preceding constructional stages is extremely small, especially if the ends of



example A

example B



example C

Fig. 16.
Examples of various methods of connecting the sheath to the anchorage.

the sheath are provided with sealing caps, as discussed in Section 4.6. In the examples A and B the sheath is cut off in the vicinity of the anchorage already at the time of fixing the tendons in the formwork. From the point of view of corrosion protection it is important to leave the sheath in position around the strand for as long as possible. Only just before the final tensioning of the tendon the last part of the sheath may be removed.

5.4.3 Curtailment of tendons

After completion of tensioning and final anchorage, the tendon has to be cut off. The Committee considers the use of a grinding wheel to be better than burning off, for in the latter method, if it is done inexpertly, there is a risk that too much heat will be imparted to the tendon and the wedges. As a result, grease may locally soften and seep away and structural changes in the steel of the tendon and wedges may occur. Such changes cannot subsequently be detected. Heat evolution due to grinding is much less and more localized, so that the hazard of deterioration in the properties of the steel is much less. Incidentally, it is to be noted that no instances of damage unmistakably due to inexpert burning off the tendons have come to the Committee's attention.

The requirements laid down in the general code for in-situ concrete [27] are applicable to the depth of concrete cover that must at least be provided over the end of the tendon. The minimum cover required in a dry environment is 20 mm. Although the end portion of the tendon protruding beyond the wedges is not under stress, it is regarded as prestressing steel in so far as the depth of cover to be provided is concerned. It must also be borne in mind that the protective mortar filling subsequently placed in the anchorage recess is quite likely to be more porous than the surrounding concrete. The additional code for unbonded tendons [26] requires the interposition of a water-excluding layer between this mortar and the steel components in the recess, however. For this reason the Committee considers that, in principle, it is permissible to deviate by up to 5 mm from the above-mentioned specified minimum cover, i.e., a cover of not less than 15 mm to the tendon end could thus be accepted.

Directly after curtailment of the tendon (by grinding) the anti-corrosive measures described in Sections 5.4.4 and 5.4.5 must be applied. It is not permissible to postpone these measures until a later time, because capillary absorption of moisture through the small cavities around the core wire of the strand cannot be ruled out. In particular, it has been found impracticable to ensure that in the tendon manufacturing process these cavities are completely filled with grease, as has emerged, inter alia, from the experiments described in Sections 4.2 and 4.3.

5.4.4 Anti-corrosive measures

The anti-corrosive measures envisaged here comprise the final finishing treatment applied to the anchorage whereby good protection against penetration of moisture is

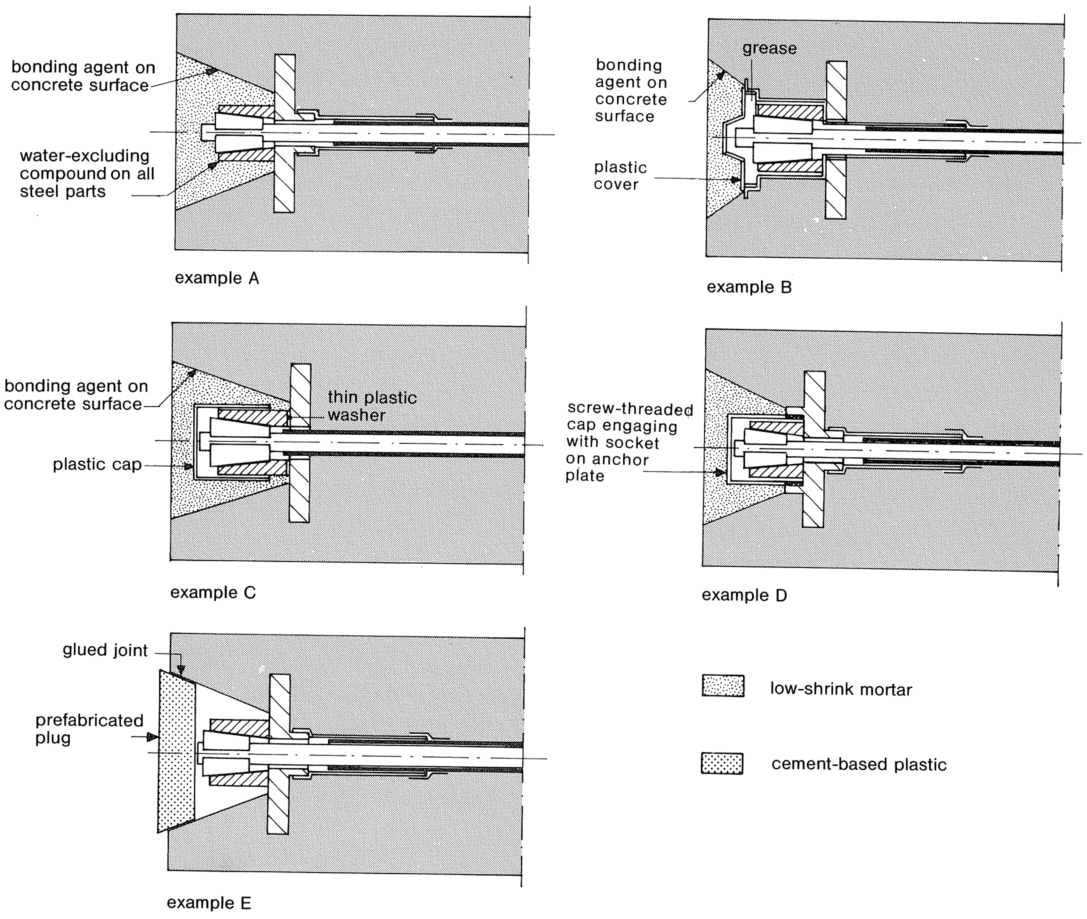


Fig. 17. Examples of various methods of sealing the anchorage.

obtained. Some possibilities of achieving this result will now be discussed with reference to the examples shown in Fig. 17. The examples A, B and C presented here correspond to those in Fig. 16.

The finishing arrangements adopted in example A are substantially similar to those in the series d in slab II employed in the exposure test (Section 4.2). In the light of the experience gained in that test it can be stated that effective protection against moisture penetration can be obtained with proper execution of the end anchorage sealing arrangements. After curtailment of the tendon in the anchorage recess, the grease on the end of the tendon and any grase on the anchorage components is removed, but without using solvents for the purpose. Next, all the visible steel parts of the anchorage components and tendon are coated with an effectively water-excluding compound. The careful application of this sealing layer between the steel parts and the protective mortar subsequently packed into the recess is considered necessary by the Committee in order to prevent access of water through the mortar to the steel.

Then the concrete lateral surface of the anchorage recess is provided with a bonding agent for preventing shrinkage cracking at the mortar/concrete interface. The bonding agent should be applied in accordance with the manufacturer's instructions, or else an adverse effect may result. The recess may be filled with stiff low-shrink mortar. Using a so-called non-shrink mortar will mostly not offer an advantage, as these special mortars often nevertheless develop shrinkage later on.

In example B a plastic cover with a quantity of grease is fitted over the end of anchorage enclosure immediately after curtailment of the tendon. The recess can then be filled with mortar. As the joint between the cover and the anchorage enclosure is not completely watertight, a bonding agent must be applied to the concrete face of the recess as an extra precaution to prevent water penetration to the steel. In that case it is unnecessary to apply strict requirements as to the watertightness of the joint of the cover.

In example C a close-fitting plastic cap is slid over the steel grip securing the end of the tendon. This is done immediately after curtailment. The anchorage recess can then be filled with mortar. Here, too, it is important to prevent a shrinkage crack from forming at the mortar/concrete interface, and a bonding agent should therefore be used. It is to be noted that in this solution a short length of the tendon sheath protrudes beyond the anchor plate. It is therefore necessary suitably to adapt the dimensions and possibly the design of the anchorage system so as to ensure that the wedges will not come into contact with the sheath.

Example D is a variant of B and C. In this case an externally screw-threaded plastic (or possibly cast iron) cap is secured to the anchor plate. A cast iron cap may be the preferred type in a situation where, for example, the subsequent cutting of an aperture in a floor slab, or an outbreak of fire, poses a threat of tendon fracture with the hazard that ejection of the fractured tendon could be dangerous to the surroundings.

In the Committee's opinion the solutions described here can provide good corrosion protection at the anchorage. As already stated, some of them are still in an experimental stage, so that it is not yet possible to report on practical experience. The Committee decided not to formulate requirements with regard to the materials to be used for protecting the anchorage zone, so as not to discourage or obstruct new developments.

A final example offers the possibility of sealing the anchorage recess by means of a prefabricated plug which has to be glued in position in the recess (example E, Fig. 17). One of the attractive features of this solution is that it makes visual inspection a relatively simple matter, but its suitability has yet to be established by tests and on the basis of experience in actual practice.

The solutions represented by examples B and D can in principle also be adopted for dead-end anchorages. In that case, with B, the attachment of the plastic cover to the plastic anchorage unit should be so secure that the joint remains closed and lets no moisture through during the placing and compaction of the fresh concrete. With D, adequate sealing against moisture is provided by the screw-threaded connection with proper workmanship.

5.4.5 Curing

In order to prevent rapid loss of moisture and attendant shrinkage of the sealing mortar in the anchorage recess, effective curing is considered essential. In the slabs subjected to exposure tests (Section 4.2), in which the mortar was applied under strongly drying climate conditions (laboratory environment), the loss of moisture was counteracted by covering the end faces of the slabs with plastic sheet. On the actual construction site the application of a curing compound to the finished mortar surface could, for example, be a suitable possibility.

The finished surface of the low-shrink mortar applied in the situations A to D in Fig. 17 will often be vertical, a fact that restricts the possibilities for curing treatment.

6 Summary and conclusions

Under its terms of reference, Committee C26A carried out literature research and supplementary tests with a view to clarifying the situation with regard to the corrosion protection of the prestressing steel in prestressed concrete construction with unbonded tendons. The need for these investigations arises from the fact that in such tendons the steel is not directly surrounded by concrete forming a protective environment.

In the Introduction (Chapter 1) it is pointed out that the durability of a structure with unbonded tendons is determined not by the corrosion protection alone, but that damage may be caused by anchorage failure, by faulty design or by careless execution.

The problems associated with the protection of unbonded tendons against corrosion are described in Chapter 2. The most significant problem is that of moisture exclusion: if moisture is prevented from penetrating to the prestressing steel, corrosion will not occur. Therefore, with no access of moisture, there will be no ordinary corrosion nor stress corrosion or hydrogen embrittlement to cause tendon fracture. In any assessment of the corrosion protection arrangements it will have to be ascertained to what extent the grease and/or the sheath are able to stop moisture from penetrating. It will also have to be determined what measures offer sufficient safeguards against the entry of moisture via the anchorage.

From a study of the literature (Chapter 3) it emerges that the greases commonly used with unbonded tendon systems are not impermeable to moisture, so that these greases give only temporary protection against any moisture that enters. More effectively protective greases are available, but cost about twice as much. Besides, it is not really necessary to use these higher-grade greases, for it is quite feasible to prevent entry of moisture, provided that the tendon is enclosed in a good sheath, the anchorages are correctly executed, and a properly tight connection of the sheath to the anchorages is established. All the same, certain (but not excessively stringent) requirements should be imposed upon the grease with regard to its workability and stability. Also, the grease must not contain constituents such as chlorides, sulphides and nitrates which are themselves liable to attack the steel. The requirements applicable to greases intended for use with unbonded tendons were formulated (in qualitative terms anyway) as far back as 1969 in the "Tentative recommendations for concrete members prestressed with unbonded tendons". In recent years, a Japanese steel manufacturing firm and a working group of the FIP have made efforts to formulate the requirements for these greases in a more quantitative way.

The corrosion protection of the complete unbonded tendon system was studied with the aid of exposure tests extending over a total period of $4\frac{1}{2}$ years. For these tests, two prestressed concrete slabs with unbonded tendons were used, with several different methods of sealing the anchorages. The following conclusions can be drawn from the results of the two exposure tests (see Section 4.2):

- outdoor exposure for $2\frac{1}{4}$ years and $4\frac{1}{2}$ years had no seriously adverse effects upon the tendon system;
- in many cases there was rusting, both on the anchorages and on the tendons;
- in a few cases some rust formation on the tendon just behind the anchorage was found to have occurred; such rusting is liable to cause tendon fracture in the longer term;
- the application of a rust preventive paint (anti-corrosive) to the concrete surfaces of the anchorage recess is to be discouraged (because the bond between the mortar and the paint is not good enough to prevent the formation of a shrinkage gap or crack, while this treatment moreover fails to give any definite protection against moisture penetration);
- using a non-shrink mortar for filling the recess was not found to offer advantages over the other mortars used in the tests;
- the best results with regard to corrosion protection were obtained when an epoxy bonding agent was applied to all parts of the anchorage recess before the mortar filling was introduced.

To supplement these exposure tests under practical conditions a number of tests under artificial conditions of increased severity were carried out. These tests yielded the following results (Sections 4.3 to 4.7):

- if there is no effective sealing of the anchorage recesses, moisture can easily penetrate into the tendons through the anchorages in consequence of temperature variations;
- the normal types of unbonded tendon grease offer little resistance to moisture penetration in the long run;
- deliberately introduced impurities (chlorides and/or sulphides) do indeed accelerate

the corrosive attack of the steel, but this effect is "overshadowed" if chloride-containing moisture can penetrate to the steel;

- a specially developed grease provides substantially better corrosion protection;
- there are no satisfactorily serviceable methods of analysing the composition of greases and of ascertaining the presence of corrosion inhibitors and the absence of harmful constituents in the grease;
- the development of a good method for the determination of the amounts of free chlorides, sulphides and nitrates in greases should be encouraged;
- the high-density polyethylene (HDPE) sheath applied with the aid of extrusion offers a good possibility of preventing the penetration of moisture to the steel;
- in the manufacture, transport, storage and installing of sheathed unbonded tendons it is necessary to take due care not to damage the sheath and thus puncture or rupture it;
- special measures to prevent moisture penetration via the anchorages are to be encouraged: the use of a plastic anchorage enclosure and effective glueing of a watertight plug in the anchorage recess are promising developments in this respect.

Some final considerations on the corrosion protection of unbonded tendons are presented in Chapter 5. The conclusions are based on a judicious assessment of the findings of other investigators, the results of the Committee's own experimental research, and the opinions formed by the Committee in the six-year period occupied by this study.

With regard to the grease the Committee arrived at the following conclusions (Section 5.2):

- the grease should have a good anti-corrosive action and good workability;
- lubricating greases based on mineral oil - provided that anti-corrosive agents (inhibitors) have been added - as well as greases specially developed for unbonded tendons can suitably be used;
- the greases normally used for unbonded tendons are not sufficiently impermeable to moisture, so that the moisture-excluding function must be performed by adequate sheathing;
- special types of grease are commercially available which are sufficiently impermeable to moisture; to what extent the higher cost (about 6% higher per metre of tendon) is prohibitive cannot be assessed by the Committee;
- in order to find out whether the greases employed offer sufficient protection from moisture, they should be tested - within the context of certification for suitability - by the intermittent immersion testing of greased steel plates; more particularly, the plates are intermettently immersed in a 3.5% solution of NaCl for 28 days;
- the chemical purity of the greases may vary considerably; any harmful constituents may attack the steel if moisture penetrates to it;
- the development of suitable methods for analysing the content of chlorides, sulphides and nitrates in greases should be stimulated;
- it is preferable only to use greases containing not more than 50 ppm of chlorides, sulphides and/or nitrates;

- in order to ascertain whether a grease does not contain inadmissible amounts of these constituents, stress corrosion tests should - for certification and for monitoring the quality during the validity period of the certificate - be performed on a tensioned unbonded tendon of which the sheath has been partly removed or provided with perforations (testing in distilled water, at an initial stress of 80% of the characteristic tensile strength, for a period of 6 months).

With regard to the sheath the Committee arrived at the following conclusions (Section 5.3):
- the sheath is an essential part of the unbonded tendon system;
- high-density polyethylene (HDPE) of the usual thickness (0.75 mm minimum) gives substantial protection against moisture penetration;
- the sheath should be applied by means of the extrusion method;
- during the manufacture, transport, storage and installing of the sheathed unbonded tendon it is necessary to take effective measures to avoid damaging the sheath.

With regard to the anchorage the Committee arrived at the following conclusions (Section 5.4):
- for protecting unbonded tendon systems against corrosion it is necessary to take effective measures to prevent penetration of moisture from the ends;
- during transport, storage and installing of the sheathed tendons, their ends should be closed in a watertight manner (e.g., with greased HDPE caps);
- the tendon sheath should be connected in a watertight manner to the anchorage unit (some suitable methods are described);
- the development in which the metal anchorage parts are enclosed in an anchorage enclosure made of plastic should be encouraged (besides, the joints between the component parts of split anchorage units should be suitably greased to achieve optimum exclusion of moisture);
- when the tendons have been tensioned, their projecting ends should be curtailed by grinding off, immediately followed by measures to prevent the absorption of capillary moisture into the tendon;
- the anchorage recesses should be sealed with waterproof mortar that bonds to the concrete and will not subsequently form a shrinkage crack or gap at the interface;
- developments aimed at sealing the recesses with glued-in prefabricated plugs are to be welcomed; in general, further research in devising an optimum sealing method is desirable.

On the basis of the considerations offered in this report, recommendations have been prepared which, in the Committee's opinion, should be embodied in codes of practice for unbonded tendon systems.

Acknowledgement

The authors wish to record their indebtedness to the excellent literature study [5] carried out by the late Dr. J. W. Boon (whose death occurred in 1981), which formed an essential part of the work of CUR-VB Committee C26A.

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