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GROUTING OF DUCTS IN POST-TENSIONED PRESTRESSED CONCRETE

by R W Taylor

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GROUTING OF DUCTS IN POST-TENSIONED PRESTRESSED CONCRETE

BY

R W Taylor

SUMMARY

This final report of the contract reviews the work already reported in detail in the eleven supplementary reports cited at the end of this report. This work includes literature reviews, laboratory investigations, observations of site practices and simulated full-scale trials.

Many of the problems associated with the grouting of the ducts in post-tensioned prestressed concrete stem from the generally unsatisfactory conditions and practices employed on site. Tests on full size duct assemblies have shown that even under nearly ideal conditions, voids can be left within a grouted duct when current techniques are employed. A number of practical problems have been identified. The precautions necessary to reduce the likelihood of voids being formed within the duct have been discussed and suggestions made that should eliminate the most obvious of the practical faults.

Further full-scale tests are advocated to investigate the flow of well formulated and tested grouts along curved cable ducts that carry stressed cables. The methods of injecting grout and the techniques of duct venting also need further study. One important suggestion that merits consideration relates to the permissible bleeding from acceptable grouts. The current limit of 4% would seem to be unnecessarily high.

A small number of grout tests have been identified as being of practical potential for site use. It is advocated that these be evaluated in a future programme on practical grouting procedures, including tests on different formulations of grout.

INTRODUCTION

It has been found that the grouting of ducts in post-tensioned prestressed structures is often unsatisfactory and that voids can exist within the ducts, in many cases exposing the tendons. Investigations on actual sites indicated that little importance is attached to this vital operation and that problems are frequently encountered. To investigate the problem further a research contract was placed with the Cement and Concrete Association by the Transport and Road Research Laboratory. The aims of the research were to:
Observe the grouting operation on site and to identify where problems arise.

To undertake a critical review of the grouting operation.

To review the factors affecting the ability of grouts to fill ducts.

To evaluate techniques for the on site testing of grouts.

To design grouts capable of filling ducts

To carry out full-scale grouting trials to determine why voids are formed and how they may be avoided.

At various stages in the project the work dealing with specific topics has been reported; these reports (11 in all) are listed as references to this report.

OBJECTIVES OF GROUTING

It is common practice to use Portland cement-based grouts to protect the steel cables used to post-tension concrete structures. These cement grouts protect the steel provided they completely surround the cables, remain highly alkaline and are not carbonated or penetrated by chlorides or other deleterious materials. These grouts can also help to transfer loads between the structure and the stressing cables through the interface bond.

In order to satisfy these goals the grouts must be correctly formulated and must fill the ducts completely. Unfortunately studies of the effectiveness of grouting procedures (Woodward1,2) have shown that voids can be left within the ducts with potentially serious results. This problem is not unique to the UK and similar observations have been made in Japan where on one bridge 35% of the ducts contained voids and 10% of the ducts were less than half full(3).

In this study the main emphasis has been placed on the specifications of grouts and on certain aspects of the grouting procedures. No consideration has been given to the transfer of stress through the bond between the cable and the grout.

CURRENT GROUTING PRACTICE

As an important part of the study, observations were made on a number of grouting operations and these are detailed in Report No. 2 of this project(4). Even on the sites where successful grouting was apparently achieved, a number of problems were met and the general organisation of grouting operations was poor with virtually no contingency plans to call upon when problems occurred. Many R.E's were not experienced in grouting and they left the full grouting operation to the 'specialists' who were not always trained adequately themselves and often did not appreciate the importance of achieving fully grouted ducts. Many of the points observed on site visits are covered by current specification proposals and they will be referred to as relevant later in the report. The studies on site clearly demonstrated that grouting operations were not being uniformly performed and that when problems occurred, as is inevitable, it was nearly always impossible to take effective remedial action. It is against this background that current specifications are now reviewed.
Current Specifications

The current DTp specification is given in reference 5 and that from BS8110 in reference 14. The BS8110 requirements are more demanding than those of the DTp but both rely heavily upon the quality of the supervision in the absence of universally accepted tests either of the 'quality' of the grout or the effectiveness of the filling of the duct.

Duct design and construction

Ducts are usually formed from corrugated steel tubing that is often galvanised to provide protection from corrosion prior to its encasement in concrete and grout. Where necessary ducts are joined with leak-proof connectors, and vents, through which grout can be pumped or can discharge, are fitted at intervals along the length of the duct. Currently these vents must be provided at the crests of any profile and at intervals not greater than 15m.

As the ducts cannot easily be inspected after the surrounding concrete has been placed, it is essential that they be closely examined prior to the concreting and that they are securely fixed to avoid movement during the placing of the concrete. The duct profiles must be smooth and devoid of discontinuities. Any damage to the ducts must be repaired since any hole is a source of mortar leakage into the duct during the subsequent concreting operations.

Properties of grout

The specifications for grouts differ substantially between the DTp and BS8110. The former limits grouts to BS12 ordinary Portland cement mixed with water at a maximum W/C ratio of 0.45. Admixtures are only permitted when authority is given by the engineer. Apart from a bleeding test no performance test is specified.

In BS8110 a wider selection of grout components is permitted but more closely defined performance requirements are given. The bleeding test is similar to that of the DTp specification. In addition there is a suggested fluidity test - flow through a cone - and a minimum cube strength test for the hardened grout of 30 N/mm² at 28 days.

Qualitative descriptions of a suitable grout are also given in BS8110. Basically the grout should have a high fluidity so that it can be pumped, but also it must be cohesive so that it remains a continuous ribbon as it is pumped through the curved ducts and around the steel cables. The grout must be able to penetrate into the cable strands without major segregation of the grout constituents occurring due to the effects of filtration under pressure. The bleeding test referred to above provides one measure of the cohesiveness of the grout, though this test does not involve the application of pressure.

The grout must also have low shrinkage to ensure that ducts remain filled.
Preparation of Grout

The previous section describes briefly the main requirements for a successful grout. Grouts comprise cement and water but other constituents may be added to help to satisfy these needs. Suitable admixtures, pulverised fuel ash, ground granulated blast furnace slag or a proportion of sand may be used, provided evidence is available regarding the suitability of the particular combinations. In view of the absence of widely accepted tests that measure the quality of a grout, it is difficult to judge when such combinations are satisfactory in all regards.

Specialist contractors are normally responsible for grouting operations, but as seen in the reports on the site observations, good and consistent mixing practices are not always followed. The mixers should be capable of producing a colloidal grout. High shear mixers are frequently used, though other types can be satisfactory. The mixing time is critical and a rigorous procedure that will depend upon the mixer type, should be followed meticulously once tests have established the correct sequence.

Once mixed the grout should be held in a tank with slow agitation to keep it ready for use.

The later parts of this report consider the problems that occur with grouts which often do not satisfy the specified requirements.

Grouting Procedure

It is assumed that the ducts are properly designed, have no abrupt changes of section or sudden bends, are not holed or damaged and have been checked for air tightness prior to the grouting operation.

The grout is then injected from a low point at a pressure of up to 0.7 N/mm² until it flows from the first vent outlet. It is not sufficient just to let grout reach a given vent, enough out-flow should be allowed until the quality of the grout is equal to that being supplied. The first vent is then sealed and the process is repeated at succeeding vents until the duct is completely filled. After closure of the final vent the pressure on the grout should be maintained for at least five minutes and pressure gauges should be used to check that leakages do not occur.

The precautions that should be taken regarding the preparation of the ducts before grouting starts and the actions, to be taken should blockages occur, are described in BS8110.

It can be seen that grouting procedures are fairly rigorously defined, yet as Woodward has observed (1,2), success is not always achieved. It is not difficult to see why. The procedures are relatively sophisticated when compared with most construction site operations and it is often difficult, if not impossible, to fulfil all of the specified requirements. A major part of this project has been to seek better ways to specify and test grouts on site, to improve the effectiveness of pumping and grouting operations and to understand more about the influence of interactions between the duct and cable geometries and the grouts on the effectiveness of the grouting process. These subjects are now considered in more detail.
PROBLEMS WHICH OCCUR IN PRACTICE

The usual procedure of injecting a water cement grout into one end of a duct assembly and successively sealing the vent tubes along the duct as grout flows from them would seem a straightforward task. It is, however, a vital operation as the grout must completely fill and seal the duct if it is to protect the steel tendons against corrosion. Recent investigations\(^{1,2,4}\) of bridges constructed since 1950 have shown that the grouting has not always been of the required standard; serious voids and even empty ducts have been found in some demolished structures.\(^{\text{Fig. 1}}\) Part of this contract has been to identify what could go wrong on site and the reasons for the errors or malpractice.

Duct assembly

Dealing first with the unsatisfactory conditions that may exist inside and around the actual duct being grouted. Not enough care is taken in jointing ducts and fitting vent pipes to ensure that during concreting, mortar cannot enter the duct to cause a possible restriction that could result in a grout blockage. Unless mortar or other debris has found its way into a duct there should be no reason why a suitable grout should not pass freely along it. Improved vent pipe saddles should be used, properly located over a hole of at least 10mm dia. drilled in the duct. Driving a bar down the vent to puncture the duct is not good enough. Vent pipes must be better protected at deck level as a pipe that has been sheared off or damaged causes additional problems and can act as a surface water drain into the duct.

An improved method of sealing the vent pipes should be devised in order that they may be easily vented and resealed once the duct has been filled with grout. Arrangements must be made for the collection of grout flowing from vent pipes. Obviously large quantities of grout cannot be allowed to flow over the structure, but the duct must be allowed to vent before being sealed. Currently, the total absence of a collection system causes considerable panic if more than a cup full of grout should escape before the vent is plugged. This project has shown that a reasonable amount of grout must be allowed to flow from a vent in order to reduce the risk of voids being left within the duct. A recent survey\(^{2}\) of 12 structures showed that many of the grouted ducts contained voids, some large enough to expose the tendons and occasionally, a duct could be totally devoid of grout. An inspection of two bridges - one being demolished - and the other, after its collapse, showed that there is a risk of tendons failing due to corrosion. In these two bridges there were a number of partially grouted ducts and some severely corroded tendons. The reasons for the shortcomings in these two cases are as yet unknown, but attention to the duct and fittings as outlined above would improve the chances of completely filling the duct with grout.

Mixing and pumping of the grout on site

Grouting is a very dirty and unpleasant operation to carry out even under ideal conditions. To expect a high standard of workmanship and attention to detail from men working in the conditions normally experienced by a grouting team is unreasonable. Many of the problems encountered during grouting are caused by either blockages or ill fitting pipe connections, both the result of using badly maintained equipment. Provisions should be made for thoroughly washing down the plant and pipe lines at regular intervals. The specification\(^{5}\) requires this to be done at least every 3 hours and at the end of each day. This is plainly not being done, witness the condition of
the plant on site. Old hardened grout becoming dislodged from the plant or pipe line will cause a restriction and probably a blockage, therefore, the equipment must be clean at the start of each grouting session.

Apart from being clean, the plant etc., must, of course, be in good working order. In theory nothing could be simpler than adding 2 or 3 bags of cement to a measured quantity of water and mixing it for 2 minutes. Unfortunately, with much of the plant currently in use, even the measured quantity of water cannot be relied on due to the condition of the water tank, valves and overflow pipe.

If a high speed paddle mixer is being used to mix the grout, the grout should pass through a suitable strainer of approximately 1mm mesh positioned between the mixer and pump. Such a strainer will remove anything likely to cause a blockage before it is too late. If the mixer is the type which uses the 'high shear' system there would be no need for a strainer as the grout should have passed through the close tolerance mixer/pump immediately before being fed into the duct.

It is important to improve working conditions for the operatives and to provide easy access and improved communications between the mixing station, the bridge deck and, if necessary, both end anchorages.

Access to the anchorages or bridge deck is often over a muddy area of earth works and up through a forest of starter bars. Relatively comfortable and convenient working conditions are essential if this rather precise operation is to be carried out correctly and conscientiously.

The following comments are typical of those made after a site visit:

"A lack of technical awareness of the importance of grouting on the part of the Resident Engineer who was happy to accept the expertise of the subcontractor as a guarantee of successful grouting."

"When a duct became blocked there was no predetermined procedure for dealing with the problem."

"Specifications were not adhered to. There was no testing of the grout only a visual check on the grout as it emerged from the vent."

"Poor preparation of plant, hoses etc., and unsatisfactory checking of vent tubes, anchorage capping, etc."

"Generally unsatisfactory environment with poor access. Lack of understanding and communication between operatives."

Most comments concerning the grouting operation are in a similar vein to these and have been reported many times - yet little has been done to improve the situation. These facts must be faced and dealt with, if not they will continue to be repeated over and over again totally nullifying any advances that may be made in grout formulation. Good site practice is inhibited by pressures to finish the job quickly and, in the absence of suitable containers, to minimise grout spillage over the structure. These are fundamental problems of contractual procedures, supervision and adherence to specification and must be resolved. The aim must be to "Plan for Quality" rather than to hide behind mainly irrelevant tests. Testing is important but it must be a relevant test conducted at the right time. For example, the DTp Specification for Road and Bridge Works states - "grout
should be allowed to flow from the vent until the consistency is equivalent to that being injected." Thus, if a suitable test for consistency was available and if time was allowed for the necessary testing to be done then a more enforceable specification requirement could be adopted.

PROPERTIES OF GROUTS

Rheology

Since the flow behaviour of a cement grout has a considerable effect on the filling of a post-tensioned duct, some understanding of its rheology is important and the subject is dealt with in more detail in Report No. 6 of this project(6)

Rheological properties of cement grout can be time dependent, shear dependent and dependent upon the chemical surface charge. Grout rheology is therefore complex and there is no agreed rheological model on which to base research.

A large number of fluids are classed as Newtonian fluids. In a Newtonian fluid with no forces between the particles within the suspension, the rate of shear is linearly proportional to the applied shear stress as shown in Fig 2. Thus the viscosity of the fluid can be determined by a "single-point test."

Cement grout unfortunately is a non-Newtonian liquid. Depending upon paste composition and testing conditions, cement pastes have been shown to exhibit flow behaviour approximating to one of the following types.

(i) Bingham, as illustrated in Figure 2. Here the applied shear stress is linearly related to the rate of shear but a yield stress must be reached before shearing occurs.

(ii) Pseudoplastic, for which the apparent viscosity decreases with increasing shear rate as illustrated in Figure 3. "Shear-thinning" is said to occur.

(iii) Dilatant, for which beyond an optimum value the apparent viscosity increases with increasing rate of shear as illustrated in Figure 3. Here "shear thickening" is said to occur.

In its simplest form cement grout can be considered to act as a Bingham. This means that, for any method of test, at least two determinations at different rates of shear must be made to establish its flow behaviour as indicated in Figure 2. Hence the viscosity values obtained in this project using the simple site viscometer are apparent values, valid only at the applied rate of shear and for the grout age, temperature etc., involved. All the other tests for flow properties used in this project are also single point tests with the same general limitation and give no indication of the effect pumping pressure may have on the grout. Other instruments for checking fluidity or flowability including two point viscometers, are discussed in the section on testing methods.
**Figure 2** Flow curves for Newtonian and Bingham liquids

**Figure 3** Flow curves for Dilatant and Pseudoplastic liquids
Material parameters affecting cement grout flow are

- volume concentration of solids in suspension
- time after mixing
- particle shape, size and distribution
- content and form of calcium sulphate
- chemical composition
- mixing history
- temperature
- type of admixture and concentration

The most important factors influencing grout flow are the volume concentration of solids in suspension, which is a function of water/cement ratio, cement fineness and admixtures.

The ease with which a grout flows is dependent upon interparticle spacing. Increasing the water/cement ratio or reducing the cement fineness increases the interparticle spacing which reduce the 'viscosity' of the grout. A change in cement fineness also influences the reaction kinetics.

It has been shown in this work that most grouts with water/cement ratios between 0.4 and 0.45 can be satisfactorily pumped through severe restrictions provided that the grout is well mixed, free of lumps and does not suffer from unreasonable bleeding under pumping pressure — i.e. pressure filtration. These then are the important properties affecting the grouting of post-tensioning ducts and any related work on the rheology of cement grouts must take these practical considerations into account. The aims are twofold: to produce a satisfactory grout using the materials available under the conditions existing on the site and to maintain the properties of that grout within acceptable limits for the duration of the work.

In practical terms the factors that influence the flow of water/Portland cement grout are water/cement ratio, the cement, the type of mixer used and the mixing regime. Not surprisingly water/cement ratio stood out as the variable having the major influence on the fluidity of grout mixes tested.

As far as cement effects are concerned, using an air-set cement can lead to problems as it will often produce a lumpy mix; even then an efficient mixer could overcome this effect by breaking up the agglomerates. If, as required in the specification, only fresh cement is used in the preparation of grout there should be no problem with consistency provided the grout is correctly mixed. The work reported in Report No.10 of this project (7) possibly exaggerates the effect of mixer type as the low-shear mixer used was a very inefficient grout mixer. Different forms of low-shear mixing used later in the project produced more satisfactory grouts.

As already stated, the rheology of cement paste is very complicated and site testing can probably do no more than give an indication that reasonably consistent grout is being produced. Grout giving a FIP flow time between 7 and 10 sec (or the corresponding apparent viscosity value) should have acceptable rheological properties.
Bleeding and Pressure Filtration

The bleeding and filtration characteristics of a grout are closely related and have equally important effects on the successful filling of post-tensioned ducts. The bleeding of grouts is discussed in more detail in Reports No 5 and 7 of this project.\(^{(9,10)}\)

Bleeding or settlement of the cement within a duct or anchorage will cause voids possibly exposing the steel strand. In near horizontal ducts the voids can extend along the length of the duct allowing corrosive fluids to enter and attack the steel. Water filled voids in the ducts of prestressed concrete have been known to freeze and crack the unit.

It is obviously important for a grout to bleed as little as possible. Unfortunately, the optimum conditions for low bleeding are the worst for easy flow, practical grout mixes must therefore be a compromise between the two properties and some bleeding must be expected.

The Department of Transport specification\(^{(5)}\) allows a grout to bleed by a maximum of 4% provided the water is re-absorbed within 24 hours. The requirement that the bleed water is re-absorbed is hard to justify as 4% bleeding in a 80-100mm diameter duct could form a void approximately 6mm deep along the length of the duct whether the water is re-absorbed or not.

Results from work on this project suggest that 2% would be a realistic maximum value for total bleeding and that as the bleeding has taken place within about one hour of placing, venting and re-grouting of the duct within that time could be useful.

Water/cement ratio was again the variable having the major influence on the maximum bleeding of the grout tested; the 0.46 w/c ratio grout bleeding, on average, 50% more than the 0.39 w/c ratio grout.

The temperature of the mixed grout has a marked effect on the rate of bleeding but not on the actual amount of bleed water released. Typically a change from 30\(^\circ\) to 10\(^\circ\) would double the time taken to reach maximum bleed.

The pressure filtration characteristics of a grout are important as they influence the ease with which water can be forced to segregate or bleed from the grout under pumping pressure. In practice this should not cause any problems; as the name suggests, the grout needs to be filtered through a severe restriction to force the water out and such a restriction should not be encountered in a sound duct assembly.

The pressure filtration characteristics of a grout are however, closely related to the bleeding characteristics of that grout. A filtration test could, therefore, be used in place of the much slower bleeding test to check grouts on site.

Compressive Strength

The 7-day cube strengths recorded in this work were significantly influenced by the water/cement ratio of the grout, the mean strengths for water/cement ratios of 0.39 and 0.46 being 50 and 35 N/mm\(^2\) respectively.

It is obvious that any change in the actual water/cement ratio of the grout due to dilution by water already in the duct could seriously affect the properties of the grout. Within the scope of this project it has not been
possible to research what effect such dilution could have, for instance, on permeability, bond strength with the strands or the freeze-thaw resistance of the grout. However, the topic is discussed in Report No 9 (11) of this project.

METHODS OF TESTING GROUTS

There are obviously many highly complex test methods that could be used to check the various properties of cement grouts; the work in this project has concentrated on tests that could possibly be used to control the quality of grout on site. Specifications must be realistic and the tests required must be suitable for site use if there is to be any hope of enforcement. A full account of this work on test methods is given in Report No 8(12) of this contract.

Flow tests

The most common test is the flow cone; three cones with slightly different geometries are available and in each case the test involves measuring the time taken for a given volume of grout to flow from the cone. Flow cones are well suited for site use but a calibrated container and a stop watch are needed to carry out the test. The main site problem with the test is the need to keep both the cone and calibrated container scrupulously clean and the fact that the test is rather insensitive when used on the more fluid grouts. Some very fluid grouts incorporating a superplasticizer with apparent viscosities of between 1-3 poise, still recorded FIP flow cone times of around 7 sec.

A flow cone test carried out correctly could indicate a change in the fluidity of a site grout and the operatives could be alerted in time to take action.

Another possible flow test for site use is the flow trough, in which a litre of grout is released from a hopper and allowed to flow along a horizontal trough. The length of the resulting grout slick is measured against a scale on the trough side. Like the cones, the flow trough is robust and simple to use. However, it does require accurate levelling and is more difficult to clean than the cones. The plain cement water grout tested in this work with water/cement ratios between 0.37 and 0.47 resulted in slick lengths of between 200 and 550mm respectively and the test is probably on a par with the flow cone test as far as sensitivity and suitability for site use.

Immersion tests

The Otto Graf viscometer or Walz immersion test consists of a 65mm bore steel barrel, 875mm high, fixed into a solid base. The barrel is filled with grout and a bullet shaped probe is then timed as it falls through the grout; the test is repeated twice and the average time for the second and third test is recorded. This test is mentioned in the German Federal Republic's standard which states that the whole test is required to be repeated after 30 minutes. The result of the first test should not be less than 30 sec and the 30 minute result not be more than 80 sec. In the work covered by this report there was no difference between the means of readings taken at 30 minute intervals, however, the values for the 0.39 water/cement ratio grout were outside the requirement of the German standard having a mean value of 120 sec.
This test like the flow cone is very sensitive to 'poor' mixes and requires considerable care in setting up the apparatus and in conducting the test. Absolute cleanliness is again important and could be a problem on site. The test would seem to have no advantage over the flow cone or trough tests.

**Viscometers**

A number of quite involved and relatively expensive viscometers are available, many of them being capable of carrying out sophisticated tests on cement grouts. Usually the tests could only be conducted by trained operatives in a site laboratory and with the present limited understanding of the theory of grouts and grouting, the results would have little practical use.

A comparatively simple, portable viscometer costing around £400 has been used in this work. It is a single point test and therefore gives only the apparent viscosity of the grout. The results show the instrument to be reasonably sensitive and yet able to deal with 'poor' mixes.

For site use the viscometer would need to be protected from wind and weather and the small metal cup which rotates in the grout sample would need to be cleaned after each test. With minor modifications it would be a useful site test and more reliable than the flow tests described above, particularly with the more fluid grouts incorporating a superplasticizer.

**Density**

A practical, site tested instrument for measuring the density of mud from drillings is the mud balance. The balance consists of a graduated arm supported on a knife edge; at one end of the arm there is a cup for the material under test, at the other end a sliding counter weight.

Unfortunately, the range of grout densities used for duct filling would cover only 4% of the mud balance range and the balance would not be sensitive to the small changes which need to be measured when converting density to water/cement ratio.

Without doubt the most accurate site method for the determination of density and hence water/cement ratio has been the density bottle method. Unfortunately, the facilities of a site laboratory would again be needed as great care must be taken with the test.

In the test a bottle is weighed and its volume accurately determined. The bottle is then partially filled with grout and the weight of grout determined. Next the bottle is topped up with water and reweighed allowing the volume of grout to be calculated. From this information the density of the grout can be calculated with a high degree of accuracy. The water/cement ratio of the grout can then be determined from a simple table or graph.

**Bleeding or settlement**

The test method specified by the Department of Transport (5) gives no indication of how or where the depth of water should be measured. Earlier work (10) has shown the wall effect at the side of a container to reduce the settlement by as much as 20% compared with the central area. Most bleeding or settlement tests have a number of weaknesses and are seldom carried out
correctly under site conditions. A method developed for this project is as follows:

A 2 litre sample of grout was collected in a 160mm diameter cylindrical container with a sealing lid. (Nominal 100mm deep sample). At intervals the lid was removed and the container gently inclined so that any bleed water could be removed by pipette for measuring, the water was then returned to the sample and the lid resealed. When this test is carried out at 30 minute intervals it is possible to determine the maximum bleed and the time at which this occurs within practical limits. Although this proposed method of measuring bleeding would seem to be a considerable improvement over some of the other rather loosely defined tests, it must still be used some 2 hours in advance of grouting. Any results obtained from grout sampled as injection was taking place would, therefore, be useless other than as a compliance control.

Pressure filtration

Perhaps more important than the rate of free standing bleeding of a grout sample is the ease with which water can be forced to aggregate from the grout under pressure. One of the tests investigated in this project was the use of a pressure filtration cell. A complete kit suitable for site use is available commercially costing approximately £500. With this equipment, the rate at which water can be forced from the grout sample when subjected to various pressures can be established. The filter is designed to retain particles greater than 1.2 um in diameter and will, therefore, retain most of the cement particles. Filtration is complete in about 15 minutes when the water remaining in the grout is about 0.22 times the weight of cement in the sample. In this work a pressure of 0.14 N/mm² (20 psi) was applied to the grout and the expelled water measured at 5, 10 and 15 minute intervals. The test requires considerable care in assembling the apparatus and again cleanliness is most important, however, a site laboratory would not be essential as the equipment is self-contained and could be used on the site. Using this test, programmed or spot checks could be made on the grout and with a result being available in approximately 15 minutes, any necessary action could be taken to correct or reject the mix.

Some further work is necessary to establish the relative importance of the bleeding and pressure filtration tests. From the work to date, it would seem that the pressure filtration test would be the more suitable site test in terms of the value of its results and the method of test.

Strength

It has not been possible to research the effect of grout strength on its bond characteristics or on its durability. However, it does seem reasonable to suggest that it is more important to ensure complete duct and anchorage filling with the designed grout than to worry about its strength, weak grout being better than no grout.

Little importance can be placed on strength tests, indeed, codes and specifications differ in their requirements and in any case, what use can be made of results available 7 days after the duct was filled? It would seem more important for example, to enforce the requirements dealing with minimum temperatures at early ages and to ensure that fresh grout is not subjected to sub-zero temperatures.
7-day cube tests were carried out on most of the grouts used in this work. An analysis indicated that the strength was only affected by the water/cement ratio of the grout and that the mean strength of even the 0.46 water/cement ratio grout was 35 N/mm^2 (CP 110 and BS 5400 require 17N/mm^2 at 7 days and BS 8110, 30 N/mm^2 at 28 days).

Other tests

In addition to the foregoing tests, one or two test methods have been developed in the course of this project. Whilst some may be worthy of further development, at this stage they are unlikely to be of any practical value on site and will only be outlined below.

Flow resistors. This test can be used to investigate the pumpability of a grout, the reaction of the grout to pumping pressure and the ease with which pumping can be stopped and restarted. The flow rate at various pressures can also be measured. More work would be needed to ensure that any results from this test could be confidently converted to full scale site use.

Penetrometer. The penetrometer test has been developed at the Cement and Concrete Association to examine the setting and stiffening processes of cement grout. A probe is driven into the sample and the depth and force required are monitored. The shear threshold can then be computed. It is a technically sound test but of questionable value to this work.

Continuously recorded settlement. Because of the shortcomings of the bleeding test a test was developed to monitor the surface settlement of a grout sample. A float resting on the grout surface is connected to a displacement transducer, the output is plotted against time on a recorder. The rate of settlement, maximum settlement and time to maximum settlement can all be recorded under temperature controlled conditions. A useful test not suited to site use.

Discussion of tests

In practice, little attention is paid to site testing of grouts and often any information that is gained is unreliable. Much of the equipment and many of the tests available are not suitable for site use.

It is important that grouts should be formulated and thoroughly tested before they are needed on site. It is necessary with the current bleeding test, for example, to check a proposed mix the day before it is expected to be used. Taking a sample of grout for a bleed test as it flows into or out of a duct is pointless as the grout in the duct will have stiffened considerably before a result is available from the test. The pressure filtration test however, could possibly be used to check the bleeding characteristics of a grout as it was about to be used as a result would be available in about 15 minutes.

Site testing of grouts should be confined to a quality control function, ensuring that the agreed properties are maintained during the grouting operation. A simple yet reliable check on the water/cement ratio using a flow cone or viscometer is probably all that is needed for plain grouts. If more fluid grouts incorporating a superplasticizer were being used the task becomes a little more difficult and a viscometer may be necessary as a flow cone would not be sufficiently sensitive.
In the work covered by Report No. 10(7), the mean apparent viscosity value recorded for a 0.39 w/c ratio grout was 34 poise and the mean value for a 0.46 w/c ratio grout was 20.5 poise. In the later work covered by Report No.11(8) the recorded values were 35 poise and 20 poise respectively. Far less agreement was recorded for the FIP flow times; in the earlier work the mean flow time for a 0.39 w/c ratio grout was 18.2 sec and for a 0.46 w/c ratio grout, 9.5 sec. In the later work using only a high-shear mixer the values were 10.2 sec and 7.8 sec respectively. It is interesting to note that these two figures give a mean FIP flow cone time of 9 sec; exactly the same mean value was obtained for the high-shear mixer in the earlier work suggesting that the larger range of overall FIP flow times recorded in the earlier work was largely due to the influence of the inefficient mixer used for half of those tests.

Flow cone times are obviously very sensitive to lumps or even local thickening within a grout mix, viscometers however, are more tolerant of such conditions and will average the viscosity of the remaining mix. It is very debatable which test yields the most useful information in practical terms and more work could be done on this aspect of testing. The most suitable overall test would seem to be the simple viscometer test as described in the text above. The test has been used successfully throughout this project and with minor modifications, could be used on site. The instrument gives a steady reading which can be noted more easily than recording flow times in some of the other tests. A major plus, for this test is that only a small steel cup would need to be cleaned after each test.

**ADMIXTURES FOR GROUTING**

Admixtures can be used to modify the properties of a cement-water grout, to accelerate or retard set or to modify the bleeding or segregation characteristics of the grout.

There are, however, drawbacks to using admixtures. The additin of a third or even fourth ingredient complicates the mixing procedure for example, an admixture may not behave exactly the same with all cements and its effect could be temperature dependent.

The need for admixtures, with one exception, has not been identified during the work of this project. The exception being the use of a superplastizer to produce a very fluid grout, improving its duct filling potential.

If further work or discussions with grouting contractors established a need for one or more admixtures, a programme of research would be required to ensure a full understanding of their effects.

Admixtures for grouting is the subject of Report No. 4 (13) of this project.

**GROUTING TRIALS**

The final stage of this project involved grouting tests on simulated duct assemblies. The testing was broken down into two parts; in part 1 grouts were pumped through a number of artificial restrictions and in part 2, full size duct and tendon assemblies were grouted. Throughout this work the opportunity was taken to investigate further the tests which were considered suitable for site use. A full report of this section of the project is given in Report No.11 (8)
The most reported problem from site is one of grout blockage, it is suspected that the blockage is usually due to bad housekeeping on the part of the operatives. Dirty mixing and pumping plant, and dirty valves and hoses can easily cause blockages when old grout becomes dislodged and causes an obstruction. As it would be unproductive to simulate such bad practice, it was decided to investigate the effect on well mixed grout, of various restrictions including a section of closely packed strands.

Two cells were constructed, one containing a number of drilled plates, the holes in the final plate being only 2.5mm diameter and representing a quite severe restriction. The second cell represented a section of 100mm duct containing thirty one 12mm diameter strands. The strands were arranged in a tight bunch and assembled in the cell so that injected grout would have to pass between the strands to emerge from the free end.

The grout pressure was monitored at the inlet to cell 1, between the two cells and at the outlet from cell 2. A number of grouts with water/cement ratios between 0.37 and 0.47 were tested in this assembly with the majority flowing quite successfully through the restrictions at reasonable pressures. The 0.37 water/cement ratio grout was virtually unpumpable and caused the maximum pumping pressure of 0.65 N/mm² (90 psi); a 0.39 water/ratio mix also caused problems and would seem likely to result in blockages as the grout soon becomes very stiff as water is filtered out.

Grouts with water/cement ratios of 0.42, 0.45 and 0.47 all flowed well even against an imposed back pressure of up to 0.45 N/mm² (65 psi). Cell 2 containing the strands should be a more severe test than anything found in a well constructed duct as the grout would normally be able to flow around rather than between the tightly bunch strands. This cell, however, caused very little pressure drop and the grout appeared to flow through easily.

In these part 1 tests the imposed restrictions to grout flow had very little effect although, obviously, any lumps within the mix or any form of debris carried along with the grout would immediately block the grout flow.

These tests support the view that to avoid blockages on site, overall cleanliness must be improved and that a suitable strainer should be installed at least whenever there is the possibility of a lumpy mix being produced. These results also suggest that within a well constructed duct assembly there should be no restrictions likely to cause a grout blockage.

In the second part of this programme, short lengths of full size ducting were grouted; after the grout had hardened, the ducts were cut open for inspection and the success of the grouting assessed.

The duct assembly consisted of two 3m lengths of 85mm bore steel ducting, joined by a 1m length of transparent, flexible plastic hose; seventeen 12mm strands were threaded into the duct. The duct assembly was supported on a steel frame and could be set-up in a hogging or sagging configuration. It was intended to use a new assembly for each test. A centre vent pipe with shut-off valve was provided and shut off valves were installed at each end of the duct. Pressure transducers were fitted at the pump, at the centre vent pipe and at each end of the duct. The grout for these tests was mixed in a '3 bag' high speed paddle mixer and pumped by a 'Mono' hand pump. A full report for these tests is included in Report No.11(8).

The first test had to be aborted because of problems with the pump. This gave an unexpected opportunity to examine the problem of removing water
and/or grout from a duct as it was decided to flush out the duct and repeat
the test using the same ducting.

The first problem with flushing out a duct is containment and disposal of
the expelled grout and slurry and one can only imagine the difficulty this
would present on site. A copious supply of water would be needed to
completely clean a duct and as the volume of water that can be pumped, at a
sensible pressure, through a duct is governed by the size of the inlet and
outlet vents it does seem unlikely that a full size duct could be cleaned in
this way. Once the water has a free passage through the duct it will flow
without removing any more grout. This is also true when air is used to
remove water from the duct. When the full bore air flow from a site
compressor was connected to the short section of ducting used in this test,
there was sufficient free air way for the air to pass without removing any
more grout or water. Obviously, in the absence of drain vents, considerable
quantities of water could remain in a duct valley or anchorage even after
the duct had been blown through with air.

Grouts with water/cement ratios of 0.39 and 0.42 were used, without
difficulty to grout hogging and sagging duct assemblies. The grouting was
carried out with care, under good conditions and strictly to specification.
It was therefore, rather disturbing to find on inspection that the ducts had
not been well filled. In the case of two tests on hogging ducts, large
voids extending almost the full length of the duct were discovered. A
single test on a sagging duct resulted in an almost completely filled duct
with only small voids. The only change in conditions for this test was the
temperature for the sagging trial was approximately 100 lower than for the
hogging trials. It is unlikely this temperature change would affect the way
in which the grout filled the duct and it is difficult to see why the change
in configuration should improve the duct filling. Unfortunately, it was not
possible in the time available to carry out any more tests on this
phenomenon and more work should be done on duct assemblies with more than
one crest and valley.

It was noted during these tests that vent pipes soon became full of grout
and were of no value once they had been sealed, it is suggested that a vent
must be maintained 'live' for a considerable time after the initial filling
of a duct if it is to serve any useful purpose bleeding air or water from
the duct.

In one test an attempt was made to regroup the duct the day after initial
filling. The vent was cleared of grout and used to feed new grout into the
duct, however, the grout would not flow into the duct even when rodded with
a stiff wire. Further investigation revealed a 'atlagmite' of the original
grout effectively sealing the bottom of the vent. This type of problem must
make the possibility of any effective regrouping very remote.

In all of these tests the grout was sampled at the pump and again when it
first issued from the duct end; on two occasions there was a suggestion that
cement was being deposited within the the duct as the grout was flowing
through. The tests showed that the water/cement ratio had increased by 0.02
as it passed through the duct, a possible cause for concern in full length
ducts if it were true.

The main technical problem to emerge from this work was how to allow
entrapped voids to move within the grouted duct towards effective vents.
Obviously it was difficult for voids to move in a thick grout and easier for
them to move in a very fluid grout with the additional problem of the thick
grout blocking the vent tubes. For the final trial it was agreed to develop a grout with very low viscosity yet still with acceptable bleeding characteristics in the hope that any entrapped voids could be satisfactorily vented from active vent pipes.

A number of trial mixes incorporating a superplasticizer were produced, the most suitable one was found to have a water/cement ratio of 0.43 with a superplasticizer dose of 0.5\% by weight of cement. When prepared in the full size paddle mixer it resulted in a FIP flow cone time of between 8-9 sec, an apparent viscosity of 4 1/2 poise and a maximum bleed of just under 2\%.

During the trial, the duct appeared to fill satisfactorily and was sealed after normal venting. A large void could soon be seen forming at the duct crest and the duct was revented. Further steady pumping of grout into the duct with the vent open produced considerable movement of grout and air along the duct towards the vent; when the vent tube appeared to contain good grout the valves were closed and the grout left to set. This test resulted in a well filled, void free duct.

This final test using very fluid grout was most encouraging; the grout remained 'live' within the duct even under a pressure of 0.2 N/mm² (30 psi) and air could move towards the high point for at least 30 minutes. This general technique and use of vent pipes is certainly worthy of further consideration. Rather than the visual check on the grout bleeding from the vent tube used in this test, an approved flow or viscosity test should be used. The visual check was only satisfactory here as the quality of the grout at the duct crest was clearly visible through the transparent section of duct and the duct was not sealed until all voids had been vented.

This section of the project, grouting full size sections of duct, has probably produced the most valuable insight into the likely cause of voids and blockages in actual prestressed ducts. Most of the following recommendations for improved site practice and further work stem from these full scale trials.

RECOMMENDATIONS

Design of ducts

Duct and tendon assemblies are incorporated into concrete structures in order that they may be prestressed; the size of tendon and duct profile is, therefore, designed to satisfy the stressing requirements of the unit. The resulting duct sizes and profiles do not necessarily form a very satisfactory passage for the injection of cement grout. However it should be remembered that steel in badly grouted ducts can corrode causing a failure of the structure and designers should give the vital operation of grouting their ducts the close attention it deserves.

An obvious problem involves strand/duct ratio; in ducts with diameters above about 50mm containing more than one strand there is unlikely to be a problem injecting the grout. Smaller ducts, particularly when they contain only one comparatively close fitting strand, leave only a small passageway for the grout which could cause problems in long ducts. Strand/duct ratios should perhaps be given more thought particularly when using the smaller ducts and some research could be directed towards this problem.
Some thought should also be given to the provision of bottom drain vents. They are not popular, being difficult to install and requiring attention below as well as above the duct during grouting. Such vents would provide the grouting contractor with his only means of draining a duct before or during grouting. A further interesting possible use for these vents would be to use one or more to inject the grout into the duct. The grout would then be able to flow towards the high vents and towards each end of the duct rather than along its full length from one end. The whole question of bottom vents is likely to be very contentious due to the practical problems involving falsework and shuttering.

Top vents require more attention in design and more care in their installation, than they at present receive. Good, adaptor saddles should be fitted to the duct and made grout tight so that mortar from the concrete cannot enter the duct; the vent hole should be drilled through the duct wall after the saddle has been fitted and should be as large as is practicable.

More care must be taken to protect vent pipes at deck level and improved methods of sealing these pipes should be devised in order that they may be easily vented and resealed.

Joints in ducting should have adequate overlap and be constructed so as to prevent any ingress of mortar during concreting. A responsible person should thoroughly check the ducts and vents immediately before concreting, possibly using compressed air to test for leaks.

Grout formulation and testing

Because of the limited range of cement water grouts investigated in this work, few recommendations can be made about the formulation of grouts in general. However, some interesting observations have been made on the work that has been done and on how it could affect site grouts. It must be stressed that these observations are based mainly on small scale trials and may not apply to full scale work.

Well mixed, plain water-cement grouts with water/cement ratios between 0.40 and 0.45 should have the required characteristics for actually pumping into and along a prestressing duct. With improved grouting techniques, it is possible that a well filled, void free duct could be produced particularly with the higher water/cement ratio grouts.

There does not appear to be the need to use admixtures to achieve good flow characteristics or to satisfy the 4% bleeding limit. However, it may be necessary to use a water reducing admixture if this limit is reduced to 2%. There is also some limited evidence that the duct filling ability of the grout may be improved by use of a superplasticizer and that entrapped air may move more freely within the ducts. One such grout has been tested with excellent results.

Apart from errors or malpractice, this work indicates that only changes in water/cement ratio significantly affect the grout properties and that within reasonable limits, factors such as cement source, temperature, mixer type and mixing time are of secondary importance.

It is possible this work has not identified the grout properties necessary for pumping along long and tortuous ducts; for instance, the pressure filtration test may not relate sufficiently to the cohesiveness of the
grout. As with grout formulation, it must be stressed that the grout tests here recommended may need careful interpretation for use in full scale work. It should also be realised that even the most sophisticated testing will not ensure trouble free grouting unless equipment and site procedures are improved and maintained at a high level.

Sensibly, the grout testing should be divided into two parts; a full series of tests before grouting starts to ensure that suitable grout can be produced from the equipment and materials available and a simple quality control test that can be carried out during the actual grouting operation.

Well in advance of grouting, samples of site mixed grout should be tested for fluidity using a simple viscometer and/or the FIP flow cone, the values established in these tests would then be used as target values in the same tests conducted during the grouting operation. Bleeding and pressure filtration should be checked using the improved tests outlined in a previous section on test methods. These last two tests, particularly the pressure filtration test, could be repeated at intervals as grouting takes place, however, these two properties should not change unless the water/cement ratio is adjusted and such a change should be detected by the regular fluidity tests.

The best site laboratory method for resolving any doubt about the actual water/cement ratio of a particular mix would be the density bottle method described in the section on test methods.

It is important that site personnel understand and trust the quality control tests that may be used. Obviously, it is equally important that the tests are carried out correctly. A test must, therefore, be "site user friendly" and the results obtained from the test should be easily understood and meaningful. Each result could perhaps be plotted on a suitable graph giving a visual indication of any variation or drift in the quality of the grout.

The single point viscometer test would seem to be the most suitable of those investigated. The test, including cleaning the equipment takes 2-3 minutes, the result is displayed on a meter and very little skill is required to carry out the test. It has been shown to provide very reliable information on the grout flow properties over a wider range of viscosities than would be possible with flow cones.

Equipment and site procedures

By far the most obvious and important recommendations that can be made to improve the quality of the whole grouting process concern the condition of the grouting equipment and site procedures.

The condition of much of the equipment seen on site is totally unacceptable and should be treated as such by the responsible engineer. Equipment, including hoses and valves should be free of all old grout. The operation and condition of all valves and connectors and methods of sealing vents must be confirmed before grouting is allowed to start. Most important, the method of metering water into the mixer must be shown to be efficient and reliable. Old wired-up pipes are not acceptable. Equipment must be cleaned regularly before any collecting grout has time to set. This means at least at the end of a 1/2 day shift, equipment should then again be inspected before grouting is allowed to continue.
An adequate, controlled and reliable supply of water must be made available, the mixer operator should not have to load the mixer tank by bucket. Washing down facilities must obviously be provided and provision made for dealing with the resulting slurry.

These points are among the most obvious to anybody observing a grouting operation and unless they are dealt with, will continue to cause problems on site. No amount of research into the formulation or testing of grouts will improve the situation, if for instance, a valve is blocked by old grout or the water/cement ratio drifts erratically due to unreliable metering of the mixing water.

These proposals may not be welcomed on site but that is a problem that must be faced. The same can be said of current site procedures; the two topics are, naturally, closely linked.

Quite simply, more time needs to be allowed for the grouting of each duct and provision made to collect grout emerging from vents. This would allow for more logical techniques to be employed. It is suggested that vent pipes should be only temporarily sealed as the duct is filled and that they should then be opened with the grout under sufficient pressure to cause it to just flow from the vents. Pressure could then be relaxed for some minutes before repeating the venting with grout again just flowing from the vents. Further research is required to establish how often this should be done and if there is any advantage in sealing the vents and pressurising the grout between venting.

If pressure is applied, water would possibly be filtered off into any voids but these voids would be unlikely to move towards a vent through the stiffer grout. Better results would probably be obtained using a more fluid grout without pressure, at least until the vents are finally sealed. The advantages of injecting grout from one or more bottom vents should be considered and the practical implications investigated.

It is important to improve the general working environment for the grouting operatives and to provide easy access for them around the structure. Above all a responsible engineer should ensure that an agreed procedure is understood by all the grouting operatives and that this procedure is then rigorously followed. This procedure must include the action to be taken in the event of a problem arising.

**SUGGESTIONS FOR FURTHER RESEARCH**

Further research should initially concentrate on the grouting of full size sections of ducting. As such work progresses, areas of research such as grout formulation, injection pressure and testing may be identified and researched as necessary.

The results obtained from the work in this project suggest that a duct can be filled more efficiently using a very fluid grout containing a superplasticizer. The ability of such a grout to fill a full range of duct sizes and configurations and to satisfy all the usual criteria needs investigation.

An improved yet practical grouting technique needs to be developed and this should include any associated site test methods.
Meaningful values for the permitted bleeding of grouts should be established. If it is found that admixtures are necessary to improve flow or reduce bleeding to an acceptable level, a full series of tests would be required.

The effect of the proposed admixtures on a range of possible cements would need to be confirmed.

Finally, probably the most difficult task will be to try to develop methods for locating any voids that may exist and to devise ways of dealing with them before the structure goes into service.

CONCLUSIONS

Observations made on site visits clearly demonstrate that current specifications are not being enforced and that the grouting operation is left almost entirely in the hands of the specialist sub-contractor who does not always appreciate the crucial objectives of his task. The same critical comments are frequently reported from site yet little is done to improve the situation. A responsible engineer should ensure that an agreed procedure is understood by all involved in the grouting operation and that this procedure is rigorously followed.

Many of the problems associated with the grouting of ducts are believed to stem from the generally unsatisfactory conditions and practices employed on site. It is important to improve the working conditions for operatives and improvements must be made to all aspects of site practice, particularly the general condition and cleanliness of equipment. Tests support the view that within a well constructed duct assembly there should be no inherent restrictions likely to cause a grout blockage, blockages only being caused by debris introduced into the duct during concreting or grouting.

Grout must be allowed to flow from vent pipes until it is considered that all voids have been vented from the duct. Further research is needed to establish the most effective method of filling and venting ducts.

In the absence of drain vents, it is unlikely that a duct could be satisfactorily flushed out with water or drained using compressed air. It has also been shown that any attempt to re-grout a duct, via a vent pipe, after the initial grout has set is unlikely to be successful.

Apart from errors or malpractice, only changes in water/cement ratio significantly effect the grout properties. In the absence of accepted site tests on the quality of the grout, it will be very difficult to impose any meaningful 'quality control' on the production of grouts. Specifications must be realistic and the tests required must be suitable for site use if there is to be any hope of enforcement. The simplest practical site test for the fluidity of grout is the FIP cone test. The most suitable overall test however, would seem to be a simple viscometer test providing a reliable check on the water/cement ratio of the grout.

The use of a superplasticizer to produce a very fluid grout can improve the duct filling potential of that grout. With this one exception, the need for admixtures has not been identified.

The present permitted value for maximum bleed of 4% is excessive, the results of this work suggests a maximum of 2% would be reasonable with no qualification on the water being reabsorbed.
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REFERENCES


FIGURE 1

EXAMPLES OF POOR GROUTING FOUND IN SOME DEMOLISHED STRUCTURES