



GROUTING OF POST - TENSIONING TENDONS

Introduction

The VSL Grouting Package

Cementitious Grout

Grouting on Site

Inspection and Monitoring of Tendons

Repair of Tendons with Defective Grouting

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PREFACE

The concept of prestressed concrete has been around for one hundred years, although handicapped in the early days by a lack of suitable high strength materials. Its real development began some sixty years ago and has progressed since then – in terms of technology, systems, achievable spans and engineering ingenuity – has been remarkable. Without question, it is an economic and technically efficient system, in countering the weakness of concrete in tension by explicitly introducing a precompression to resist imposed loads.

Having said that, it had not been without its traumas in the last two decades. Mostly, these were concerned with durability, mainly due to corrosion caused by chlorides emanating from sources such as de-icing salts and seawater. While the vast majority of structures have behaved satisfactorily, sufficient examples of deterioration were found to cause concern – and to question the quality of grout and grouting especially.

In the UK in particular, a ban was introduced in 1992 by the Highways Agency on grouted post-tensioned concrete bridges, until satisfactory new standards and practices were introduced. This took four years, culminating in reference [1] to the present Report (with a second edition due to be published shortly – reference [17]). Performance requirements for grouts were set, new grouts were developed and extensive field trials undertaken. The sensitivity of grout and grouting to variability in practice was fully recognized and dealt with. However, it was also found necessary to consider all aspects of design, detailing, materials and workmanship in a coherent comprehensive way.

Parallel activity has occurred in other countries, and internationally, work has been coordinated under the auspices of FIP (now fib). It is reasonable to claim that, in the last decade, the whole process of prestressing and grouting has been the subject of a rigorous review – leading to new technology, and a re-statement of good practice – and how to achieve it.

In writing the Preface to The Concrete Society TR47 (Reference [1], I gratefully acknowledge the co-operation of all sections of the industry. This included the prestressing companies, all of whom operate internationally. Since then, they have been adapting the new general standards and practices, to suit their individual systems – all supported by extensive research and development. This particular Report is a classic example of that. I am especially attracted to the emphasis put on the following:

- ## The need for a holistic approach, embracing design, detailing, materials and construction practice;
- ## Recognition that grouting is a skilled and sensitive operation, requiring specialist experience and expertise, to carry it out properly;
- ## The questioning attitude to past test methods for grouts and grouting, while putting forward proposals, which give a better measure of key characteristics and properties;
- ## The obvious desire to adapt and upgrade VSL technology, to give a much better balance between load capacity and durability performance, than in the past.

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(June 1995 –November 1999).

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1. Introduction

1.1 Durability of post-tensioned structures

For a long time concrete structures, and in particular prestressed concrete structures, have been considered inherently durable with little to no need for maintenance. More recently it has been recognized that this is not true, and that concrete structures can suffer durability problems under certain conditions. In many cases, such problems were accompanied with corrosion of the non-prestressed and prestressed reinforcement in the structure. However, the corrosion of the reinforcement is usually not the root cause of the durability problem but rather a consequence of inadequate consideration for durability in the overall design of the structure.

It has been recognized that a design for durability relying on a single layer of protection cannot guarantee reliable

overall protection of the reinforcement. Therefore, the concept of multi-layer protection has been created, [1]. In this concept the first and perhaps most important layer of protection is the overall concept and design of the structure. A key element in this design is to keep water off the structure and the reinforcement, and/or to assure that it drains quickly from the structure. A second layer of protection can be provided with water-proofing membranes in particular on critical surfaces exposed to water and other aggressive media such as de-icing salts. A third layer of protection in concrete structures is provided with dense concrete designed specifically for low permeability. A fourth layer of protection for the tendons of post-tensioned structures has been introduced in the early 1990's, and consists of a leak tight encapsulation of the tendons with robust, corrosion resistant plastic. The last layer of protection of post-tensioned structures is provided directly onto the prestressing steel in

the form of cementitious grout, or by other types of protection systems applied in the factory such as grease and plastic sheathing for monostrands.

Grouting, as reviewed in detail in this report, is the last, and is only one, of the layers of protection of tendons in post-tensioned structures. While high quality grouting is important for the durability of tendons, it alone cannot guarantee the durability of tendons. It is the owner's and the engineer's obligation to select and specify a suitable combination of independent layers of protection adapted to the particular environment in which the structure is built. Additional layers of protection provided during construction have a relatively insignificant cost compared with repair of durability problems of a structure in operation.

1.2 Past experience with post-tensioning tendons

While the idea of prestressed concrete is much older, the real

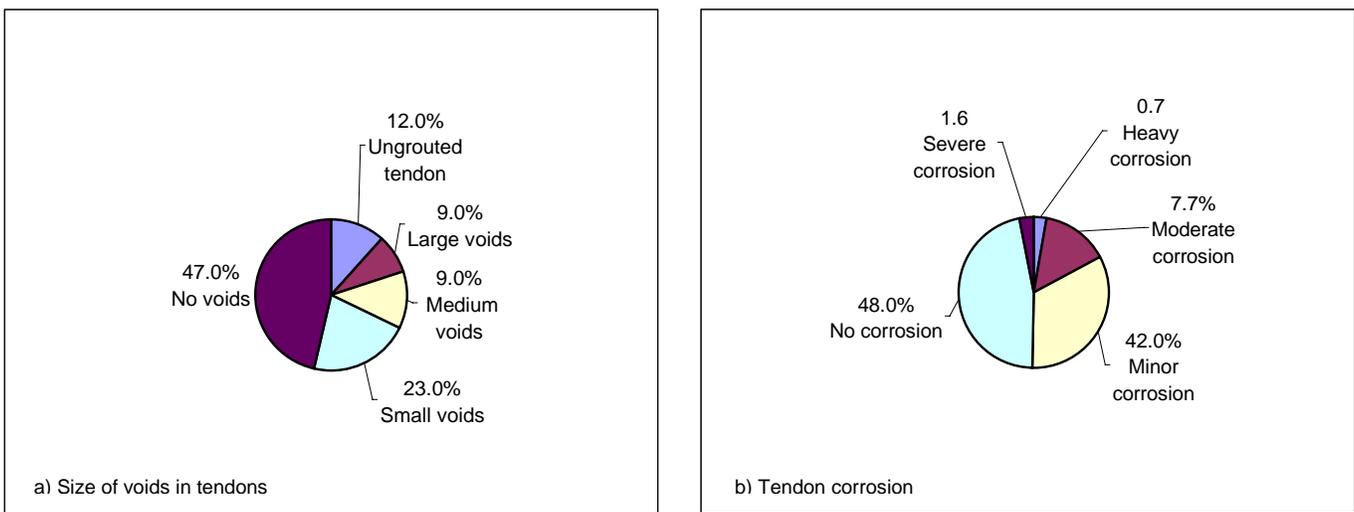


Fig. 1: Results of post-tensioning tendon inspection of 447 bridges in the UK, [4].

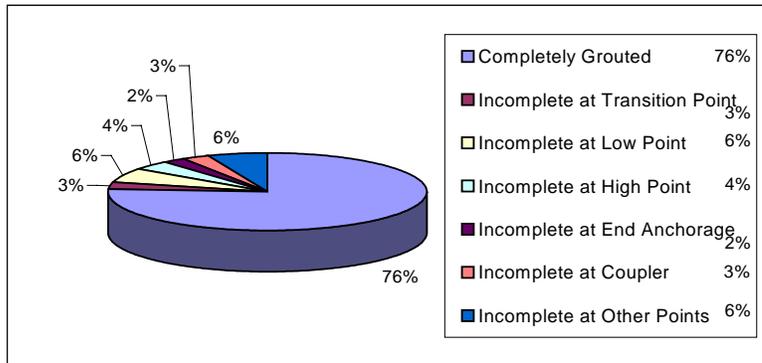
use of the technology started in the second half of the 1940's with projects by E. Freyssinet, F. Dischinger, G. Magnel, U. Finsterwalder, F. Leonhardt and W. Baur, and many others, [2]. Hence, one could say that prestressed concrete has existed for about 50 years. Most of the projects built in prestressed concrete in accordance with the rules for good design, detailing, and practice of execution have demonstrated the excellent durability of prestressed concrete in general, and of post-tensioning tendons in particular. In [3] e.g. it is stated that "It must be emphasized that instances of serious corrosion in prestressed concrete structures are rare when one considers the volume of prestressing material (strand, wires and bars) that have

been consumed worldwide over the years".

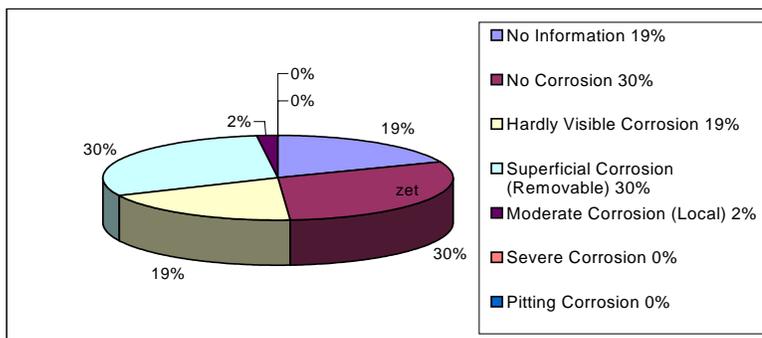
The technology of prestressed concrete did receive extremely negative press with the temporary ban of prestressed concrete bridges using post-tensioning tendons introduced in 1992 by the Highways Agency in the UK. The temporary ban was only lifted four years later after a detailed review of all aspects of bridge design and detailing, of the specifications for materials and grouting works, and of the qualification of personnel and companies. As a consequence of this action in the UK, a series of systematic investigations into the durability of prestressed concrete and post-tensioning tendons were initiated in the UK, France, Switzerland, Austria, and elsewhere, [4,5,6].

While all these investigations confirmed that the large majority of prestressed structures and post-tensioning tendons show excellent durability with insignificant corrosion defects only, if any, they all found some instances with durability problems and post-tensioning tendon corrosion.

In [4], e.g., a summary of findings of a total of 447 state owned post-tensioned bridges inspected in the UK is presented. The following results were found: 47% of the post-tensioning tendon ducts were completely grouted, i.e. had no voids; 23% of the ducts had small voids; 18% had medium to large voids; and 12% were not grouted at all, see Fig. 1. In these 447 bridges, 10% of the post-tensioning tendons showed moderate to severe corrosion.



a) Type of voids in tendon



b) Tendon corrosion in incompletely filled tendon ducts

Fig. 2: Results of post-tensioning tendon inspection of 10 bridges in Vienna, Austria, [5].

In [5] information on an investigation of 10 bridges built in Vienna between 1956 and 1978 is provided. A total of more than 10,000 duct locations were opened locally, and the status of tendon grouting and tendon corrosion was recorded. The results of this investigation confirmed that the actual performance and durability of the post-tensioning tendons is excellent, and document the good quality with which these projects were built. 76% of all the opened duct locations were completely filled. The 24% of duct locations which were not completely filled were essentially found in one project with stressbar tendons for which a undersized duct diameter had been used. Of these 24% duct locations with grouting defects, only 2% showed moderate/local corrosion, i.e. 48 out of 10,000 loca-

tions. The remaining locations showed either no corrosion, minor or superficial corrosion which could be removed by cleaning with a soft cloth, see Fig. 2.

In [6] investigations on 143 projects, including 107 bridges, 23 ground anchor projects, and 13 others, are presented. The majority of the structures documented good durability of the post-tensioning tendons or ground anchor tendons. Of the 14 bridge projects with grouting defects the majority of corrosion problems in the tendons was caused by ingress of water containing chlorides. A durable and leak tight encapsulation of the tendons, e.g. with robust plastic ducts, was considered essential to improve the protection and to assure the durability of grouted post-tensioning tendons.

More recently, durability problems due to incomplete grouting and corrosion have been reported in the USA. On the Mid-Bay project in Florida, one completely and one partly failed external tendon were found during a detailed inspection, [7]. During inspection many end anchorages of the external tendons located at the high point of the tendon profile were found incompletely filled with grout.

While each of the above reports contains some very specific information, the results of all investigations show some common trends and conclusions. These may be summarized as follows:

(1) Review the detailing of post-tensioned structures

and of the post-tensioning tendons: It is, e.g. not surprising that tendons, anchored at a location where water from the bridge deck drains over the anchorage, and where no sealing of the anchorage is provided, may develop corrosion of the prestressing steel at some time. It is not surprising either that tendons crossing porous mortar joints without encapsulation in a durable sheath may experience corrosion. Relatively small improvements in the detailing of post-tensioned structures and the post-tensioning tendons will significantly enhance the durability of these structures and tendons, often at only a marginal cost, if any.

(2) Review the specifications for cement grout for post-tensioning tendons: It has been shown that the specifications used today are not stringent enough in terms of acceptance criteria or are using test methods which are not able to detect poor performance of a particular grout mix. This comment applies in particular to the requirements and tests typically used for the bleed of grout. Grouts with excessive bleed or segregation will almost inevitably produce locations inside a tendon, such as at high points of the profile, which are left partially grouted. If such locations are dry with possibly a film of alkaline grout on the tendon there will be no corrosion of the prestressing steel. However, if water is available and/or finds access there is a risk of corrosion. Introducing tighter specifications for the quality of grouts has a cost since often excess water will need to be replaced with cement and specific admixtures. However, this extra cost is marginal for the project.

(3) Rely on post-tensioning specialist contractors with well-trained and experienced personnel for the execution of the post-tensioning works and grouting: All grouts whether prepared on site from cement and admixtures or ready-mixed grouts are eventually mixed with water on site before injection. Utilizing personnel who understand the importance of this activity and who have sufficient experience with grouting to realize if there is a problem, and react, is an absolute necessity to assure good quality grouting. It is important that owners and their representatives only accept specialist companies with well-trained and experienced personnel for post-tensioning activities. Leonhardt already said: "The responsibility involved in the design and construction of prestressed concrete requires that only engineers and contractors may carry out this specialized work who have collected sufficient knowledge and experience and who can assure an accurate and careful execution", [2].

1.3 Bonded versus unbonded tendons

With the above referenced problems found in grouted tendons, the discussion on the best option of corrosion protection of tendons has been launched again. This question is not new and different times and people have chosen their preference in the early years of post-tensioned concrete. For example, unbonded tendons have been preferred by Dischinger in early post-tensioned structures, [8]. How-

ever, under the influence of Freyssinet and other prominent engineers, the advantages of structures with bonded tendons were emphasized and this type of tendon became the common practice. External unbonded tendons were banned in the UK in the 1970's after some problems have been found. External tendons have later been strongly promoted by Jean Muller and other French engineers in conjunction with precast segmental bridge construction in France and in particular in Florida. Under the auspices of SETRA (State design office of highway authority) many bridges have been built in France using either external tendons only or a combination of internal bonded, and external unbonded tendons. While this construction practice was not accepted previously, the German highway administration recently declared unbonded tendons as the preferred type of bridge tendons, [9].

The above clearly documents that there is not one superior type of tendon. A particular preference of one type rather seems to be the consequence of a personal choice of engineers or of a particular period of time. As history has shown, these preferences change. It may therefore, be appropriate to repeat the strengths and weaknesses of bonded and unbonded tendons again for reference. In our opinion, there is no one type of tendon which answers to all requirements, and it is up to the engineer to select the type of tendon best suited to a particular project and construction method. A systematic en-

forced switch from one practice to another is neither justified by past experience nor warranted in terms of risk.

Advantages of grouted bonded tendons can be summarized as follows:

š **Provision of active corrosion protection:** The prestressing steel is actively protected, i.e. passivated, against corrosion through the alkaline environment provided by the cementitious grout. To initiate corrosion prestressing steel first needs to be depassivated.

š **Provision of bond of the tendon to the structure:** Bond allows a significant increase of the prestressing force in a cracked section after decompression, and permits the pre-stressing steel to reach the yield or even ultimate strength. This has significant effects on the strength of the section, on the crack distribution in the prestressed member, and on the energy dissipation of the member, [8]. Bond has also a very beneficial effect on the redundancy of a prestressed member. A local defect in the tendon remains local, i.e. the tendon force is not affected over the entire tendon length.

š **Cost effectiveness:** Cementitious grout is a very cost effective injection material for which long and good experience exists. The compatibility of cementitious grouts with prestressing steel is well proven over a long period of time.

Advantages of unbonded tendons can be summarized as follows:

š **Future adjustment of prestressing force:**

Prestressing forces of unbonded tendons can theoretically be adjusted at any time during the design life of a structure. However, all necessary tendon details for later stressing need initially be provided such as access and clearance for jacks, and sufficient overlength of prestressing steel to connect the jack to the strand. While re-stressing of tendons was a justified concern when long term losses due to creep and shrinkage of concrete, and relaxation of prestressing steels, were not yet well understood, this is no longer the case today. The authors are not aware of any recent case where re-stressing of a tendon was necessary due to excessive losses of tendon force. We would like to give a word of caution because re-tensioning of a tendon, initially stressed to 70-80% of its strength, at some time during the design life of the structure is certainly not an easy task. Hence, if an increase in prestressing force is ever required, the best option seems to be to provide additional tendons to the structure. A number of recent standards such as AASHTO, [10], actually require new structures to be detailed for the addition of future external tendons to potentially increase the prestressing force to accommodate potential increase of loads or excess loss of tendon force. According to these standards,

anchorage and deviation details need to be provided to allow addition of a fixed number of tendons, e.g. 2 per section, or of a given percentage (AASHTO: 10%) of the initial prestressing force. This procedure keeps the initial investment to a minimum, and greatly facilitates the future addition of tendons to the structure, if ever needed.

§ **Facilitated inspection of tendon:** Since unbonded tendons are placed externally to the structure, access to the tendon for inspection is facilitated over a substantial portion of the tendon length. Such access is not usually available near the anchorages and/or at tendon deviation points where such tendons often are anchored or deviated in massive diaphragms.

While access to the tendon is facilitated, inspection of the prestressing steel inside the tendon or bundle of prestressing strands is not necessarily provided. Hence, special inspection or monitoring devices still need to be used to collect information on the actual performance and durability of the steel.

§ **Replaceability of tendons:** Unbonded external tendons may be replaced at any time during the design life of a structure. Replacement is preceded by either de-tensioning of the tendon if the necessary tendon details have been initially provided, or by

gradual cutting of the tendon according to specific procedures adapted to the particular site and tendon type. The actual removal of the tendon is then possible if appropriate details have been provided initially at anchorages and deviation points. Installation of a new tendon can then follow. The authors are of the opinion that tendon replacement should only be considered if there is a significant risk of unexpected tendon failure with consequential damage or risk to persons. In all other cases, and in particular if the structure can accept additional prestress, rather addition of new than replacement of existing tendons should be considered. Such favourable conditions to avoid replacement exist in particular for bonded tendons in structures with sufficient concrete dimensions.

1.4 Plastic ducts for bonded post-tensioning tendons

Provision of a corrosion resistant and leak tight encapsulation of the tendon can assure a very effective protection of the tendon. This concept has been used since many years for the protection of prestressed ground anchors. In the early 1990's, VSL introduced the corrugated plastic duct system, PT-PLUS, for bonded post-tensioning (PT) tendons which together with suitable accessories such as connection details and anchorage caps provides a complete leak tight encapsulation of the post-tensioning tendons.

The UK has made the encapsulation of tendons in plastic

ducts compulsory in 1996, [1]. As a further step forward, the concept of verifying the leak tightness of the system has been introduced at the time. This verification is done by air pressure testing of the assembled duct and anchorage system. Pouring of concrete is only approved when the duct system is confirmed to be sufficiently air tight.

If the encapsulation of tendons in plastic is supplemented with specific details at the anchorages, a "Electrically Isolated Tendon" (EIT) can be provided. In addition to the above mentioned advantages, an EIT allows monitoring of the provided encapsulation at any time during the design life of the tendon. A simple measurement of the electrical resistance between the tendon and the structure can be used to confirm the intactness of the encapsulation of the tendon at any time. It can, in particular, be used to confirm the proper installation and the compliance of the tendon with the project specifications at the time of construction. Encapsulation of tendons in plastic duct systems combined with EIT measurement has been introduced in Switzerland in 1993. Since that time more than 20 bridge structures have been built with this concept. The positive experience with the concept has now led to the introduction of new guidelines for the protection of tendons in Switzerland [11]. While still accepting some application of corrugated steel duct in benign environment, these guidelines require encapsulation of tendons in plastic, in general. EIT is specified for a percentage of tendons to verify the encapsulation, and in general,

lation, and in general, for structures exposed to stray currents.

Complete encapsulation of post-tensioning tendons in plastic ducts and EIT are effective protection methods. When combined with high quality grouting, they are considered a major step forward to achieve reliable long-term durability of post-tensioning tendons.

1.5 Intent of the report

The intent of this report is to provide a sound basis for owners, engineers, and contractors to have total confidence in the technology of grouted, bonded post-tensioning. This is achieved by:

- § Providing information on services available from the VSL Group, your specialist contractor for post-tensioning and related engineering, on any aspect related to grouting and post-tensioning (Chapter 2).
- § Providing information on recent progress in the design and testing of cementitious grout mixes and improving existing knowledge on the interaction between cement, water, and admixtures (Chapter 3).
- § Providing information on state-of-the-art grouting procedures on site to assure complete filling of post-tensioning tendons with grout over the entire length of the tendon, see Fig. 3 (Chapter 4).

- § Providing information on available inspection and monitoring techniques on existing grouted post-tensioning tendons. Such techniques allow to either confirm their good health or to detect defects to allow subsequent repair (Chapter 5).

- § Providing information on available repair methods for grouted post-tensioning tendons which have been successfully used (Chapter 6).

This report is specifically written for grouting of post-tensioning tendons either internal or external to the structure. The report does not cover grouting of ground anchors or stay cables.

As recognized during recent investigations of post-tensioned bridges, careful detailing of the structure for tendon layout, anchorage and coupler locations, etc. is essential for the durability of post-tensioning tendons and the structure. However, this aspect goes beyond the scope of this report, and the interested reader is referred to other publications, such as [1,8].

2. The VSL Grouting Package

2.1 General systems and services

The VSL Group provides a comprehensive range of services in connection with post-tensioned structures, including:

- § Assistance to owners, engineers and contractors with preliminary and final design studies of post-tensioned structures.



Fig. 3: Properly grouted tendon section

- § Assistance to contractors with the selection and details of the construction method of post-tensioned structures.
- § Detailed design of the post-tensioning system adapted to a particular project.
- § Supply and installation including stressing and grouting of the post-tensioning system.
- § Supply of post-tensioning materials, equipment, and supervising personnel.
- § Complete erection of post-tensioned bridge decks such as precast segmental superstructures working as a subcontractor.
- § Use of other VSL Systems such as slipforming or climbforming, rock and soil anchors, stay cables, heavy lifting, bearings, expansion joints, stressbar systems, the retained earth system VSoL, PT-PLUS™ plastic duct system, [12, 13], etc.
- § Design and execution of repair and strengthening works for concrete structures.
- § Design and execution of specialized foundation works such as diaphragm walls, barrets, caissons, piles, soil grouting, etc.
- § Design, supply and execution of members made of the ultra-high performance concrete, DUCTAL™.

The actual extent of the VSL services will usually be determined in discussions with the owner, engineer, contractor, and the VSL Organisation. In many cases the combination of several VSL Systems and Services is possible on a particular project. This enables the use of labour and equipment to be rationalized with corresponding cost savings.

The reader is encouraged to visit the Internet sites of the VSL Intrafor Group at <http://www.vsl-intl.com> and <http://www.intrafor.com> for more details on our systems and services, or to consult our brochures, e.g. [14].

The VSL Group can offer a wide range of specialized publications on the above systems and services. Please contact your nearest VSL Organisation for a copy.

2.2 The VSL grouting package

Grouting has been considered by many as a simple activity of mixing cement and water, and pumping it into a duct. In addition to this perceived simplicity, it is an activity where people's hands can get dirty. It has therefore, attracted much less interest and attention than placing and stressing operations, and has been often considered something "everyone can do" anyway. With the past experience reported under Section 1.2, and with the knowledge collected in recent research presented later in this report, an increasing number of clients and engineers have started to realise how complex the grouting of a post-tensioning tendon actu-

ally is. Already the individual grout constituents, cement and admixtures, are complex materials. The interested reader is referred to specialist literature such as [15]. The interaction between the individual constituents is even more complex. However, the properties of the grout are also affected by the equipment used to mix and pump it. The properties of the grout inside a post-tensioning tendon are further influenced by the detailing of the tendon and vents, the ambient conditions, and the grouting procedures utilized. Last but not least, all these activities are carried out by human beings with different backgrounds, education, and training.

In view of the above complexity and the many interfaces to manage, only a global approach considering all activities as one package will assure optimum results. **In the authors' opinion it is in the owner's best interest to consider the post-tensioning and grouting as one package, and subcontract the entire package to one "Single Source" post-tensioning specialist contractor such as VSL.** If assigned such a full package, VSL will use VSL-HPI Grout™ which is a high performance cementitious grout offering performance characteristics which have been optimised with VSL proprietary procedures. Our technical staff will provide post-tensioning system details which are fully compatible with the grout materials, equipment, and procedures intended to be used on site. This can be further complemented with the use of the VSL PT-PLUS™ plastic duct system. VSL will then assure that the grout will be in-

jected by experienced, well-qualified and trained personnel, with VSL optimised grouting equipment. The grouting works will be carried out in compliance with our standard procedures adapted to the particular conditions of the site, and applying state-of-the art testing and QC procedures as presented later in this report.

The overall objective of VSL with the above full package approach is to enhance the durability of post-tensioned structures by improving the quality of grouting. Owners, engineers, and contractors relying on the above approach will quickly realize the advantages provided.

3. Cementitious Grout

3.1 Common grout specifications and recent trends

Specifications for cementitious grouts changed little over a long period of time up until quite recently. The "Fédération Internationale de la Précontrainte" (FIP) Guide to Good Practice on "Grouting of tendons" can be considered as a fairly representative document for grouting up to today, [16]. Most national standards in Europe and Asia, and recommendations such as the ones issued by the Post-Tensioning Institute (PTI), used the same or similar grout testing procedures, and either the same or similar acceptance criteria. The FIP Guide to Good Practice also has become the basis for the European Standards, EN 445, 446, 447 for Grouting, [17].

The main properties considered relevant for the performance of grouts in these documents are:

- § **The flowability of grout:** This was considered important to ensure complete filling of the tendon duct.
- § **Volume change of grout:** This was considered important to be maintained within a specified range around zero to completely fill the tendon duct.
- § **Bleed of grout:** It was considered important to limit free water inside the tendon duct, and any bleed water to be reabsorbed by the grout within a specified time.
- § **Strength of grout:** This was considered to provide an indication of the grout quality with respect to its bond and shear strength.
- § **Resistance of grout to freezing:** This was considered important for applications in cold climates.

Table 1 gives a summary of the specified properties in the documents of FIP, [16], and European Standards (EN), [17]. The recent revision of the PTI Guide Specification for Grouting, [18], is also shown for reference. It includes additional tests for setting time and permeability of grout.

Table 1 also summarizes the

test methods or specimens used to check the properties. These are flow cones with an efflux opening of \approx 10-12.7 mm; small scale plastic cylinders of diameter and height in the order of 100 mm (FIP), or cylinders of 50 mm diameter and 200 mm height (EN) for volume change and bleed; and prisms, cubes, or cylinders in the order of 50 to 100 mm for strength.

Recent investigations and experience on sites have shown that the specifications [16,17] are either not relevant, or that the specimens and test methods are not representative of the real behaviour of grout inside a tendon duct. The first comment applies in particular to the strength of grout. A well designed grout mix will typically develop a strength much in excess of the specified values. The second comment applies to the bleed and volume change of grout. It has been realised recently that the bleed behaviour of grout inside a plastic container of the specified size is insignificant compared to the real bleed behaviour inside an inclined duct with prestressing strands. Fig. 4 shows the bleed and volume change behaviour of two grout mixes in different test specimens. The grout called "Common Grout" used a plasticizing and expansive admixture with a water/cement ratio of 0.38. The grout called "Optimised Grout" used another plasticizing, and a

stabilising admixture but without expansion with a water / cement ratio of 0.32.

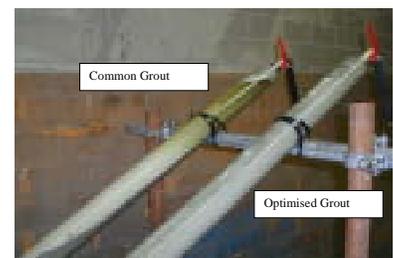
The Common and Optimised Grout mixes had comparable



a) Standard bleed test in 100 mm containers



b) 1 m high tubes with and without strand



c) 5 m Inclined Tube with 12 strands

Fig. 4: Bleed and volume change behaviour in different test specimens.

Property	FIP Guide [16]	EN 447 [17]	PTI [18]	Test method/specimen
§ Flowability / Fluidity	¹⁾	Ω25 seconds	11 to 30 seconds	Flow cone (\approx 10 or 12.7 mm)
§ Volume change	-2% to + 5%	- 1% to + 5%	0% to + 0,1 %	Plastic cylinder (100-200mm high)
§ Bleed	Ω2%	Ω2%	0% ¹⁾	Plastic cylinder (100-200 mm high)
§ Strength at 7 days	Ø20 MPa	Ø27 MPa	Ø21 MPa	Cube or cylinder (50-100 mm)
at 28 days	Ø30 MPa	Ø30 MPa	Ø35 MPa	
			¹⁾ Wick-Induced test at 3h	

Table 1: Common specifications for grout

Note: 1) No limit is specified, but water/cement ratio is recommended to not exceed w/c Ω0.40 to 0.45

flow times. Four different test specimens were used, i.e. plastic container of about 100 mm height, plastic pipe of 80 mm diameter and 1m high without strand, plastic pipe of 80 mm diameter and 1 m high with one strand, and a 5 m long tube of 80 mm diameter inclined at 30 degrees to horizontal with 12 strands. All four specimens were filled with the same batch of each grout mix.

The results for bleed and expansion were quite different from one test specimen to the other. The 100 mm container, typically specified in standards, showed only an insignificant difference in bleed between the two grouts. Actually, both grout mixes would have satisfied the specification of Table 1. The 1m high pipe without strand showed both grout mixes with no bleed. However, the common grout showed significant expansion due to the expansive admixture. This was significantly different in the 1m pipe with strand. The Common Grout now showed significant bleed but no more expansion. The Optimised Grout still showed no bleed. Finally, the Inclined Tube test confirmed the poor performance of the Common Grout with about 800 mm bleed water and no apparent grout expansion. The Optimised Grout still showed an insignificant amount of bleed in the order of 5 mm bleed water on the top of the pipe. It shall be mentioned again that all four specimens were filled with the same batch of each grout mix, i.e. there was no variation of grout properties between different specimens.

The above results were obtained in a series of tests done by VSL. The same phenomenon has been recognized and confirmed by others. It was in particular France who developed the Inclined Tube test after a series of grouting problems with excessive grout segregation and bleed had been detected on sites. The Inclined Tube test was the only test method which was able to realistically reproduce the phenomena found on site. This led the French administration to specify the Inclined Tube test as basis for the approval of a particular grout mix before its use on site, [19]. Later on, in order to reduce the expenses for testing on site, the UK introduced the idea of the 1.5m pipe with a number of strands such as to fill about 30% of the pipe section as standard bleed test, [20]. A European working group on the approval of post-tensioning systems introduced the 1m pipe with one single strand under the name of "Wick-Induced" Bleed test, [21]. A similar test has been introduced by PTI, [18].

The above evidence has confirmed that the grout test methods and acceptance criteria which have been used, and are still being used in most places around the world, are unfortunately not representative of the real performance of grout in a tendon duct. They are not able to correctly differentiate between a poor and a good quality grout. These test methods need to be replaced quickly by test procedures which are confirmed to be representative, with more stringent acceptance criteria. Only such representative test methods with stringent

acceptance criteria will consistently assure that exclusively good quality grout mixes are used for the injection of post-tensioning tendons. The Inclined Tube test has been confirmed to be the most representative test method. This and other new test procedures are included in Appendix A to this report.

3.2 Grout constituents

3.2.1 General

Grout is composed of cement, water and admixtures. These constituents have a complex interaction. This applies, in particular, to the admixtures and certain reactive components of the cement such as tri-calcium aluminate (C_3A). Also the particle size of the cement has a significant effect on the interaction between the grout constituents. Unfortunately, many if not all of these cement and admixture characteristics or particles are not part of the material specifications of national or international standards. Hence, specifying a cement for grouting of tendons according to a national or international standard is not sufficient to assure consistent grout properties. Rather the entire spectrum of chemical and physical properties of the cement must be known, and must be maintained within acceptable tolerance, in combination with particular admixtures, to assure consistent properties and quality of a particular grout mix.

It is beyond the scope of this report to review all the parameters of grout constituents which affect the grout properties. However, the following sections will briefly review some aspects

of each constituent considered essential for good grout performance.

3.2.2 Cement

(1) Type of cement: Portland cement is recommended for grouting of tendons. Other types of cement may be considered for grouting of tendons but only after detailed testing for their suitability in particular in terms of long term corrosion protection (e.g. for slag cements) or in terms of development of hydrogen gas (e.g. silica fume cements).

(2) Specific surface of cement: The Blaine value is an indirect measure of the specific surface of cement. Blaine values of cement vary widely across the world (range of 250-450 m²/kg) and even vary between batches from the same supplier. Cements with low Blaine values (i.e. low specific surface) tend to easily flocculate, i.e. form lumps. This will create non-homogeneous grouts which have a tendency to easily segregate. Cements with high Blaine values often require larger quantities of water and admixtures to wet their surface, and to provide a certain viscosity or flow time of grout. In addition, cements with high Blaine value have an earlier beginning of setting or stiffening. The above leads to a minimum specified Blaine value of 300m²/kg to avoid easily flocculating grouts. High Blaine values do not cause performance problems. However, a reasonable upper end of Blaine values for cement used in grouts is in the order of 380m²/kg, mostly for economical reasons. As men-

tioned above, this value should be maintained within a reasonably small range of tolerance to assure consistent properties of a particular grout mix.

(3) Chloride content of cement: The cement shall only contain insignificant traces of chlorides to avoid corrosion of the tendon. A typical limit is 0.05% of chlorides by weight of cement.

(4) Tri-Calcium Aluminate (C₃A) content of cement: C₃A is strongly reactive with admixtures. Its content in cement may vary widely around the world (range of about 2 to 12% of clinker). A relatively low C₃A content is desirable but may not be easy to obtain. Cements with medium to high C₃A content are more delicate in their interaction with admixtures, and necessitate a detailed testing series to assure compatibility of the cement with a particular admixture.

(5) Age of cement: Cement carbonises with age and with this reduces its reactivity with admixtures and water. On the other hand, freshly produced cement may still be inadequately cooled. Hence, the age of cement to be used for grouting of tendons must be controlled, and kept within a reasonably small range of a few weeks. Alternatively, the cement may be sealed in air tight containers for longer storage.

(6) False set and flash set of cement: These are two phenomena which are related to the calcium sulfate in the cement. If calcium sulfate is added in the form of gypsum, this may, when mixed with wa-

ter, provide a structure inside the cement having some rigidity, i.e. stiffening the grout. This is known as "false set". On the other hand, "flash set" results in cements which have insufficient sulfate present effectively to stop the hydration of tri-calcium aluminate (C₃A) to the hydrate rather than to ettringite. Flash set is accompanied with the release of considerable amounts of heat. Cement which shows either of the two phenomena is not suitable for grout, and must be avoided.

(7) Source of cement: With what was said in Section 3.2.1 it is clear that only cements of one particular source or supplier may be used for a particular grout mix for grouting of tendons.

The interested reader is referred to specialised literature for more details on the characteristics of cements, [15].

3.2.3 Water

(1) Water quality: Water must be free of impurities which could influence the setting of the grout and must not contain substances which are harmful to the prestressing steel. In general, it may be assumed that drinking water satisfies these requirements. In case of doubt, or if no drinking water is available, the water should be analyzed in a qualified laboratory and contents of organic particles, sulfates, sulfides, carbonates, and chlorides should be limited to maximum values in the order of 100-500 mg/l.

3.2.4 Admixtures

(1) Type of admixtures:

Types of admixtures differ by the nature of the molecules used. They differ in their degree of efficiency, i.e. the quantity needed to achieve a certain performance. Depending on the nature of molecules used they will interact differently with different sources of cement. Admixtures are available in liquid form or as powder. Admixtures are available to modify grout properties in many ways including the following: Plasticizing, stabilising, retarding, accelerating, thixotropic, expansive, etc. Admixtures with combined effects are also available. The user is advised to ask the supplier of an admixture for a detailed certificate of the product, and to perform detailed suitability testing in combination with the particular cement intended to be used for a grout mix.

(2) Shelf life of admixture:

Properties of admixtures change over time. Therefore, admixtures for which the shelf life recommended by the supplier has exceeded, should be discarded.

(3) Dry extract of admixture:

Many admixtures come in liquid form, i.e. are mixed with water. Since it is the dry content of the admixture which is relevant for the interaction with the cement, it needs to be declared and controlled within an acceptable range to assure consistent properties of a particular grout mix.

(4) Corrosiveness of admixtures:

Admixtures shall

not contain products which are harmful to the prestressing steel. This applies in particular to chlorides. But also calcium-nitrite has been reported to cause corrosion of prestressing steel. The supplier therefore, should provide confirmation that the particular admixture does not contain substances potentially harmful to the prestressing steel, and/or the suitability of the admixture should be confirmed by a qualified laboratory.

3.3 Grout characteristics

The following is a review of selected grout characteristics and of the effect of certain parameters on them. This review provides a better understanding of the behaviour of grouts, and assists in defining the relevant characteristics for grout specifications, and acceptance criteria.

3.3.1 Bleed

Water is needed in grout for the

(form lumps), and to settle (sedimentation), with the lighter water moving upwards, and collecting at the top of the grout. This sedimentation leads to an apparent reduction of grout volume. This movement of water may wash out certain components of the cement and admixtures, and thus may cause segregation of the grout.

Bleed and sedimentation of grout is probably one of the main reasons, if not the most important, for grouting and durability problems with tendons. Excess bleed water will collect at high points of tendon profiles and leave the prestressing steel in these areas without protection from alkaline grout. Such unprotected, exposed areas have been found in the investigations referenced in Chapter 1, see [4,5,6]. In cases where the bleed water was reabsorbed and ingress of additional water and chlorides was prevented by leak tight concrete cover or encapsulation by the sheath, no or only insignifi-

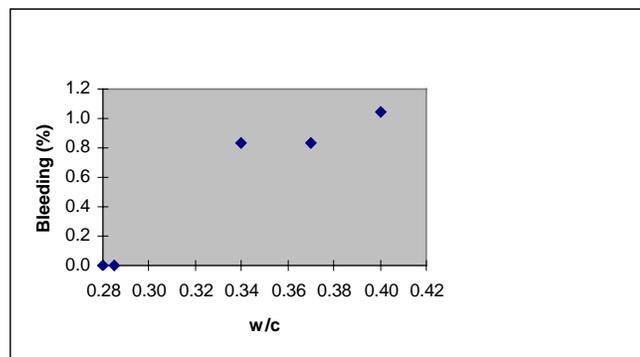


Fig. 5: Effect of water / cement ratio on bleed at 3 hours

hydration of cement. However, in practice typically much more water, than is needed for hydration, is provided to achieve a sufficiently low viscosity of grout for injection. In such a situation of excess water, the cement particles tend to flocculate

cant corrosion was found in these exposed areas even after long time. However, in less favourable cases, these locations often showed tendon corrosion.

The amount of bleed depends on different parameters of

which the quantity of water added initially is the most important. The quantity of water added to a given quantity of cement, or the water/cement ratio (w/c), must be kept as small as possible to limit the excess water. Actually, the amount of bleed is not proportional to the water/cement ratio. There seems to be a threshold at which bleed suddenly becomes significant. Likely this threshold depends on the actual grout constituents. Fig. 5 shows the effect of the water/cement ratio on the amount of bleed for one particular grout mix used in the VSL research. The threshold in this case is at a water/cement ratio of w/c – 0.30 - 0.32.

High pressure to which the grout is exposed will increase bleed. This is well known for long vertical tendons for which special grout mixes must be designed and special grouting procedures be applied to avoid problems due to bleed. For such applications, the bleed properties of grout shall be verified at elevated pressure, see [18].

As demonstrated in the Inclined Tube test, the addition of prestressing steel, and in particular strand, inside the duct significantly increases the amount of bleed water collected at the high point. A smooth duct as typically used for external tendons will further facilitate the movement of bleed water to the high point compared to a corrugated duct as typically used for internal tendons.

For all of the above said, bleed of grout must be strictly

controlled and kept to an insignificant quantity under all circumstances. The most effective measure is first of all to reduce the amount of water added to the cement as much as feasible. The desired low viscosity of grout for injection can be assured, even with low water/cement ratio, if suitable plasticizing admixtures are used.

3.3.2 Segregation and sedimentation

The phenomena of segregation and sedimentation were introduced in Section 3.3.1. As mentioned, they are a consequence of bleed and possibly other characteristics of the grout constituents which favour instability of the mix. Both effects produce grout which has a higher density near low points of the tendon profile, and a lower density at high points. As

the washing out of cement or admixture particles by the bleed water. This washing out may further cause changes of the grout properties such as a reduction of the pH-value at the high point.

Segregation and sedimentation can easily be confirmed by measurement of the density of grout at different locations and by observation of the grout colour. Fig. 6 shows the effect of sedimentation due to excess water for a particular grout mix in 1m grout pipes. The grout density of the mix with excess water drops significantly towards the top of the pipe, leaving a low density and porous grout near the top.

Grout mixes with a tendency to segregation or sedimentation will be detected in an Inclined Tube test.

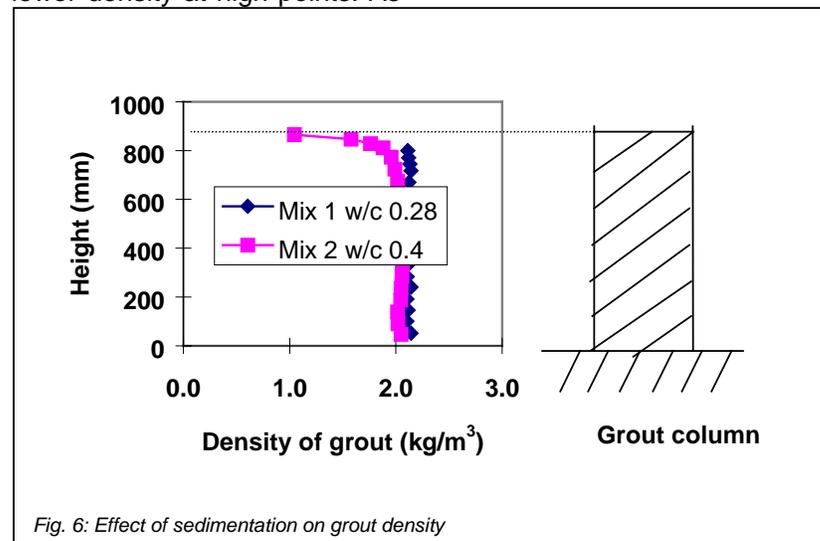


Fig. 6: Effect of sedimentation on grout density

documented in Inclined Tube tests, segregation in addition often goes with a change of colour of grout, e.g. dark grey at locations with higher density, and lighter grey and / or whitish or yellowish colour at locations with lower density. This change of colour is a consequence of

3.3.3 Viscosity and flow time

Freshly prepared grout for post-tensioning tendons must be easily pumpable for injection into the ducts, i.e. it must have a relatively low viscosity. In practice, the efflux time (flow

time) of a given quantity of grout from a cone has been used as a measure for the viscosity. Therefore, the two terms are considered equivalent for the purpose of this report.

The viscosity of grout can be reduced by the addition of water. To achieve a viscosity of basic grout without plasticizing admixtures which can easily be pumped, water/cement ratios in the order of 0.4 - 0.45 are required. This is significantly more water than needed for hydration of the cement, and will produce unstable grout mixes likely to show excess bleed, sedimentation and possibly segregation. To avoid these problems suitable plasticizing admixtures can be used which allow to reduce the water/cement ratio down to the order of 0.30 for low viscosity grouts suitable for injection in tendons. Grout mixes with low water/cement ratio are inherently more stable and less likely to show excess bleed, sedimentation and segregation.

The actual amount of water needed for a particular grout mix is often determined by trials such as to produce a desired viscosity or flow time of the grout. When using the flow cone according to the European Standard EN 445, [17] flow times should be kept below 25 seconds for injection. In practice, values between 13 and 18 seconds are often desirable. However, the absolute figure of the flow time depends to some degree on the particular application, equipment, and procedures used.

The flow time of a particular grout mix should remain stable over a sufficiently long period of time, at a given temperature range, to avoid problems during injection due to stiffening of the grout. It is not sufficient for this case to give an upper limit of the flow time. Rather the change of flow time over time is important. Grout mixes subjected to elevated temperatures are more likely to show rapid changes of flow time than grout mixes at low temperature. With suitable design and eventual use of specific admixtures, the flow time of grout mixes can be maintained stable over an extended duration of time even at high temperatures. Fig. 7 shows an example of the flow time development over time for a grout mix optimised by VSL for high temperature. Even at a temperature of 40°C, the flow time changed by less than two seconds over a period of two

the expected more rapid stiffening, see e.g. FIP Guide, [16]. However, in view of the undesirable effects of excess water on bleed, sedimentation, and segregation described above, this practice should be abandoned. Instead, the grout mix should be optimised for the expected range of temperatures with specific admixtures, and a minimum quantity of water.

3.3.4 Volume change

Volume change of grout is primarily due to two effects, i.e. shrinkage of grout and sedimentation of grout. Unfortunately, in practice the two effects are often combined.

Sedimentation of grout has been discussed in Section 3.3.1 and 3.3.2. It is best controlled by a low water/cement ratio and thus, by controlling bleed. If not controlled, sedimentation of

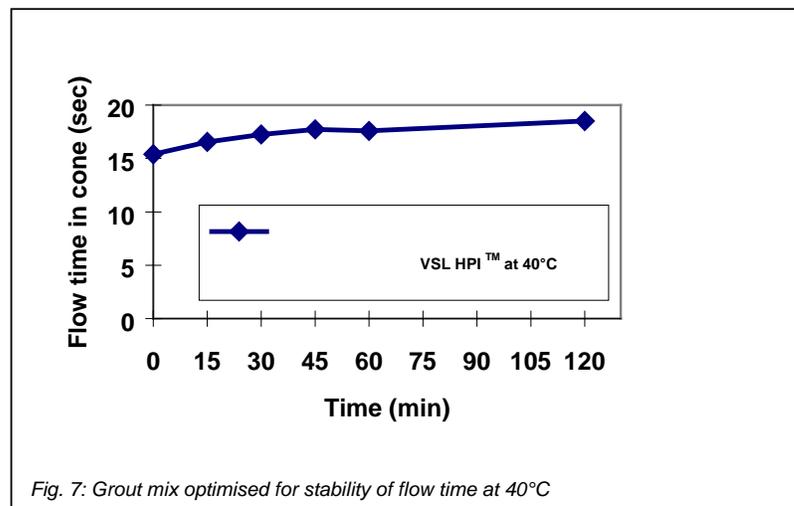


Fig. 7: Grout mix optimised for stability of flow time at 40°C

hours. This was achieved with a grout of a water/cement ratio of $w/c = 0.28$, and without cooling the constituents or grout.

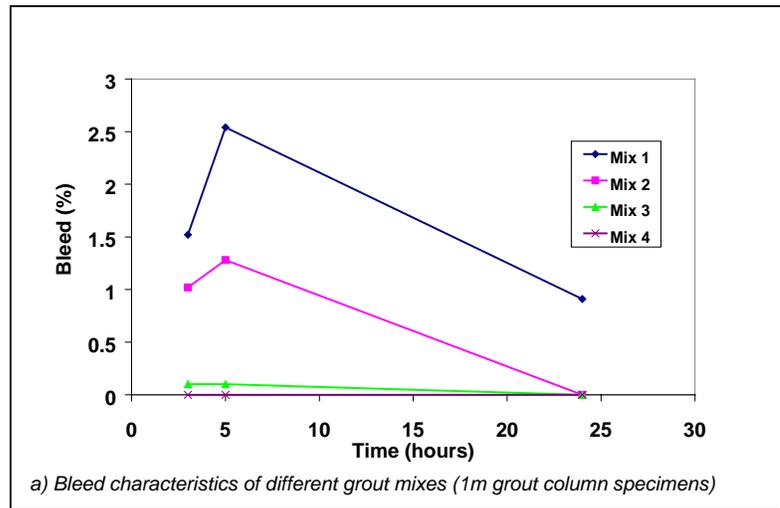
In the past, it has been recommended at elevated temperatures to add some extra water to the grout to compensate for

grouts with excess water can cause volume changes in the order of a few percent of the initial volume, in the first few hours after injection. This is shown in Figs. 8a and 8b for four different grout mixes. The four mixes were made from the same cement but differed in the

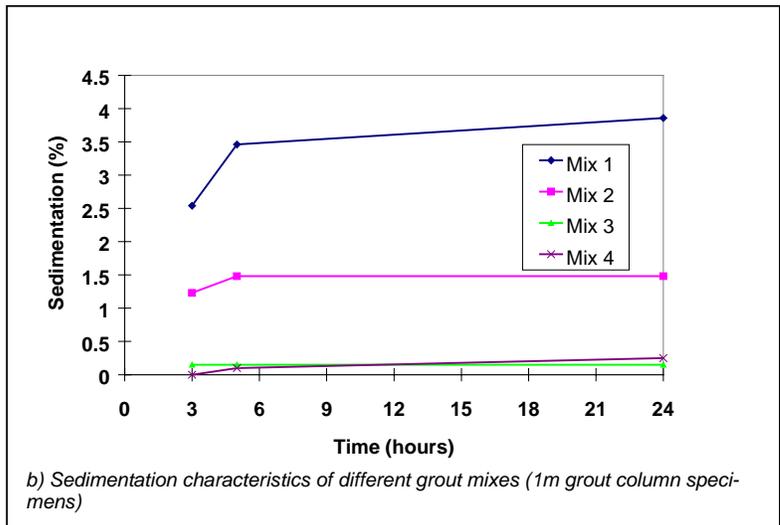
control of bleed by stabilising admixtures. It is evident that high bleed leads to high sedimentation in the order of several percent, see Mixes 1 and 2. However, if bleed is controlled, sedimentation is also controlled and remains insignificant, see Mixes 3 and 4.

Shrinkage of grout, on the other hand, is a completely different phenomenon which depends primarily on the type of the cement and to some degree on the amount of water. Fig. 8c shows selected results of shrinkage measurements on six different grout mixes over time up to 28 days. At 28 days maximum shrinkage values were below 2000 $\mu\text{m}/\text{m}$, and hence, about one order of magnitude lower than the effect of sedimentation.

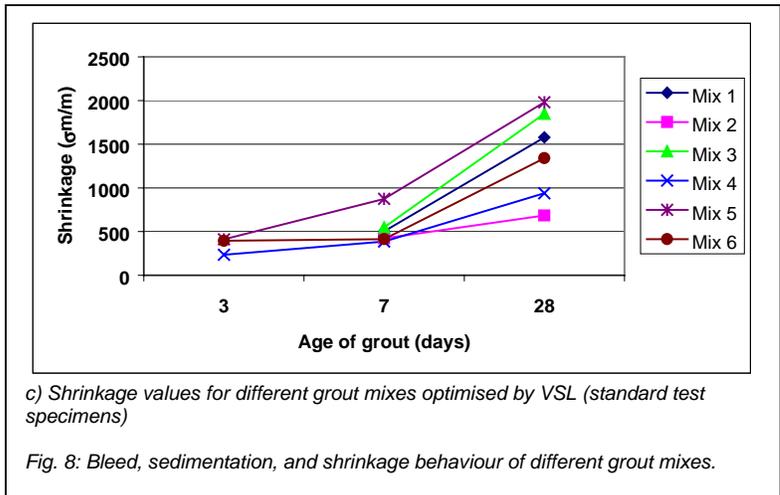
In view of the above, sedimentation needs to be strictly controlled since it can potentially cause voids in the order of a few percent of the original volume. This is best achieved by controlling the bleed of the grout. On the other hand, volume change of grout due to shrinkage is about one order of magnitude lower, and hence, insignificant for the creation of voids in the cross sectional dimension of tendons. Along the tendon axis, shrinkage is completely restrained by the prestressing steel in a similar manner to the restraint of concrete shrinkage in highly reinforced concrete sections. Based on the above, the use of expansive admixtures is not necessary. When considering in addition the results of the bleed tests shown in Fig. 4, the use of expansive admixtures is not rec-



a) Bleed characteristics of different grout mixes (1m grout column specimens)



b) Sedimentation characteristics of different grout mixes (1m grout column specimens)



c) Shrinkage values for different grout mixes optimised by VSL (standard test specimens)

Fig. 8: Bleed, sedimentation, and shrinkage behaviour of different grout mixes.

recommended at all. In fact, the testing shown in Fig. 4 demonstrated that the effect of the expansive admixture was canceled by the presence of the prestressing steel. At best, ex-

pansive admixtures create a porous grout.

3.3.5 Corrosiveness and toxicity

Grouts for post-tensioning tendons shall not cause corrosion of the prestressing steel and shall not be toxic. This can be achieved if the grout constituents are selected as discussed in Section 3.2.



Fig. 9: Mud Balance equipment for density measurement of fluid grout.

3.3.6 Density

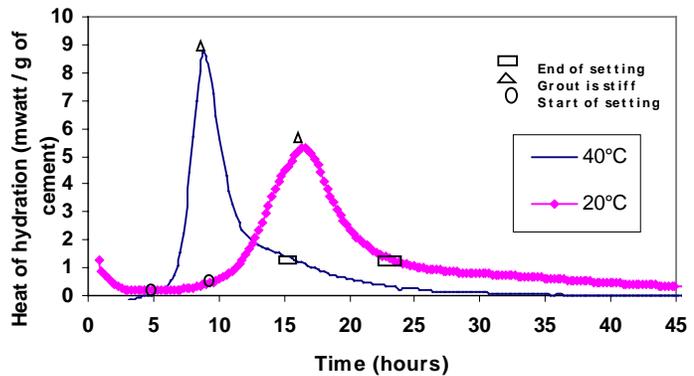
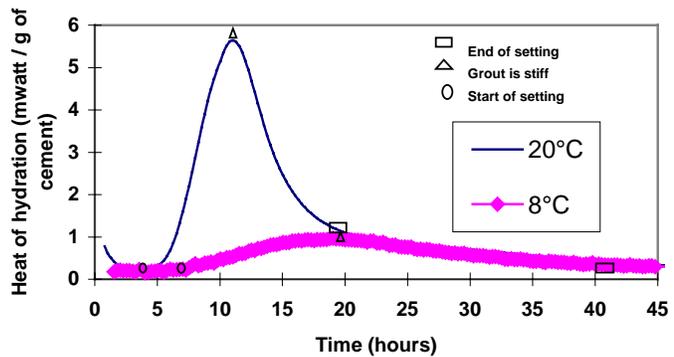
The density of grout is an excellent indication of the amount of water used in a grout mix. It can be measured easily by comparing the weight and volume of a given quantity of grout in either its liquid or hardened state. For an optimised grout mix with a water / cement ratio in the order of $w/c = 0.3$ the grout density is around $2,050 - 2,100 \text{ kg/m}^3$. For a grout mix with $w/c = 0.4$ the density will be around $1,900 \text{ kg/m}^3$ or below, because a part of the cement is replaced by excess water. Measurement of density is easily achieved on site with the Mud Balance which is typically used for geotechnical grouting, see Fig. 9. Therefore, density measurement is recommended as a control of the quality of the grout mix on site, both at the mixer and at grout vents.

3.3.7 Setting time

Stiffening and setting of grout should not commence too early due to the risk of clogging during grouting. Start of setting of grout must allow sufficient reserve time to properly finish grouting including such special

temperature. Fig. 10 shows the setting behaviour of two grouts using two different admixtures but the same cement, optimised by VSL, at 8° and 20° , and at 20° and 40°C , respectively.

The setting time of a grout mix



b) Setting behaviour at 20°C and 40°C of grout Mix 2

Fig. 10: Setting behaviour of two grout mixes optimised by VSL

activities as re-grouting etc. The actual time necessary depends on many parameters including type of cement, size of tendon, and in particular the ambient temperature. Start of setting may be significantly reduced at high temperatures, and may be extended at low

can be adjusted within certain limits to a desired value. This can be achieved by selecting a particular source of cement, e.g. choosing a low or high Blaine value, and by use of suitable accelerating or retarding admixtures. In any case, the setting characteristics of a par-

ticular grout mix at the expected temperature should be known to the user, before starting grouting works on site, and must be compatible with the anticipated grouting procedures and schedule.

3.3.8 Strength

For bonded tendons, the grout must attain a minimum strength to assure sufficient bond between the prestressing steel and the structure. Most standards specify a grout strength in the order of 25-35 MPa at 28 days, measured on cubes. Sometimes, a minimum strength is also required to transfer compressive forces across the tendon ducts, such as in slabs near columns, or for shear in webs of girders.

For an optimised grout mix with low water/cement ratio

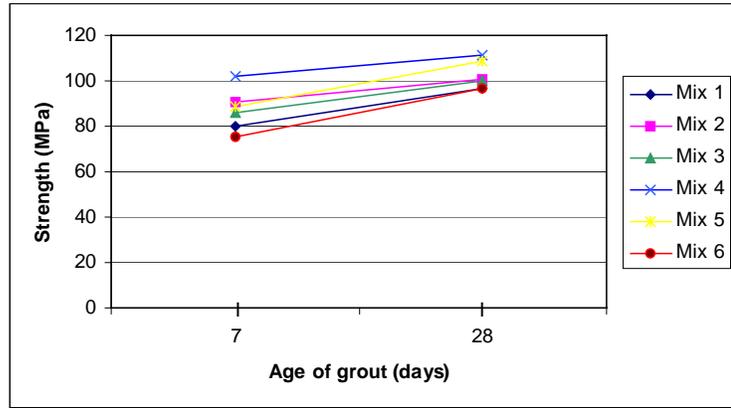


Fig. 11: Actual strength of VSL optimised grouts (40x40x160 mm prism halves)

and without expansive admixtures, typically grout strengths are achieved which far exceed the above requirements. Fig. 11 gives a summary of strengths measured on prism halves (40x40mm) for VSL optimised grouts. Compressive strengths at 7 and 28 days were at least 75 MPa and 95 MPa, respectively, and hence, far above most requirements typically specified in standards.

3.3.9 Frost resistance

For certain applications in cold

climates where freezing is a concern, grout for post-tensioning tendons must possess a sufficient frost resistance. This can be primarily achieved with a dense grout with low water / cement ratio, with as little excess water as possible.

Other methods which have been proposed to improve the frost resistance of grout include the entrainment of air in the order of 6 - 10% air pores, or the replacement of about 10 % of the water in the mix with anti-

	Item	Grout performance characteristics	Test method	Acceptance criteria
Essential	(1)	Bleed and Segregation of grout	Inclined Tube test, Appendix A1, [21] and Wick-Induced Bleed test, Appendix A2, [21]	<ul style="list-style-type: none"> § Bleed water: $\Omega 0.3\%$ ¹⁾ § Air void: $\Omega 0.3\%$ ¹⁾ § Segregation: No significant segregation visible to the naked eye <p>¹⁾ of original grout volume</p>
	(2)	Flow Time of grout	Flow Cone according to EN 445, [17]	<ul style="list-style-type: none"> § Initial Flow Time: $\Omega 25$ seconds § Change of Flow Time in 45 minutes: $\Omega 3$ seconds
	(3)	Sedimentation of grout	Sedimentation test, Appendix A3, [21]	<ul style="list-style-type: none"> § Variation of density: $\Omega 5\%$
	(4)	Corrosiveness of grout	Chemical analysis of grout by qualified laboratory	<ul style="list-style-type: none"> § Chloride content: $\Omega 0.1\%$ ²⁾ <p>²⁾ of cement weight</p>
	(5)	Toxicity of grout	Declaration of materials or chemical analysis by qualified laboratory	<ul style="list-style-type: none"> § Grout shall not contain toxic materials
For reference	(6)	Strength of grout	Test according to EN 445, [17]	<ul style="list-style-type: none"> § Compressive strength at 7 days: $\Omega 30$ MPa
	(7)	Volume Change of grout	Test according to EN 445, [17]	<ul style="list-style-type: none"> § Volume change at 24 hours: -0.5% to $+1\%$ ¹⁾ <p>¹⁾ of original grout volume</p>
	(8)	Setting Time of grout	Measurement of heat of hydration by qualified laboratory	<ul style="list-style-type: none"> § Start of setting: $\Omega 3$ hours § Declaration of start, peak, end of setting
For record	(9)	Water / Cement Ratio of grout	Weight measurement of constituents including liquid in admixtures	<ul style="list-style-type: none"> § Declaration of water/cement ratio of grout
	(10)	Density of grout	Volume and weight measurement of grout	<ul style="list-style-type: none"> § Declaration of density of grout
3)	(11)	Frost Resistance of grout	Testing by qualified laboratory	<ul style="list-style-type: none"> § Declaration of frost resistance of grout

Table 2: Proposed performance specification of grout
Note: 3) Essential for cold climate only

freeze. Detailed testing of grouts modified with anti-freeze is recommended to avoid undesirable effects on the grout performance. Entrainment of air will reduce the strength of grout. The effectiveness of air entrainment is in question and must be verified with representative size grout samples including the prestressing steel.

3.4 Recommended grout performance specification and testing

Based on the discussion and results presented in the previous section, only a small number of grout performance characteristics are considered essential. Many of the typically specified characteristics in the past are not considered essential but may still be used

for the record and as reference.

Table 2 gives a listing of the grout performance characteristics considered essential for a high quality grouting of post-tensioning tendons. These include items (1) to (5), plus (11), if relevant. Table 2 also includes characteristics (Items (6) to (8)) which are considered of lesser importance and which are typically satisfied by well optimised grouts, as a matter of course. Finally, characteristics (9) and (10) are listed for which no requirements are stated but for which the actual values should be declared for the record and future reference.

Table 2 also includes proposed testing methods, and the corresponding proposed acceptance criteria. For the proposed test methods reference is made to

the draft Guideline for European Technical Approval of Post-Tensioning Systems, [21], and to the European Standard EN 445, [17]. These references allow one to specify values for acceptance criteria. Other standards exist with test methods that can be considered equivalent. When specifying such alternative standards with different test procedures, one should be aware that likely the values of acceptance criteria will change also. Some new test methods from [21] not yet commonly known are presented in Appendix A.

3.5 Stages of grout testing

There are different stages of grout testing each one with a particular objective. The following is a brief review of these stages of testing.

Grout Test Methods	Approval Testing	Suitability Testing	Acceptance / QC Testing and Proposed Test Frequency
(1) Bleed / Segregation: - Inclined Tube - Wick Induced	x x	not required x	not required x (2 specimens / day)
(2) Flow Time - Initial - Change	x x	x x	x (1 specimen / 3h) not required
(3) Sedimentation	x	x	not required
(4) Corrosiveness	x	not required	not required
(5) Toxicity	x	not required	not required
(6) Strength	x	x	x (1 test with 2 specimens / day)
(7) Volume Change	x	x	x (1 specimen / day)
(8) Setting Time	x	not required	not required
(9) Water / Cement Ratio	x	x	x (record for every mix)
(10) Density	x	x	x (1 specimen / 3h)
(11) Frost Resistance	for specific use only	for specific use only	not required

Table 3: Recommended testing regime and test frequency in different stages

(1) Initial testing of grout:

These tests typically serve to select or determine a particular grout mix design in a laboratory. In the past the initial testing of grout was often based on trial and error procedures with testing until a satisfactory solution was found.

VSL has introduced scientifically based proprietary optimisation procedures to obtain a specific grout mix design for optimised bleed and segregation properties. These optimisation procedures also assure that all the grout constituents have acceptable properties for grout for post-tensioning tendons, and that they are compatible between each other. Grout mixes which have been designed with this optimisation procedure, and which satisfy all performance criteria, i.e. pass the approval testing, obtain the VSL-HPI[®] Grout label.

(2) Approval Testing of Grout:

These tests serve to confirm initially the compliance of a particular grout mix with the grout performance specifications listed in Table 2. Typically, Items (1) to (10) will be covered, see Table 3. Item (11) will only be verified for specific applications in cold climate. Grout produced for testing should be prepared with equipment comparable to the one intended to be used on site. Approval testing is typically done in a workshop or on site, under conditions comparable to the site where the grout is intended to be used.

These tests are one part of the approval procedure for the particular grout mix. However, in addition, adequate QA procedures must be implemented to assure the consistency of the grout constituents for the particular grout mix. If both parts are satisfied, the mix can be considered approved as grout for post-tensioning tendons, and approval tests do not need to be repeated for future applications.

(3) Suitability Testing of Grout:

These tests serve to confirm the suitability and certain performance characteristics of an approved grout mix on a specific site. This testing should be done under representative, expected climatic conditions, with the grouting equipment intended to be used on site, and carried out by the personnel intended to complete the grouting works.

Table 3 lists the testing recommended to confirm the suitability of an approved grout mix for use on site. Bleed and segregation is checked with the Wick-Induced test only in comparison to the corresponding results obtained during approval testing.

(4) Acceptance / QC Testing of Grout:

These tests serve to confirm the consistency of the grout properties during execution of the grouting works on site. Table 3 lists the testing recommended for QC on site. It includes also a proposed test frequency for acceptance tests.

4. Grouting on Site

4.1 General

Grouting work on site is a complex activity. It needs to be well

prepared. Once it has started it should not be interrupted. The assessment of the quality of grout during injection is still based to some degree on judgement of an individual, e.g. for the decision when the quality of grout is acceptable to close a particular vent. Most, if not all, activities during grouting are on the critical path, in particular for grout mixes which show an early start of setting. The actual grouting works can be physically quite demanding, are dirty, and involve safety risks, e.g. if the human skin or eyes get in direct contact with the grout. For all the above reasons, grouting work needs to be planned, and supervised by experienced technicians, with a thorough understanding of the behaviour of grout, and awareness of the potential implications of poor grouting on the durability of a post-tensioned structure. Hence, only such experienced technicians should be qualified to plan and supervise grouting works. These technicians should be capable of training the labour used for grouting, usually on site, as needed for the anticipated activities.

A satisfactory quality of grouting work can only be achieved if grouting equipment of a suitable capacity adapted to the particular project is used. Such equipment should be confirmed prior to the actual grouting work during suitability testing to be able to produce a sufficiently homogeneous grout mix.

A post-tensioning tendon can only reliably and completely be filled if the entire tendon and duct system, including anchorages, hoses, etc. is leak tight. Hence, careful detailing of the

tendon and duct system is essential. Improvised connections between ducts and anchorages, or improvised sealing of anchorages and vents, present risks which may lead to grouting defects.

The leak tightness of the tendon system may be confirmed by air pressure testing [1].

Excess water in the grout has been confirmed as a major cause of grouting and durability problems. Hence, control of the water added to the grout is essential. This includes water eventually present in the duct system. Therefore, duct systems need to be kept adequately sealed on site at all times to avoid ingress of rain or other water before grouting.

The quality and reliability of the filling of the tendon duct and anchorages depends on the suitability of the chosen grouting procedure. Therefore, only grouting procedures should be used which have been proven through sufficient experience and / or representative testing. Whenever possible, standard procedures should be applied to reduce the risk.

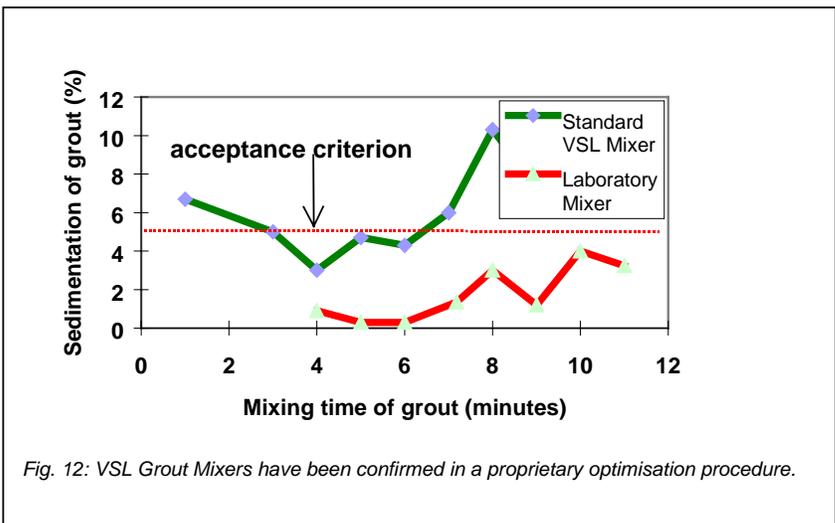
Actually, only the combination of all these above mentioned ingredients will assure a high quality of grouting on site. This fact has been recognized by some organisations and countries which have proposed and / or actually introduced an approval procedure combining the product (post-tensioning system, grout) with the qualification of the specialist contractor carrying out the works, and the equipment and procedures / method state-

ments used by the specialist contractor. FIP has produced recommendations on the "Qualification and approval of prestressing contractors and system suppliers", [22]. France has recently introduced an "Avis Technique" on the approval of grout. It is a two step procedure where an approval is needed for the product, i.e. the grout, and a separate approval for the specialist contractor, demonstrating that he is qualified to produce the approved grout with his personnel, equipment and procedures to the specified performance and quality, [23]. The UK has also introduced comparable requirements for companies as a basis for the lifting of the temporary ban of grouted post-tensioning tendons, [1].

4.2 Training and qualification of personnel

Any type of grout, whether supplied in bags as ready-mixed / pre-bagged grout or mixed on site, is finally mixed with water and injected by on site people. A consistent good quality of grout is only achieved by experienced, well-qualified personnel who receive regular training to re-fresh and up-date their knowledge. Therefore, the qualification and training of grouting personnel is of prime importance. This applies to all levels from labour to supervisor/foreman, and technician.

In the above terminology, the grouting technician and supervisor / foreman assume quite similar responsibilities. They



The different aspects of the quality of grout as a product up to its approval have been discussed in Section 3. This section will review the other essential ingredients for high quality grouting on site.

should both be able to plan and organize grouting, to select and operate grouting equipment, and to carry out grouting on site. In addition, grouting technicians should be able to select grout constituents, prepare a design for a new grout mix, and confirm it by testing. The supervisor / foreman should in particular be able to train labour

on site for their anticipated activity.

In parallel with the development work on the optimisation of grout mixes, the VSL Group has introduced a specific training programme in grouting activities for VSL personnel. This training programme addresses technicians and supervisors/foremen. It is intended to refresh and up-date their knowledge on grouting, confirm their qualification, and assist them in training their labour on site.

4.3 Grouting equipment

Suitable grout mixers adapted to the size of a particular project, and capable of producing a homogeneous grout mix are essential for achieving quality grouting. A grout mix which is not homogeneously mixed will tend to more easily flocculate and consequentially, is likely to show excessive bleed and possibly sedimentation and / or segregation. To produce homogenous grout mixes, project specifications often make reference to "colloidal mixers". According to the dictionary, a "colloid" is a liquid substance made up of very small, insoluble, non-diffusible particles (as single large molecules or masses of smaller molecules) that remain in suspension in a surrounding liquid medium of different matter. While this definition is correct in terms of objectives for a high quality grout for post-tensioning tendons, it provides unfortunately little guidance in terms of specifying how this performance can be quantified and confirmed. Based on today's knowledge there is at least one indirect test method which

test method which may be used to qualify a grout mixer for grouting of post-tensioning tendons, and to confirm its performance and capability to produce a homogeneous grout. This is the sedimentation test introduced in Section 3, and detailed in Appendix A.3. A particular grout mix can be prepared in the mixer to be assessed according to a given procedure and specific mixing time. After mixing, the sedimentation test specimen is prepared with this mix, and sedimentation measured after complete setting of the grout. Based on our present knowledge, sedimentation in this test should be limited to a maximum of 5% to assure a sufficiently homogeneous and stable grout.

Apart from the above performance requirement, grout mixers suitable for grouting of tendons need to satisfy other more practical requirements. These include:

- § Device or method to accurately weigh the grout constituents which will be used to prepare a specific mix. In particular, this addresses the weight of cement and water. A weighing tolerance of 2% is recommended.
- § Mixing reservoir with a high-speed mechanical mixer. For grouting of large volume tendons, two mixing reservoirs and mechanical mixers are required to assure continuous production and flow of grout into the tendon, at the anticipated speed of grout flow.
- § Standby reservoir with a slowly moving agitator to keep the grout continuously in motion. Mixing reservoirs are emptied into the

standby reservoir to allow the preparation of a next mix. The grout leaves from the standby reservoir into the tendon during injection. The grout should not be actually mixed but just kept in motion since excessive mixing may be harmful to the homogeneity of the grout.

- § Pumps of sufficient capacity to inject the grout at the anticipated speed into a tendon of a given size and geometry.

The VSL Group owns a large number of grouting equipment which satisfy the above requirements. As part of the research and development, VSL has also introduced a verification procedure for the performance of the mixers in terms of grout homogeneity as a function of mixing time. The results of the procedure allow to determine on optimum mixing time for a particular grout mixer, see Fig. 12.

4.4 PT System detailing for grouting

4.4.1 General

Correct detailing of the tendon profile, ducts, grout vents (inlet and outlet), connections of duct to anchorages, and anchorage caps are of decisive importance for high quality grouting. The tendon profile is typically chosen for structural reasons to balance applied loads. However, the tendon profile should also be detailed for optimum flow of the grout. Local high points where no vents can be placed should, e.g. be avoided. The tendon profile needs to be secured with sufficiently strong tendon supports at a sufficiently close spacing. Inadvertent

movements of the duct during concreting must be prevented under all circumstances. Ducts need to be made of suitable material such as sheet metal, polyethylene or polypropylene in accordance with relevant standards or recommendations. Any temporary hole in the pipe of external tendons need to be properly sealed before grouting to assure reliable corrosion protection. The duct needs to have a sufficiently large cross section to allow proper flow of the grout. For strand tendons typically the duct size is chosen such that the cross sectional area of the prestressing steel does not occupy more than about 40-45% of the duct cross section. For bar tendons, this percentage can be higher. Significant reductions of cross sections which will cause significant change of speed of grout flow during injection need to be avoided since this may cause excessive bleed and segregation of grout, or even blockages. All connections of ducts, vents, anchorages, and caps need to be leak tight to assure



Fig. 13: VLS CS 2000 Anchorage with permanent grout cap, grout inlet and cap vent

complete filling of ducts with grout.

4.4.2 Sealing of anchorages

Grouting can only be carried out once the anchor head and anchorage are properly sealed.

The most suitable method of sealing anchor heads and anchorages is with the use of temporary or permanent grout caps on the anchorages. Permanent grout caps are now being specified more frequently, in particular for fully encapsulated tendons using plastic duct systems and for external tendons. Fig. 13 shows the VSL CS 2000 - PLUS System which offers full encapsulation of the tendon with the VSL PT-PLUS™ plastic duct system. The encapsulation is completed by the plastic trumpet through the CS anchorage, and the permanent CS cap. All connections are made with special coupling devices to ensure leak tightness.

For tendons which are not specified as fully encapsulated, temporary grout caps are suitable. These can be sealed against the anchor head if the interface of anchor head and bearing plate is leak tight. Fig. 14 shows such an example for the VSL EC System.

For both the above cases with permanent and temporary solution, the cap may be removed after grout setting to verify the complete filling of the anchorage. Even immediately after grouting, tapping on the cap may be used to verify the complete filling. If necessary, grout pumping and venting can be continued through the cap till it is completely filled.

In the past, inexpensive sealing methods of anchor heads or anchorages were used which are no longer recommended. These include sealing of the anchor head with quick-setting mortar or by pouring the anchorage recess with concrete before grouting, see Fig. 15. Both these methods do not allow a proper control of the quality of grouting at the anchorage, i.e. control of complete filling, and should not be used any more.

The above sealing methods have been presented for bonded multi-strand tendons. However, they apply similarly to external tendons, and to smaller slab tendons.



Fig. 14: VSL EC anchorage with temporary grout cap, grout inlet and cap vent

4.4.3 Detailing of vents

The term vent is used here to cover both grout inlet and outlet. The diameter of grout vents should be sufficiently large to allow easy flow of grout. Typically a minimum diameter in the range of 19-25 mm is recommended for multi-strand tendons. They need to be flexible

to accommodate a particular geometry imposed by the project, and must be able to sustain the maximum expected grouting pressure. In view of the risk of ingress of water and chlorides the vents should have a leak tight valve or cap. Alternately, the vents should be located such that access of chloride laden water is positively avoided.

Vents need to be located at all locations where grout is intended to be injected into the tendon system. Vents also need to be provided at all high points of the tendon profile (duct, anchorage, coupler, cap, etc.) to allow entrapped air to be expelled and thus, to assure complete filling of the tendon with grout. Vents may be provided at intermediate locations if the vent spacing should become excessive. Acceptable maximum vent spacing is in the range of 30-70m but may go up to 100 m for particular cases. Vents at low points (drains) are not recommended and should only be considered if there is a significant risk of water accumulating during wintertime with a consequential risk of freezing.

Practice has shown that for small slab tendons which are relatively short, and/or which have a relatively shallow profile of not more than 0.5 - 0.8 m drape, no vents are generally needed at the tendon high points.

In any case, the exact layout and details of the vents should be detailed by the PT special-

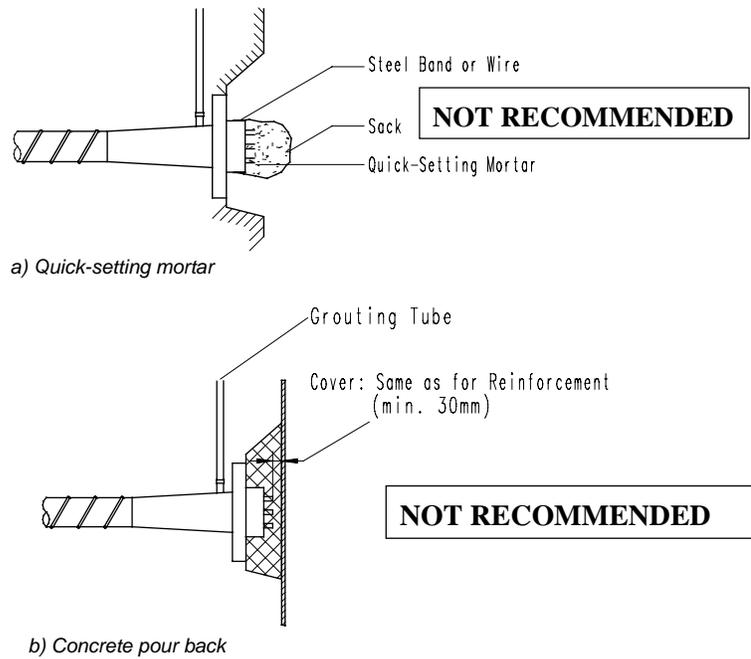


Fig. 15: Past sealing methods of anchorages which are no longer recommended

ist contractor on shop drawings, and approved by the engineer, before installation and grouting of the tendons on site.

4.4.4 Sealing of joints in precast segmental construction

Joints between precast segments represent a potential point of weakness in the protection of internal tendons crossing these joints. Sealing of the segment joints with suitable epoxy resin has been used for many years and provides sufficient protection, in general. Special compressible seals may be used around the duct to avoid ingress of epoxy into the duct. The use of O-rings in the joints is not recommended. For structures with an exposure to particularly severe environments such as de-icing salts special waterproofing membranes should be provided on

the deck in combination with epoxy resin in the joints.

Encapsulation of the tendon with plastic ducts across segment joints has been difficult. Some specific duct couplers for segment joints have been developed recently but no practical experience is available at the time of writing this report. However, the use of plastic ducts even without continuity across the joints has been shown to provide improved corrosion protection to the tendon in laboratory tests, [24].

Mortar joints between segments should not be used. They are too porous to provide an effective protection of the tendon in the joint.

Dry joints in segmental construction are acceptable if all the post-tensioning is provided externally with a continuous encapsulation in plastic sheath.

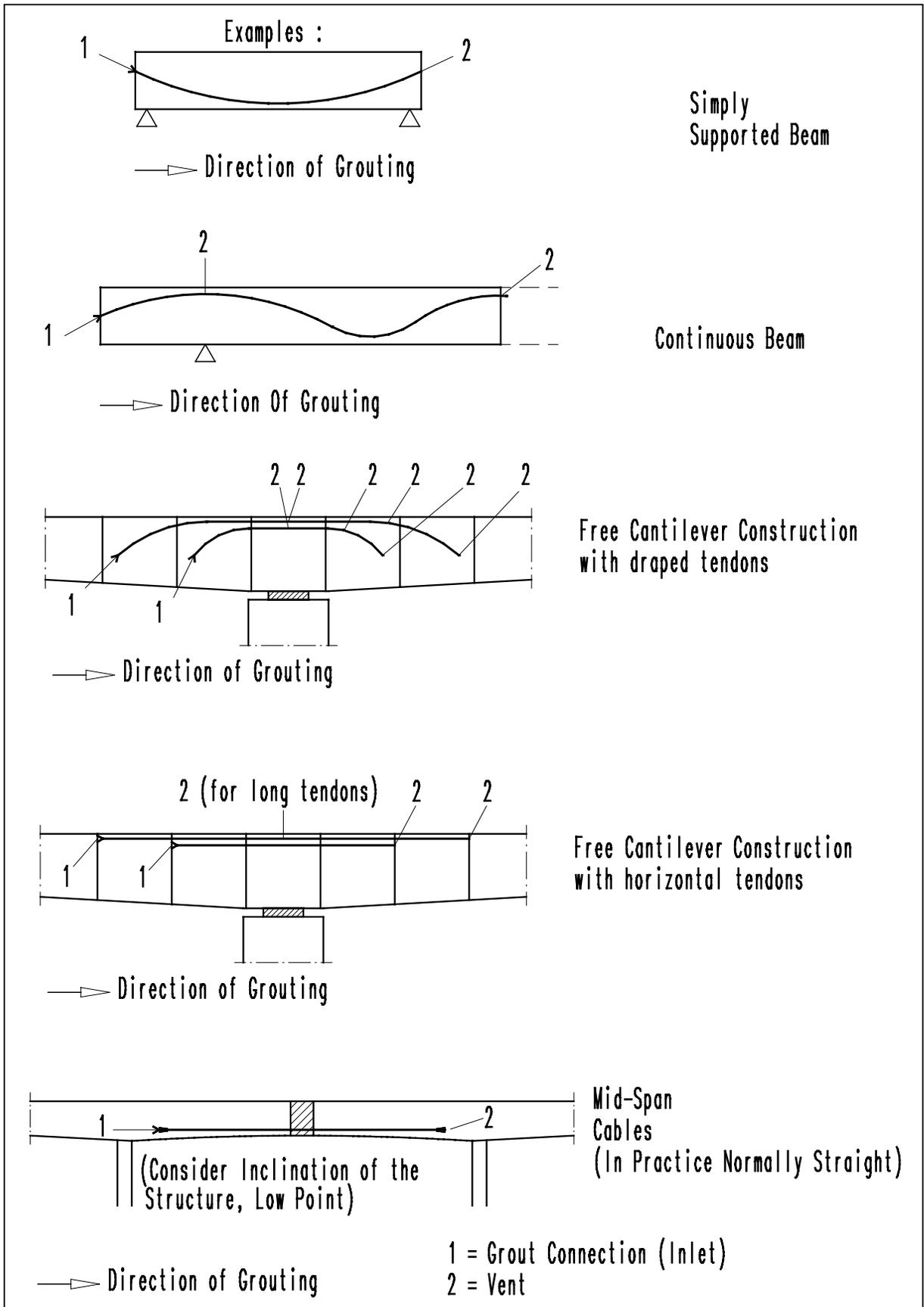


Fig. 16: Examples for grout connections and vent locations

4.5 Grouting procedures on site

4.5.1 General

Each PT specialist contractor has his standard and special procedures which are adapted to his PT systems, equipment, and experience of his personnel. Specific method statements typically need to be prepared by the PT specialist contractor based on these standard procedures, and submitted as part of the contract for a specific project.

The following is a brief summary of the general grouting procedure used by VSL for a typical post-tensioning tendon. This will allow highlighting of some important aspects of grouting. This is then supplemented with some additional information on special cases or procedures.

4.5.2 Typical grouting procedure

Many project specifications in the past required flushing of the tendons with water prior to grouting. Flushing was used to clean the inside of the duct, wet the duct surface for improved flow of grout, and to check the leak tightness of the duct. Based on today's knowledge, this is now considered bad practice. Recent specifications such as the ones issued by PTI [18], ASBI [7] and the French grouting standard [25], do not permit flushing of tendons anymore. Flushing of tendons will leave excess water in the duct system which will modify the grout properties beyond any control with likely negative effects on bleed, sedimentation and seg-

regation. Blowing of ducts with compressed air after flushing will not be able to remove all water. Grouts can now be designed such as to permit reliable grouting of long "dry" tendons even at elevated temperature. Because of the above reason, flushing of tendons with water does not form part of the VSL grouting procedures.

Instead of flushing with water, tendon ducts should now be tested with air pressure to proof leak tightness such as proposed in [1,20]. Testing for leak tightness is an essential step in the procedures to assure high quality grouting. Only leak tight duct systems can be effectively grouted.

After the grout mix has been confirmed in the suitability tests on site, and all grouting activities including equipment and training of personnel, have been properly prepared and / or done, actual grouting of the post-tensioning tendons can commence. This is typically in accordance with the following steps:

- § The grout is mixed with the appropriate water/cement ratio, the specified sequence of adding water, admixture, and cement, with the specified grout mixer, and for the specified mixing time, as per the method statement. As soon as the first mix is ready, the necessary quality control tests can be made to confirm the specified grout properties.
- § When the properties of the grout are confirmed, grouting proper can commence.
- § The grouting nozzle is fitted, in general, to the lowest grout connection or to a ca-

ble end as specified in the method statement. Examples for grout connections and vent locations for common cable types in structures are illustrated in Fig. 16.

- § Grouting should continue without interruption so that grout flows continuously in the same direction from the inlet to the cable end. While the grout moves as a solid column in upward slopes of the duct, it will often flow faster downhill than the pump provides grout. Hence, it will fill the descending branch of the duct from the following low point backwards / upwards again. This will likely cause entrapment of air at the high point which needs to be expelled via the vent at that location. To allow this to happen, the maximum rate of flow of grout in the duct should be limited to 10 to 12 m/minute.
- § When the grout flows out from the first vent, this vent is not closed until the issuing grout has a comparable viscosity and consistency as that in the mixer. This can be judged visually by experienced staff, and can be confirmed by grout density (Mud Balance) and flow time measurements. If the flow time at the outlet is less than that at the mixer, the difference should not be more than about 3 seconds. This connection can then be closed. The same criterion applies for all further vent points, including the outlet in the anchorage / cap at the cable end. At all vents, the issuing grout should be collected for environmental

reasons and to avoid staining of the structure.

§ If the grouting pressure at the grouting connection approaches 10 bar (e.g. with long cables), the grouting nozzle should be transferred to the next already filled connection and grouting should be continued from there.

§ When the entire cable is filled, i.e. when all the vents have been closed, the pump pressure is slightly raised (about 1 to 3 bar above the grouting pressure depending upon the type of seal at the anchor heads). This pressure is maintained for about one minute. If the pressure can be maintained without significant loss this can be considered confirmation that the duct system is leak tight. The inlet opening is then also closed. The grouting nozzle can now be removed and fitted to the next cable. If the pressure drops significantly, this indicates leakage. Leaks should then be located and sealed, and any void left should be topped up with grout.

§ For long tendons with several high points, vents should be opened again, one after the other, while the grout is under pressure to expel eventually accumulated air and water at high points till the grout exits at the appropriate consistency (re-grouting).

§ It is recommended to prepare a grouting report daily, including all relevant data of the mix, grout testing, identification of the grouted tendons, weather

conditions, and grout consumption. Reporting of grout consumption will allow to detect gross errors but will not permit the detection of local voids.

§ During grouting regular quality control tests should be done as listed in Table 3 at the mixer and at the tendon vent farthest away from the mixer. In addition, accessible parts of tendons should be checked by tapping shortly after grouting. All vents and caps should be checked / opened after setting of the grout, and any voids should be filled.

4.5.3 Interruption of grouting

Grouting activities of a group of tendons should be carried out without interruptions. If a fairly long interruption occurs during changing over from a completely grouted tendon to a new tendon, the entire system comprising mixer, pump and hoses should be emptied and cleaned with water.

If, during grouting of a cable, a fairly long interruption occurs, e.g. due to a blockage, the tendon must immediately be emptied by combined blowing with air and flushing with water.

For grout mixes which have not been confirmed for stability of flow time for extended periods of 2 or more hours, "fairly long" as mentioned above may be considered as exceeding about 30 minutes. For grout mixes with confirmed stability over extended periods, the period before the tendon is cleaned may be increased.

4.5.4 Special cases

4.5.4.1 Grouting in hot or cold weather

Concrete structures will, due to their mass and heat storage properties, typically have a temperature close to the average ambient temperature. Due to the difference of mass of several orders of magnitude, the grout being injected into a concrete structure must be expected to take quickly a similar temperature as the structure. This will likely occur independent of the temperature of the grout in the mixer. It must, therefore, be expected that cooling the grout in the mixer by use of chilled water or ice, or warming the grout by hot water, has no or not much beneficial effect on the grout properties once the grout is injected into the tendon and is in contact with the structure. Actually, the relatively rapid change of grout temperature during injection presents a considerable risk that the grout changes its properties from a known set of performance characteristics to an unknown set.

Based on the above considerations, and the research work done by VSL on grouts at a temperature range of 5° to 40°C, VSL now recommends not to cool or warm grouts before injection. VSL's strong recommendation is to optimise the grout mix for the expected ambient temperature on the particular site or climatic region. By using suitable cement and suitable admixtures to either accelerate or delay setting, including detailed confirmation of their compatibility with the other grout constituents, a grout mix can be designed to achieve the

specified properties even at relatively low and high temperatures. In conclusion, situations where the grout will change its temperature significantly between mixer and tendon should be avoided.

Grouting should not be done, in general, if the ambient temperature is or will drop below 5°C within 48 hours due to the risk of freezing of the water and grout.

4.5.4.2 Grouting of tendons with couplers

A coupler represents a discontinuity in a tendon, in particular for the flow of grout. It is, therefore, recommended to consider coupler locations similar to a tendon end, i.e. consider the sections before and after the coupler as different tendons, and grout them separately. Careful sealing of the coupler is necessary for grouting the sections separately. Recommended grouting details for couplers are illustrated in Fig. 17.

If for specific reasons, a tendon needs to be grouted across a coupler, the feasibility of the proposed method

should be proven by testing of a representative tendon.

4.5.4.3 Grouting of long vertical tendons

Particular attention must be given to the grouting of long vertical tendons. There is a risk of excessive bleed and possibly sedimentation and segregation as a consequence of the considerable pressure differential between bottom and top of the tendon.

VSL recommends to specifically optimise a grout mix for the expected pressure range, and thus to assure the specified grout properties at the expected maximum pressure.

In addition to the grout optimisation, some additional precautions must be taken for the tendon detailing for grouting. Firstly, the bottom anchorage must be provided with a cap or sealing method which is capable of safely accepting the expected maximum grout pressure. If the tendon is intended to be grouted in stages, intermediate vents need to be provided, preferably as suggested in Fig. 18.

For very long tendons it is recommended to provide an additional grout connection close to the top anchorage. This will permit to grout the last short section of the tendon and the anchorage without the possible effects of bleed etc. from the entire tendon length. This is considered the most reliable grouting method to assure complete filling of the top anchorage and the tendon section just beneath.

Other methods such as using a grout reservoir located above the top anchorage have been used. Such methods are considered less reliable, not easy to verify, and do only work with very low viscosity grouts with a

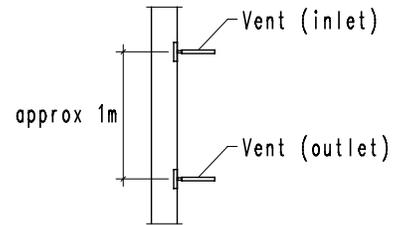


Fig. 18: Intermediate vents in long vertical tendons

greatly extended stability of flow time. It should be noted that maximum bleed in relatively small scale tests as proposed in Section 3, may occur sometimes only after 3 or more hours, see Fig. 8a. The effect of this bleed at the tendon top may be expected to be further delayed in very long vertical tendons. Hence, the grout in the reservoir needs to maintain its low viscosity beyond this time.

4.5.4.4 Vacuum assisted grouting

In vacuum assisted grouting, the tendon duct is subjected to a 85-90% vacuum before grout-

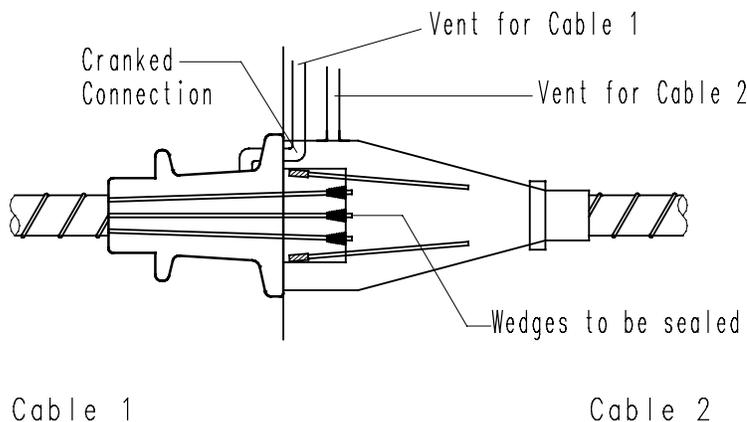


Fig. 17: Grouting details for VSL K-Coupler

ing, i.e. 85-90% of the enclosed air is removed. This significantly reduces the risk of leaving voids in the grouted tendon due to entrapped air. This can be particularly interesting for the grouting of long horizontal tendons without defined high points where normally entrapped air would collect. It is also recommended for grouting of external tendons where the provision of vents at high points is complicated or even not possible, in particular if the tendon high points are located inside massive diaphragms.

It should be noted that vacuum assisted grouting will only be feasible, and hence show its beneficial effects, if the entire duct system including the anchorages are sealed airtight. This should be confirmed by a leak tightness test prior to grouting, and corrective measures taken as needed. VSL recommends vacuum assisted grouting for improved quality for the above listed applications because of the reduced risk of entrapped air.

4.5.4.5 Delayed grouting of tendons

As a general rule, grouting should be carried out as soon as feasible after stressing of the tendons. Guidance on the maximum period of time between installation of the prestressing steel, stressing of the tendon, and grouting of the tendon with bare prestressing steel may be found in selected standards and publications. Without taking any particular precautions the AASHTO Standard Specifications for Highway Bridges,

[26], give 7, 15, and 20 days as permissible intervals between tendon installation and grouting, for very damp (>70% relative humidity), moderate, and very dry atmospheres (< 40% relative humidity), respectively. The final draft European Standard on "Execution of concrete structures", [27], proposes a maximum interval of 12 weeks between tendon fabrication and grouting, a maximum interval of 4 weeks for installation of the tendon into the formwork before casting the concrete structure, and a maximum interval of 2 weeks between tendon stressing and grouting.

If grouting needs to be delayed beyond the above proposed intervals, particular protection methods need to be provided for the post-tensioning tendon.

If the delay is known or expected before the purchase and installation of the prestressing steel, VSL recommends the use of water-soluble oils for temporary corrosion protection of the prestressing steel, and sealing the duct system and anchorage. These oils should preferably be applied in the factory by the supplier. Oils such as RUST-BAN 310 are available which have only a low effect on the bond properties of the prestressing steel. Only these types of oil should be used to absolutely avoid flushing of the tendon before grouting. While the low effect of oil on bond is usually acceptable for bonded tendons, in general, this is not necessarily the case for bond anchorages. The tendon in the bond length of anchorages must be free of oil. As mentioned under Section 4.5.2 flushing of tendons is considered bad practice in

general, and flushing of water-soluble oils for environmental reasons, in particular.

If the delay of grouting is not known up front, sealing of the duct system and anchorages, and either intermittent or continuous blowing of dry air is recommended for the temporary protection of the prestressing steel up to grouting.

Blowing of dry air can also be used for the temporary protection of tendons which have been stressed but due to sudden start of winter, with continuous temperatures below 5°C, cannot be grouted for an extended period.

4.5.5 QA procedures

Grouting activities should be covered by the site specific QA plan specified for a particular project. Standard or site specific procedures should be available which cover all aspects of the grout mix, personnel, equipment, and grouting discussed in the previous sections of this report.

During grouting, acceptance testing of grout should be performed as proposed in Section 3 of this report to assure consistent quality of the grout. All activities and measured data should be recorded in specific grouting reports.

4.5.6 Safety precautions when working with grout

Cementitious grout is highly alkaline and, therefore, potentially harmful to the human skin and particularly the eyes (risk of loss of sight). Preparation of grout at the mixer usually produces cement dust which may

be harmful if inhaled into the human lungs.

For the above reasons, personnel working with cementitious grout, must protect their eyes by protective goggles or a full-face shield during all times, and cover nose and mouth when working at the mixer.

5. Inspection and Monitoring of Tendons ¹⁾

5.1 Inspection methods

Post-tensioning tendons are structural elements essential for the safety, serviceability and durability of prestressed structures. Consequently, it would be desirable to assess their behaviour in existing structures. Such checks to detect possible defects or damages such as grout voids or tendon corrosion should preferably be done by non-destructive or at least low-destructive inspection methods and with minimum disturbance to the user.

In a report published in 1988, [29], the then available inspection methods were discussed and their usefulness and potential assessed. The conclusion was that these methods provide meaningful results limited only to localized areas, if at all. In the meantime, some of these methods were developed further and new ones have appeared.

¹⁾ Parts of Chapter 5 have been reprinted from [28] with permission by the author.

The inspection and monitoring methods listed below have either the aim to detect existing grout voids, corrosion of the

prestressing steel in progress or even ruptured wires, strands or bars in tendons.

5.1.1 Georadar and Covermeter

Experience with practical applications has shown that georadar is only suitable for the confirmation of the location of tendons. This is, however, often a prerequisite for a detailed tendon inspection. Whereas, under favourable conditions (no congestion of reinforcement) georadar allows the location of tendons to a depth of up to 500 mm, even a powerful covermeter is generally not capable to detect ducts at concrete covers of more than 40 to 50 mm and again only if light reinforcement is present [30].

5.1.2 Potential Mapping

Whereas, potential mapping (measuring the potential field) is a powerful tool for finding corroded normal reinforcement, in case of tendons it is only successful under very favourable conditions (e.g. small concrete cover to the ducts and light normal reinforcement as they may exist in thin webs of precast beams).

5.1.3 Impact-Echo Method

Since 1983, the Impact-Echo Method has been under development primarily in the United States. It is stated that it can be used for detecting grout voids in tendons [31].

In [32], the method was verified in this respect and the findings can be summarized as follows: "It is possible to use the Impact-Echo Method for checking a tendon for grout voids. It is

however a delicate operation requiring experienced personnel. The presence of cracks and other concrete defects as often found in real structures significantly influence the test results and can make the evaluation impossible." Applications in the United States have shown that under favourable conditions and in accessible areas, the Impact-Echo Method is able to identify grout voids. However, the method does not work with tendons in plastic ducts.

5.1.4 Remanent Magnetism Method

The Remanent Magnetism Method was developed in Germany for detecting fractures in prestressing steel [33]. The magnetizing and recording equipment has to be moved along the tendon path on auxiliary guidance rails and scaffolding fixed to the concrete surface. Thus it allows to localize fractures in the accessible areas. The difficulty is to cope with the disturbing magnetic signals originating from other embedded steel elements such as normal reinforcement, anchorage elements, duct couplers, steel plates, nails, etc.

5.1.5 Radiography

Today the application of radiography is limited to special cases. Even in France, where the method had formerly been widely used, it has practically disappeared. Apart from the high cost, another important reason is that most countries have national regulations for the protection of people, animals and the environment when applying radiography. Whereas, some of these regu-

lations impose total evacuation of human beings in the neighbourhood (minimum distances depend on the intensity of the source; this generally means that all traffic has to be stopped in the area concerned), others ask for traffic suspension only when traffic cannot flow continuously.

to use the Time Domain Reflectometry known from applications to coaxial telecommunication cables also for grouted tendons under the acronym RIMT (Reflectometrical Impulse Measurement). The method consists of sending high frequency impulses from an exposed anchorage through the tendon. By evaluating the re-

Institute of Technology in Zurich is reported. The aim of the project was to understand the fundamentals when applying RIMT to a prestressed concrete structure. The conclusion was that "the recorded signals do not contain information regarding the condition of the tendon but are artefacts of the measurement procedure. Thus RIMT

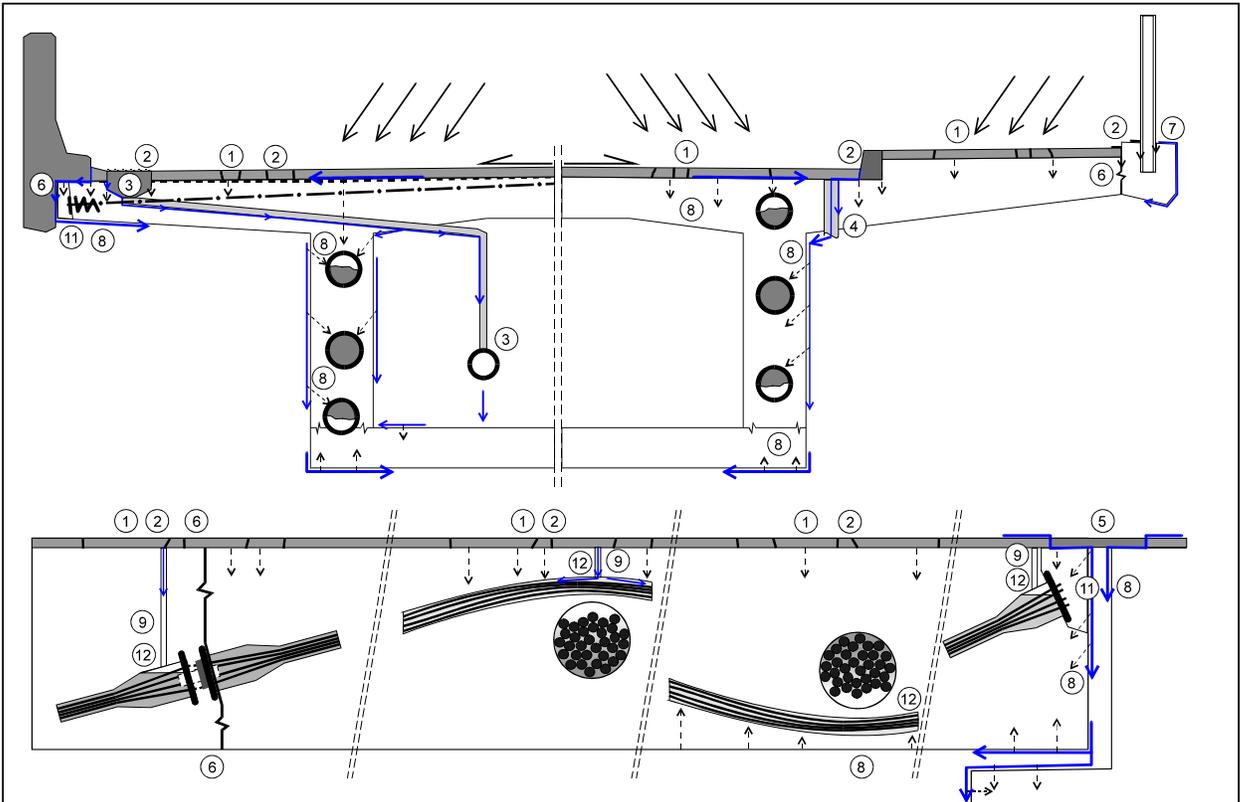


Fig. 19: Hazard scenarios for prestressing steel in a typical box girder bridge

Non-structural elements:

- 1. Defective wearing course (e.g. cracks)
- 2. Missing or defective waterproofing membrane incl. edge areas
- 3. Defective drainage intakes and pipes
- 4. Wrongly placed outlets for the drainage of wearing course and waterproofing
- 5. Leaking expansion joints
- 6. Cracked and leaking construction or element joints
- 7. Inserts (e.g. for electricity)

Corrosion protection system :

- 8. Defective concrete cover
- 9. Partly or fully open grouting in- and outlets (vents)
- 10. Leaking, damaged metallic ducts mechanically or by corrosion
- 11. Cracked and porous pocket concrete
- 12. Grout voids at tendon high points

Note: In precast segmental construction the dry packing of lifting holes, and stressing pockets in segment faces need to be checked.

5.1.6 Reflectometrical Impulse Measurement

Since about 1985, it was tried

corded reflections it was hoped to detect anomalies along the tendon path. In [34], the results of research work done at the

can definitely not be used as a diagnostic technique for grouted tendons."

5.1.7 Ultrasonic Methods

Tests have shown that ultrasonic methods (transmission, reflection) for grouted tendons have very limited possibilities. Ultrasonic waves sent from a transmitter sitting on the end of the prestressing steel can detect anomalies only in special cases (e.g. only for smooth bars or wires) and only within a few meters from the tendon anchorage [35].

5.1.8 Acoustic Monitoring

To detect failures of prestressing steel by acoustic monitoring has been known for many years in fatigue testing of tendons and stay cables. Therefore, acoustic monitoring can also be successfully applied in practice in equivalent situations such as for unbonded tendons and stay cables. Recently, trials have been carried out in Great Britain to assess whether the method can also be used for internal, bonded tendons. It is reported that these trials have been successful [36]. It could be shown that a single wire fracture can be detected above the ambient noise level, distinguished from other acoustic events and even located in position. It is too early to say to what extent and in which situations acoustic monitoring will find its place in practical application. It can, however, be expected that the method will be restricted to special cases.

5.1.9 Other methods

It should finally be mentioned that in the technical literature

further methods such as Thermography (infrared-scanner) and tomography are described.

5.1.10 Conclusions

A careful analysis of the suitability and limitations of these methods shows that none of them allows a full assessment of the conditions of a tendon. Some of them however, permit a partial assessment in ideal structural situations.

5.2 The engineer's approach to tendon inspection

While the above listed methods may allow a partial assessment of a structure and its tendons, the interpretation of the results is not easy and often, to some extent, ambiguous. However, there is one method which is quite basic and practical, and overall rates best in terms of information and interpretation. This is the careful opening of tendon ducts by drilling into them, and subsequent visual inspection with an endoscope or similar devices. Sometimes, it may be advantageous to open a window around the tendon location to obtain easier access for inspection and taking samples for investigation. Such careful opening permits to confirm the presence of voids in the ducts at that particular location, and to investigate the grout (powder) collected during drilling for the presence of chlorides or other aggressive chemicals. These methods have been used successfully for many years for local isolated inspections. More recently, these methods have also been applied for the inspection of entire series of structures, see [5],

and have allowed a reliable assessment of these structures. This method is particularly suitable if there is a reasonable doubt about the condition of a tendon at a particular location. Such doubt can be based on results of methods presented in Section 5.1, or based on desk studies. Although this method is not non-destructive, the extent of intrusion is quite moderate, and is not considered harmful to the structure or tendon, if properly closed subsequently.

There are several publications to assist the engineer in such desk studies. In [6, 37] the authors conclude that the inspection engineer when assessing an existing structure should be aware of the possible hazard scenarios for post-tensioning tendons. Figure 19 shows potential "weak points" in the case of a typical box girder bridge.

For each type of structure with its particular protection concept, the water, possibly chloride-contaminated, can reach the prestressing steel in different ways. When assessing a post-tensioned bridge, the study of the structural drawings, the construction and maintenance reports and the observations of the owner and his maintenance staff provide information regarding damaging actions and hazard scenarios. The key-question is: Where does (aggressive) water get in contact with the structure and how does it flow off?

In addition, a thorough visual inspection (preferably after rainfall) of the concrete surfaces provides information on damage locations of the un-stressed and stressed reinforcement and their location:

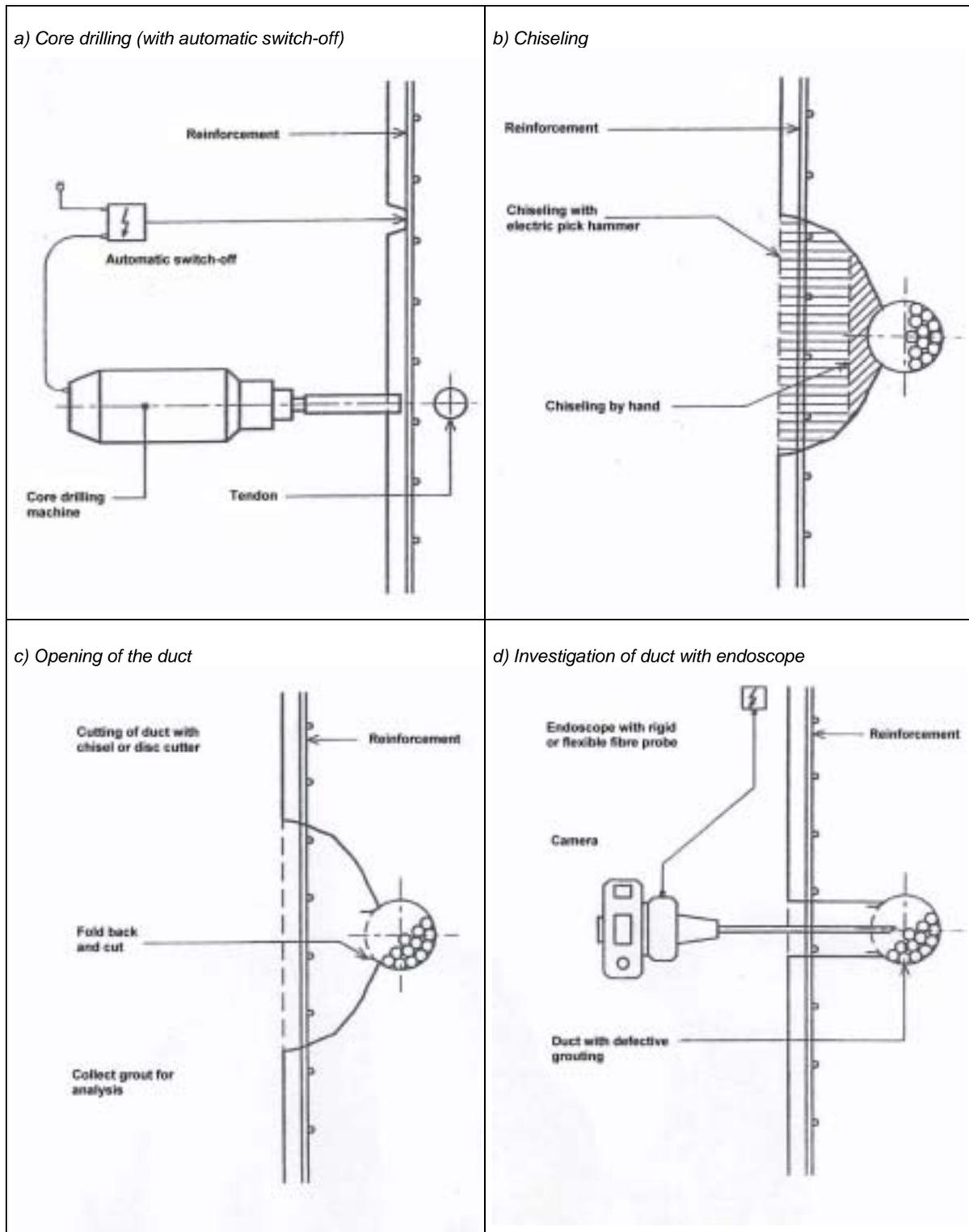


Fig. 20: Getting access to the tendon

(Courtesy of Swiss Association of Post-Tensioning Contractors (VSV), adapted from [38]).

- š Water flow, wet or moist areas
- š Discoloration (e.g. rust stains)
- š Spalling, delamination
- š Cracks
- š Honey-combing
- š Concrete deterioration by freezing and freezing-thawing
- š Joint leakage
- š etc.

The findings can then be substantiated by in-situ and laboratory investigations. Following these procedures in inspection and maintenance, potential corrosion damage of prestressing steel can be recognized and countermeasures can be taken in good time.

5.3 Monitoring - New developments

Post-tensioning systems have gradually evolved over the years. A significant step in the protection of tendons has been made with the introduction of the VSL PT-PLUS™ plastic duct system. This is a robust plastic duct system specifically developed for internal bonded post-tensioning, see [12, 13]. In addition to the enhanced corrosion protection and service life of the tendon, lower and more reliable friction values, better fatigue performance, etc. this system can be fitted with anchorage details to provide a tendon which is electrically isolated from the surrounding structure. Thus, it is possible to check the integrity of the plastic duct encapsulation by measuring its electrical resistance against the surrounding concrete and normal reinforcement. Such testing also allows to confirm

the good quality of tendon installation.

This new type of tendon, often called EIT (Electrically Isolated Tendon) has been applied since the early nineties primarily in Switzerland. Up to now, about 100 bridges have successfully been constructed using robust plastic ducts of which in over 20 bridges electrically isolated tendons have been installed. More applications are under execution or in the planning phase. The electrical resistance is periodically checked, and the results are as expected. It is important to note, that the protective envelope prevents the ingress of water and harmful substances. The grout, however must still be of high quality.

So far, these applications have been made on the basis of a draft guideline prepared by a working group under the auspices of the Swiss Federal Roads Authority and the Swiss Federal Railways. The final German version of this guideline has just been approved. It is expected that it will be published early 2002 under the title: "Measures to ensure the durability of post-tensioning tendons in bridges", [11]. Versions in French and English will subsequently also be prepared and published.

6. Repair of Tendons with Defective Grouting ¹⁾

6.1 General

As mentioned in Chapter 5, the careful opening of a tendon at questionable locations is currently the best method to verify its condition. Such a probing allows determining possible de-

fects and deterioration of a tendon including its anchorages and couplers such as:

- š Defective grouting (e.g. grout voids, grout segregation) and water access to the prestressing steel.
- š Corrosion of the metallic duct, the prestressing steel, anchorages and couplers due to the ingress of water possibly contaminated by de-icing salts.
- š Fretting corrosion of the prestressing steel due to fatigue.
- š Corrosion of the prestressing steel due to stray currents.

The inspection of a tendon by opening it locally is a low-destructive method but has to be planned carefully. The planning should not only include the opening itself but also its closing after having carried out the inspection and the possibly required rehabilitation work of the tendon.

6.2 Preparation

Based on non-destructive methods or desk studies, as described in Chapter 5, the engineer selects the tendon locations which shall be investigated. The exact tendon locations need then be indicated on the surface of the structure. This can be done based on post-tensioning shop drawings ("as built drawings") eventually supplemented with other methods described in Chapter 5 to confirm the location. It is recommended to involve the post-tensioning specialist contractor

¹⁾ Parts of Chapter 6 have been reprinted from [28] with permission of the author.

to assist the engineer with system related questions.

The closing of the tendon opening which has been created by either drilling or by cutting a window needs to be well prepared such that the tendon can be closed immediately after inspection and eventual repair, if possible on the same day.

6.3 Access to the tendon

The first step in the tendon inspection is to create access to the tendon duct or anchorage without damaging the duct or prestressing steel. The access needs to be kept as small as possible, at least initially. The following methods have been successfully used:

- Drilling of a core of 50 to 80 mm diameter. The

drilling machine can be equipped with an automatic switch-off when the core touches the metallic duct.

- Removal of the concrete cover with an electric pick hammer. The concrete just adjacent to the tendon duct should be removed preferably by hand with light equipment.

The tendon duct can then be opened for tendon inspection in the following steps:

- Cutting of the duct by hand with small, hand-held equipment such as disc cutter and flat chisel, and removal of the cut duct section. The duct opening is preferably kept smaller than the access in the concrete.
- Small samples of grout can then be removed for analy-

sis of the chloride content. Typically, a few grammes of grout per location of sampling are sufficient.

- If the duct is partially or completely without grout, visual inspection is possible and photos can be taken with an endoscope.
- If the prestressing steel is corroded, samples of corrosion products can be collected for analysis in a qualified laboratory to determine the type of corrosion.

Above methods to gain access to the tendon are illustrated in Fig. 20.

6.4 Grouting of voids

Before starting the grouting of existing voids, the exposed prestressing steel has to be carefully cleaned by a high-

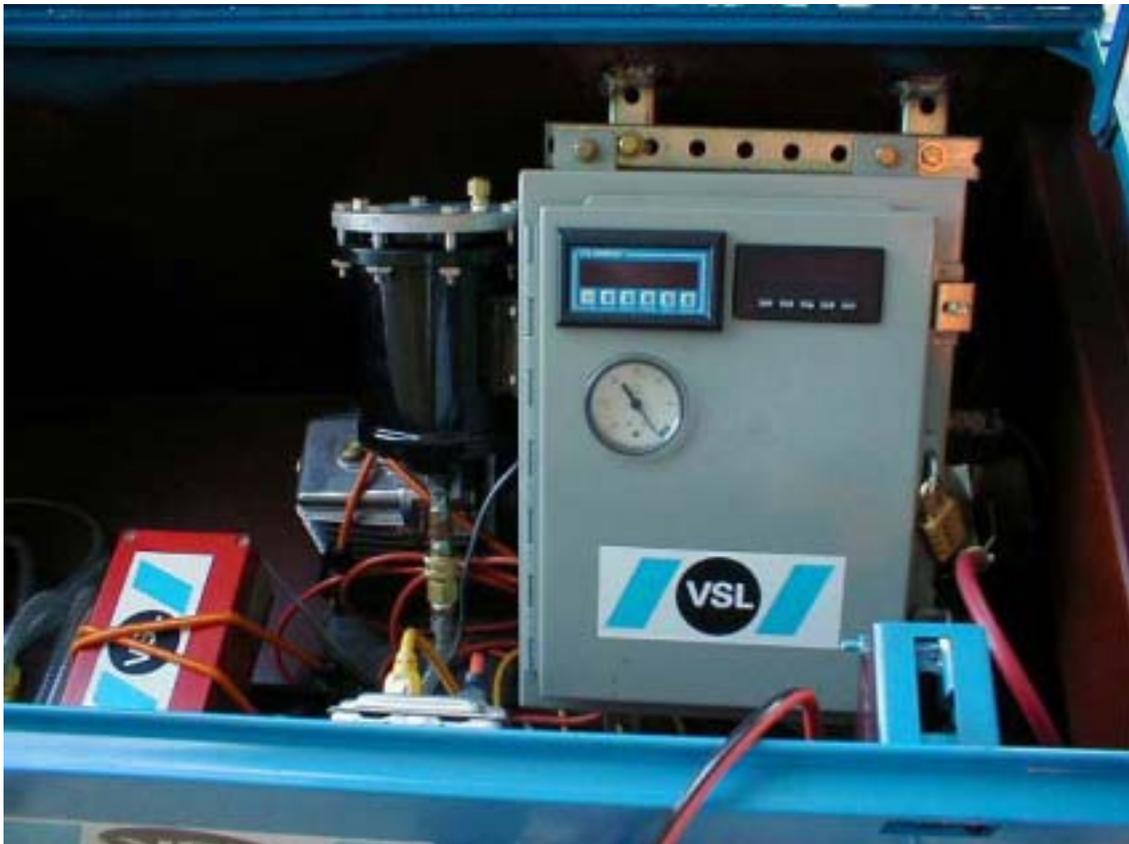


Fig. 21: Vacuum control and grouting equipment for tendons with defective grouting

pressure water jet, in particular in case pitting corrosion or chloride contamination has been found inside the duct.

In order to select the appropriate grouting procedure, it is necessary to determine the geometrical characteristics of the detected void (length, cross-section, volume etc.). In case of a larger void, vacuum assisted grouting is recommended. In special cases, the vacuum technique can also be used to measure the volume of the void and thus, determine its extent along the tendon. The vacuum pump reduces the air pressure inside the duct to a certain sub-atmospheric pressure (e.g. about 80% of the atmospheric pressure). The procedure is then automatically reversed and the air flowing back into the duct is measured and recorded. In order to determine the precision of the applied equipment preliminary tests are recommended for calibration. In principle, only cementitious, alkaline materials should be used for void filling. In case of very small voids, these can be patched by using a suitable mortar (thixotropic, if required). Tremie grouting can be applied with voids that are still comparatively small (maybe over a length of about one meter). For larger voids being several meters long, vacuum grouting is recommended using the same material as for new grouting (see Chapter 3). At the end of the grouting operation, the pressure should be increased typically 1-3 bars and kept for about 1 minute. The effectiveness of the chosen method should be tested beforehand. Fig. 21 shows

vacuum injection equipment which permits measurement of void and grout volume.

The advantage of the vacuum method is that only one access to the void at any location is required. In general, this can be the borehole which has been made for the inspection of the tendon and for taking samples to determine the chloride contamination. A comparison of the previously measured void volume and the injected grout confirms the success of the procedure. In case of discrepancies, it may be necessary to make checks by additional boreholes.

6.5 Closing of the tendon

In the following, four possibilities are given for the repair of tendon openings depending on access, see Fig. 22. In most cases, due to the presence of normal reinforcement, it is not possible to provide an additional protection by installing a half duct. Where the conditions are favourable, replacement of the removed duct section should, however, be considered. The placing of repair concrete or mortar on to the tendon grout has to generally be made "wet-to-wet" to assure optimum bond.

(1) Access to tendon from above, Fig. 22 a):

- š Roughening and cleaning of concrete surface
- š Wetting of concrete surface
- š Filling of duct and covering the vicinity of the duct with a minimum of 40 mm of cementitious grout
- š Filling of the remaining space of the opening with a shrinkage compensated cementitious repair mortar in several layers in accor-

dance with the instructions of the mortar supplier.

(2) Access to tendon from below, Fig. 22 b):

- š Roughening and cleaning of concrete surface
- š Filling of the opening in the concrete with a shrinkage compensated cementitious repair filler in several layers in accordance with the instructions of the filler supplier. In case of large voids inside the duct, the duct can subsequently be vacuum injected through a hose placed into the filler.

(3) Access to tendon from the side, Fig. 22 c):

- š Roughening, cleaning and wetting of the concrete surface
- š Placing and sealing of a formwork over the opening
- š Partial filling of the tendon opening and duct with a cementitious grout
- š Removal of the formwork
- š Filling of the remaining opening with a shrinkage compensated cementitious repair filler as in Item (2) above.

N.B.: Alternatively, a thicker cover can be formed and filled with cementitious grout. A minimum of 40 mm on a roughened concrete surface is recommended.

(4) Concrete pour back, Fig. 22 d):

Alternatively to the above methods (1) to (3), the tendon opening can be poured back with concrete. This is particularly suitable, if the openings are large, e.g. in bridge box girders:

- š Roughening, cleaning, and wetting of concrete surface

- š Placing and sealing of formwork
- š Pouring back the opening with repair concrete.

protection systems.

6.6 Repair of external tendons

In all the above cases (1) to (4) it may be considered to provide an eventual protection of the concrete surface against ingress of humidity or chlorides with special surface

External tendons are over the majority of the tendon length placed outside of the concrete. Therefore, access to the tendon is much facilitated compared to internal tendon as discussed in

Section 6.3. In most cases, access to the tendon reduces to the careful opening of the duct. Typically, this is a HDPE pipe which can be opened by cutting with a knife or similar tool. The actual investigation of the tendon is similar to internal tendons described above. The same comment applies for the cleaning of any eventual voids.

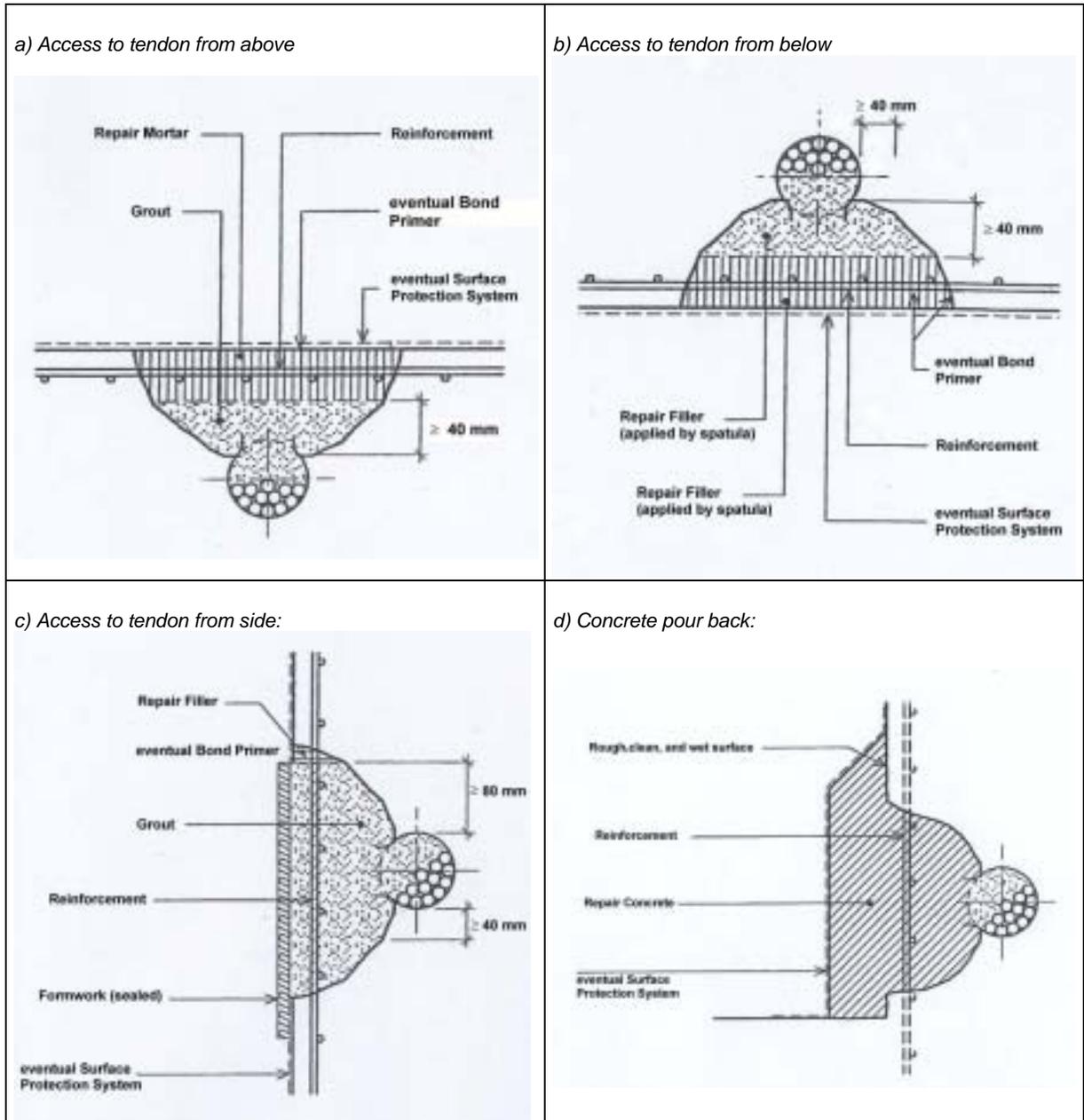


Fig. 22: Closing of tendon openings (Courtesy of Swiss Association of Post-Tensioning Association (VSV), adapted from [38]).

For external tendons, the duct can be closed e.g. with an HDPE sleeve with special grout connections, properly sealed, and then injected under vacuum. This method may even be applied for defects located inside diaphragms if access to the void is possible via the duct from outside the diaphragm.

If the damage of external tendons, e.g. by corrosion, is beyond repair, and if the tendon system permits, these tendons can be removed and replaced. For the majority of external tendons which used bare strand and cementitious grout inside a HDPE pipe, the tendon replacement must be carefully planned, and executed by experienced post-tensioning specialists. When a single strand is cut within the tendon length, bond to the grout and adjacent strands will prevent it from freely shortening and releasing its force over the entire tendon length. Rather its force will be transferred over a relatively short distance on either side of the cut to the adjacent strands. Hence, the force in the remaining strands increases at the location of the cut. If cutting individual strands at the same location is continued, there is an inherent risk of a sudden failure of the remaining strands when the increasing stress approaches the ultimate strength. This sudden failure may be avoided if the following procedures for the cutting of a tendon are followed:

- š` Slice and remove the HDPE pipe in the free tendon length.

- š` Carefully remove the grout in the free length and expose the tendon. This may e.g. be done by tapping or chiseling, with personnel placed behind protective shields.
- š` Place the sliced HDPE pipe around the exposed tendon, and secure the pipe with metal bands. Leave short sections of about 1m open for access to the tendon on either side of tendon deviators and anchorages.
- š` Install protective cages in front of access zones to tendon, fixed to the structure.
- š` Start cutting the first strand by a disc cutter at the first opening, and repeat this at each opening. Make sure that at any tendon deviation point there is no more force unbalance than one strand. Make sure that the cut strand releases its force and elongation between tendon deviation points.
- š` Cut the second strand similar to the first one, and repeat the procedure until all strands are cut.
- š` When all strands are cut, pull the tendon from the anchorage and from the deviators. If there is no double tubing at the deviator which allows removal, this section may be removed by chiseling and/or high pressure water jet.

The above described method has been successfully applied in a simplified manner on a number of single span tendons removed recently in Florida, [39]. However, the method is also applicable to longer tendons running over several spans.

The above method is also applicable to external tendons with soft injection such as grease or wax, and monostrand tendons, if details for a controlled tendon detensioning have not been provided.

7. Conclusions

The present report has provided a summary of the knowledge on cementitious grouts used for post-tensioning tendons. It is a collection of selected information from state-of-the-art publications, vast experience of VSL across the world, and of up to date results of an extensive research and development program carried out by VSL between 1998 and 2001. The main aspects and conclusions may be summarised as follows:

- š` Today's commonly used test methods for cementitious grout for post-tensioning tendons such as [16,17], and the corresponding acceptance criteria, have been shown to be often not representative of the actual conditions inside a tendon, and not stringent enough, to consistently assure that only high quality grout is used for grouting of post-tensioning tendons. New test methods have been proposed and have been confirmed to be representative for the conditions inside tendon ducts. These tests include in particular the Inclined Tube test, see Appendix A1. Owners and engineers now need to apply and specify these test methods and acceptance criteria on all their projects. Grout based on old test methods and acceptance

- criteria, typically called "Common Grout", should no longer be accepted for future construction.
- § Special grouts can be designed for high performance characteristics, including negligible bleed, sedimentation and segregation, and stability of flow time over extended periods. They can also be designed for very specific characteristics such as for use in low or high temperature, or for high pressure in long vertical tendons. Grouts which have gone through such a rigorous design and optimisation procedure in VSL obtain the label "VSL-HPI™ Grout".
 - § Grouting works on site need to rigorously follow specific grouting procedures. These procedures, when applied consistently by well-trained and qualified personnel of specialist contractors, with specific equipment, will reliably produce good quality and complete filling of post-tensioning tendons for excellent long-term protection.
 - § There are some specific site procedures, which based on today's knowledge and capabilities, should no longer be used. This applies in particular to the flushing of tendon ducts with water. Also the modification of grout temperature by the use of chilled water or replacement of parts of water by ice in hot climates is no longer recommended.
 - § A number of inspection and monitoring methods exist to verify the actual conditions of a post-tensioning tendon. These non-destructive methods allow a partial assessment of the conditions of a tendon. However, the one method which is quite basic and practical, and overall still rates best in terms of information and interpretation, is the careful opening of tendon ducts by drilling into them, and subsequent visual inspection with an endoscope or similar devices. This method can be applied in particular if there is a reasonable doubt about the condition of a tendon at a particular location based on desk studies or based on non-destructive test methods. Although this method is not non-destructive, the extent of intrusion is quite moderate, and not considered harmful to the structure or tendon, in general, if the opening is subsequently properly closed.
 - § A number of repair methods exist which allow reliable and effective repair of tendons with defective grouting. In particular for relatively large voids in tendons, a practical and effective method of repair is to drill into the tendon void, clean the void, and inject a low viscosity grout under vacuum.
 - § High quality grouting must be complemented with other independent layers of protection to guarantee long term protection of the tendons, and durability of the structure. These other layers include, in particular, a dense concrete cover over the tendon. Significant improvement of the protection can be provided by complete encapsulation of the tendon in a robust plastic duct system including transitions to anchorages, and permanent anchorage caps such as provided by VSL PT-PLUS® in the CS 2000 system.
 - § The use of high performance grouts in post-tensioned construction has a cost since excessive water in the formerly called common grouts is replaced with cement and special admixtures. Such high performance grouts have to be specifically designed and tested which represents additional costs. Overall, costs of a high performance grout mix are expected to be at least the double of a typical common grout. Considering that grout materials typically represent about 2-4% of a post-tensioning contract which may represent in turn 10-15% of the total construction cost of a bridge, this increase of grout material cost is considered insignificant for the owner, and certainly is good value. A similar comment applies to the cost of PT-PLUS™ plastic duct system, see [40]. If life cycle cost was used as basis of the above comparison, the use of high performance grout and PT-PLUS™ plastic duct system, is expected to show overall cost savings.
 - § VSL is proud to have contributed to a better understanding of the behaviour of cementitious grout for use in post-tensioning tendons, and to the execution of grouting works. We trust that this report will help to reinforce the confidence of owners and engineers into

the reliable long-term protection provided by cementitious grout.

š VSL can offer a wide range of systems and services including all the aspects related to grout and grouting presented in this report. This is one, but certainly not the only, reason why VSL should be your preferred PT specialist contractor. VSL will be happy to assist you in any question related to grouting. VSL has prepared a model Specification for Post-Tensioning Works including grouting works which can be made available to interested parties. Please contact your nearest VSL representative for a copy.

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Appendix A: Specific recent grout test procedures

A.1 Inclined Tube test

A.1.1 Objective

This test serves to determine the bleed properties and stability of a grout, at full scale and includes the filtering effect of strands. It also allows confirmation of the proposed grouting procedures, in particular the effect of time between ending an initial grouting and starting of re-grouting on site, if specified, and equipment used on site. The intent of the test is to confirm that a duct on site can be completely filled with the proposed grout, equipment and procedure, without unacceptable bleed and segregation of the grout.

A.1.2 Test method

In a first test phase, the bleed water and air accumulated on top of a tube filled with grout shall be determined. The grout is injected under pressure and is setting such that water losses due to evaporation are prevented. In a second phase, the effect of re-grouting of a tube on bleed water and air accumulated shall be determined, if such a procedure is envisaged by the PT specialist contractor in the grouting method statement.

A.1.3 Test equipment and set-up

- § Two transparent PVC tubes, of approximately 80 mm diameter and 5 m long, equipped with caps at each end including grout inlet at the lower end, and grout vent at the top. The tubes shall be able to sustain a grout pressure of at least 1 MPa.
- § 12 prestressing strands Ø 0.6" per tube, i.e. a total of 24.
- § Grouting equipment as per the grouting method statement.
- § A thermometer with automatic recording.

A.1.4 Test procedure

- § The two tubes are fixed on their supports such as to avoid noticeable deflections, at an inclination of 30° ± 2° against a horizontal reference line. 12 strands shall be installed in each tube. The caps are subse-

quently installed on the tube ends (fixed with glue), see Fig. A.1.

- § The grout is prepared as per the grouting method statement. Specimens shall be taken from the grout mix to confirm flow time per EN 445, [17]. In case of a thixotropic grout, other suitable methods shall be used.

- § Grouting of first tube :

Grout is injected into the first tube (Tube 1) from the bottom end. When the grout exits from the vent at the top with the same consistency as it enters at the bottom, the valve shall be closed, and the grout pressure shall be maintained for the duration specified in the method statement. Subsequently, the valve at the bottom is closed, and grouting of Tube 1 is considered complete.

The level of air, water, and any other eventual liquid on top of the grout shall be measured, see Fig. A.1. Such eventual liquid on top of the grout can be distinguished from the grout by its whitish to yellowish colour, usually clearer than the grout. A minimum of 4 measurements of levels shall be taken between 0 and 24 hours after completion of grouting, with one measurement just before re-grouting of Tube 2 is started. The following 4 measuring intervals are suggested : 30 minutes, 1 hour, 2 hours, and 24 hours after grouting.

- § Grouting of second tube :
Grouting of Tube 2 shall follow the same procedure

as used for Tube 1, and shall be done quasi simultaneously with Tube 1. At a time specified in the method statement for re-grouting, the mixing of grout in the equipment is started again, and the flow time of the grout is determined again.

Subsequently, the valves of inlet and vent of Tube 2 are opened again, and grouting is started again. This will allow any liquid accumulated on top to be replaced by grout. When grout exits from the vent on top, the valve is closed, and the grout pressure is maintained for the duration specified in the method statement. Subsequently, the valve at the bottom is closed, and re-grouting of Tube 2 is considered complete.

The time between initial grouting and re-grouting, and the duration for the second mixing activity, shall comply with the grouting method statement. Typically, this time will be between 30 minutes and 2 hours.

Similar to Tube 1, the measurement of levels are done between 0 and 24 hours after completion of the initial grouting. One of the measurements shall be taken just prior of re-grouting of Tube 2, followed by measurements 30 minutes, 1 hour, and 2 hours after completion of re-grouting.

A.1.5 Measurements and observations

The following measurements and observations shall be made and recorded:

- § Description of test set-up

- § Grout mix design, origin and certificates of all grout constituents
- § Mixing procedure of grout
- § Flow time of grout mix before initial grouting, and before re-grouting (or viscosity of a thixotropic grout)
- § Method statement for grouting specified by the PT specialist contractor
- § Measurements of level of air, water, and eventual liquid on top of the grout
- § Any observations and comments on the formation of bleed or liquid, or on difficulties encountered during the test
- § Any observations and comments on cracking of the grout, with location, orientation, and approximate widths of cracks
- § Development of air temperature during the entire test period
- § Photos illustrating test set-up, and details of top end of tube with air, water, and eventual liquid.

A.2 Wick-Induced Bleed test

A.2.1 Objective

This test serves to determine the bleed properties of a special grout. It is considered to be more representative than the bleed test as per EN 445, [17].

A.2.2 Test method

Bleed is expressed as the percentage of the bleed water depth on top of the grout column divided by the original grout column height, up to 3 hours and after 24 hours.

A.2.3 Test equipment

- § One transparent PVC tube, of approximately 60 to 80 mm internal diameter, and 1 m long, equipped with caps at each end, as used in the sedimentation test, see A.3.
- § One 7-wire strand $\therefore 0.6''$ of one metre length such as to fit inside the tube.
- § Grouting equipment as per the grouting method statement.
- § A thermometer with automatic recording.

A.2.4 Test procedure

The grout mix specified by the PT specialist contractor is prepared in the grout mixer intended to be used on site. The transparent tube is placed and held vertically on a surface free from shocks or vibrations. The strand is placed standing inside the tube and held concentrically. The tube is filled with grout to about 10mm below the top and sealed to prevent evaporation. Up to 3 hours and after 24 hours the bleed water depth on top of the grout column is measured.

A.2.5 Measurements and observations

The following measurements and observations shall be made and recorded:

- § Description of test set-up
- § Grout mix design, origin and certificates of all grout constituents
- § Mixing procedure of grout
- § Flow time of grout mix before filling of tube (or viscosity of a thixotropic grout)

- § Record temperature of grout constituents before testing, and air temperature during test period
- § Record type and size of strand installed in column
- § Record the original grout column height
- § Record bleed water depth at the top of the grout column up to 3 hours and after 24 hours
- § Determine the bleed ratio of the grout column as the depth of bleed water divided by the original height of the grout column
- § Photographic documentation, and comments (not required for testing on site).

A.3 Sedimentation test

A.3.1 Objective

This test serves to determine the sedimentation properties of a grout. It is considered as a

A.3.2 Test method

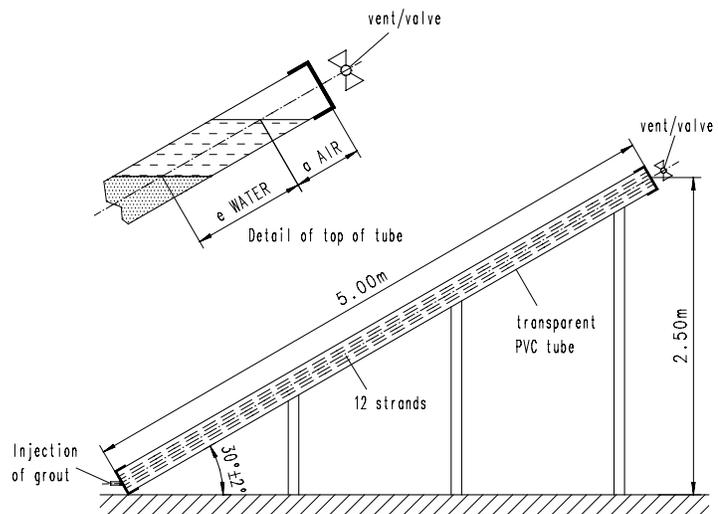
Sedimentation is measured as a percentage difference in density of the grout between the samples taken from the top and bottom of the test specimen.

A.3.3 Test equipment

- § Two transparent PVC tubes, of approximately 60 to 80 mm internal diameter, and 1 m long, equipped with caps at each end.
- § Grouting equipment as per the grouting method statement.
- § A thermometer with automatic recording.

A.3.4 Test procedure

The grout mix specified by the PT specialist contractor is prepared in the grout mixer in-



measurement of the homogeneity of the grout mixed in the equipment intended to be used on site.

tended to be used on site. The two transparent tubes are placed and held vertically on a surface free from shocks or vibrations. The two tubes are filled with grout to the top and sealed to prevent evaporation. At least 24 hours after filling,

but after setting of the grout, the grout columns shall be removed gently from the tubes. The grout columns shall be marked and subsequently cut into equal slices of about 50mm each over the entire height. The relative position of each slice in the column shall be recorded. The density of each slice shall be measured by an approved method.

A.3.5 Measurements and observations

The following measurements and observations shall be made and recorded:

- š Description of test set-up
- š Grout mix design, origin and certificates of all grout constituents
- š Mixing procedure of grout
- š Flow time of grout mix before filling of column
- š Record temperature of grout constituents before testing, and air temperature during test period
- š Record the density of each slice of both grout columns
- š Determine the sedimentation ratio, R, of each of the

grout columns as the variation of grout density between the bottom, D_{Bot} , to the top, D_{Top} , of the column as follows:

$$R = 1 - (D_{Top} / D_{Bot})$$

- š Report any particular observation such as eventual bleed water on top of the grout column at the time of removing the grout column (presence of water and quantity), or discoloration of grout columns.
- š Photographic documentation, and comments.