Advances in Grout for Post-Tensioned Duct Protection – an Overview of Mixture Design and Test Methods

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Abstract

An effective protection of post-tensioned ducts against corrosion can be achieved by filling the duct with cement grout. This therefore depends on the properties of the injected grout and its ability to adequately fill and protect the duct. For many years, the grout used in such applications was simply proportioned with cement and water to achieve standard specifications, such as initial fluidity, shrinkage, bleeding, and compressive strength. Deterioration of post-tensioned concrete bridges is often linked to corrosion of steel tendon due to poor protection. Therefore, considerable progress in developing new generation of grouting materials and test procedures has been achieved. The objective of this paper is to review current technologies for specifying test procedures and mixture proportioning of grouts used to fill post-tensioned ducts.

Keywords: Cement grout, bleeding, durability, fluidity, post-tensioned.

1. Introduction

The integrity of post-tensioned bridges relies on the tensile strength of the tendons. Therefore, the protection of steel tendons against corrosion is potentially of even greater concern, since the corrosion of tendons could lead to catastrophic failure of the bridge. A few cases of tendon corrosion have come to light since the mid 1970s; and in the late of 1980s and early 1990s, a number of post-tensioned bridges were found to have corroded and failed tendons to some extend that it was necessary to replace their deck [1-5]. For example, four bridges, in Switzerland, Japan, Wales and Belgium, collapsed because of corroded and fractured tendons [6]. Unsatisfactorily injected tendons, which is caused by inadequate flow properties, excessive bleeding and sedimentation of the grout, is considered as the main reason [6]. National authorities have therefore launched various research initiatives to revise standards and improve the quality of grout [3-5]. New generation of grouting materials and test procedures to improve the durability performance have been then proposed. The objectives of this paper is to review current technologies for specifying test procedures and mixture proportioning of cement grouts used to fill post-tensioned ducts.

2. General Considerations

An adequate protection of post-tensioned ducts against corrosion is achieved through an effective grouting of the duct with cement grout. An efficient grouting may be achieved using a grout with proper properties. Indeed, cement grout intended for use in post-tensioned duct must meet several performance criteria. The ideal characteristics of grout for post-tensioning application would probably include the following:

1. Adequate fluidity to assure that smooth pumping and good filling ability can be achieved with the available placement equipment.
2. Good ability to maintain the flow characteristics at the desired level for a sufficient period of time.
3. Acceptable cohesiveness to minimize bleeding, sedimentation of solid particles, and creation of water

lenses or voids.

4. Good resistance to volumetric change to minimize shrinkage cracking.
5. Adequate strength to assure transfer of the stress, high impermeability to limit the ingress of contaminant, and good ability to provide corrosion protection.
6. Adequate resistance to frost durability that may be required in some special applications.
7. Robust formulation to limit the fluctuation of its properties due to involuntary operator error.

3. Major Advances in Cement Grout for Post-Tensioned Duct

Historically the cement grouts intended for use in post-tensioned ducts have been simple mixture of portland cement and water, with W/C specified below 0.44 [2]. On the other hand, quality control of the grout is mainly based on the flow cone and bleeding tests, which are conducted in accordance to ASTM C 939 (Standard Test Method for Flow of Grout) and ASTM C 940 (Standard Test Method for Expansion and Bleeding of Grout). With the advent of new materials and technology in the last 10 years, advances have been achieved in grouting technology.

3.1 Evolution of Materials

In the past 50 years, normal cement (ASTM Type I) has been largely used. In Japan for example, the use of normal cement (ASTM Type I) is a common practice. In North America, the use of portland ASTM Type I cement with silica fume and fly ash replacements [2], portland ASTM Type III cement with silica fume replacement is also used in some special cases [7]. In Europe, a portland cement complying with type CEM I according to ENV 197-1 shall be used [8]. However, in some member countries it is allowed to use cements with a total content of up to 20% of granulated blast furnace slag or fly ash [8]. Although a variety of materials are used worldwide, the specifications call for the use of materials with a cl^- content lower than 0.1%, by mass of cement [3, 8-11].

The partial replacement of cement by cementitious materials, called also mineral admixtures, is actually a common practice. Post-Tensioning Institute (PTI) Committee of USA recommends the use of flay ash, ground granulated blast furnace slag and silica fume [10]. The main advantage from the incorporation of such materials is to enhance rheological properties, reduce bleeding and maximum temperature that can develop during hydration; hence reduce the risk of shrinkage cracking. Because of the environmental awareness, and in order to contribute in the sustainable development, it can be predicted that the grouting technology will be shifting to the use of binary or ternary blended cements in the future.

3.2 Development of Advanced Admixtures and Test Methods

Various chemical admixtures, such as high-range water-reducer (HRWR), bleeding and sedimentation reducers, expansive agents, corrosion inhibitor admixtures, air-entraining agent, and additives able to impart favorable properties to the grout have been developed. The use of such admixtures to achieve specific properties is actually well accepted in grouting technology [1-10], but they should not contain substances in quantities, which will affect the protection performance. The use of HRWR in cement-based grout has lead to the development of low W/C high-performance grouts. On the other hand, admixtures to enhance bleeding and settlement resistance, to provide expansion in the plastic state to compensate for shrinkage, to increase the corrosion resistance, and to improve the frost durability of grout are widely used. However, the use of aluminum-based expansive admixtures arouses some debate in the industry. Since the aluminum particles react with the soluble alkalis in the cement to form hydrogen gas that cause an increase in volume of grout, some believe this can lead to hydrogen embrittlement. However, this is now less of concern and no evidence for its occurrence is generally found. On the other hand, the evaluation of a variety of post-tensioned concrete constructions in California revealed that the "elimination of the expansive admixture had no apparent effect on the quality of the grout [2]. Actually, this type of materials can be used, if necessary, in Japan and is blended in GF 1720A material. PTI don't encourage the use of such materials in post-tensioned ducts [10]. However, in Germany, for example, their use is permitted [5] and the working party reported there is no evidence to corroborate this fear [3,4]. On the other hand, the Canadian Standard (CSA) recommends that post-tensioning grout should have a maximum expansion of 5% that can be achieved through adequate dosage of aluminum-based admixtures [9]. The major advances regarding materials and test procedures achieved in this field are summarized in Table 1.

Table 1　Summary of new developments in terms of materials and test procedures

Chemical admixtures & additives		Test procedures
Material	Advantages	
• High-range water – reducer (HRWR)	• Low W/C grouts, with high bleeding and sedimentation resistance and impermeable hardened matrix with adequate protection performance can be developed • Adequate fluidity level and smooth grouting operation	• Modified flow cone with different opening orifices • Mini-slump test [11,14] • Rheological measurements with coaxial-viscometer [11,14,15,16] P-flow cone [15] • Large scale tests to evaluate the filling performance of the grout • Injectability evaluation, such as sand column test [AFNOR P 18-891] • Bleeding under pressure [10-12] • European bleeding test [17] • Accelerated corrosion test [2]
• Anti-bleeding agents	• High bleeding resistance combined with adequate fluidity level [2,7,14,19]	
• Anti-shrinkage agents	• Reduce the risk of shrinkage cracking • Enhance bond stress	
• Corrosion inhibitors	• Increase corrosion resistance [2,14]	
• Air-entraining agents	• Increase frost durability resistance of grout [1,7,14] • Reduce the water demand	
• Spirit agents	• Lower the freezing temperature of water, thus reduce the possibility of frost action [1] • Increase frost durability resistance	
• Mineral admixtures (fly ash, silica fume, etc.)	• Enhance fresh and hardened properties • Reduce bleeding [7,11,14]	
• Filler materials	• Reduce temperature rise (less cracking) • Reduce bleeding	

4. Recommended Mixtures Proportions

Researchers, cement and admixtures suppliers as well as bridges authorities have proposed various grouts with adequate fresh and hardened properties. An extensive review conducted on the subject revealed that the majority of post-tensioned grouts were proportioned with a W/C varying between 30 and 50% [1]. The working committee recommends a maximum W/C of 40% for common grouts. On the other hand, 35% W/C grouts are recommended for special cases [3,4]. In USA, the document most often referred to regarding specifications for grouts of bonded post-tensioned structures is the Post-Tensioning Manual of the PTI, which call for the use of a W/C typically lower than 44%, although in some case a W/C of up to 53% is allowed [2,10]. The Canadian

Standard CSA limits the W/C to a maximum value of 45%. On the other hand, the Ministry of Transportation and Communication of Ontario (Canada) call for providing a grout with a maximum W/C of 50% for post-tensioning ducts with length less than 45 m and 55% for ducts longer than 45 m [7,9]. German regulation recommends the use of medium fineness cement grout with a W/C ranging between 36 and 40% and containing 20 to 30% of pulverized limestone or quartz. Additives materials may be used but before their incorporation they should be tested [1]. Table 2 summarizes some recommended grout formulations.

Table 2 Recommended cement grouts for post-tensioned ducts protection

Authority	Mix proportions	Additives	Remarks
Smith, 1961 [1] Canada	• 40% W/C grout • Water-reducing • Retarder • Aluminum Powder		
Presstressed Concrete Development Group, 1961, UK [1]	• 40 – 50% W/C grouts	Should be used only if they improve grout quality	Ordinary or blast furnace cements
Bulgakov, 1961, [1] Russia	• 35 –40% W/C grouts • Plastizing agents		
Hope and Ip, 1988, Canada [7]	• 33% W/CM grout • 1% Melment F10 HRWR • 0.067%, by mass of CM • uncoated aluminum powder	10 to 15% of silica fume replacement	ASTM Type 1 cement
Lankard et al., 1993 USA [2]	• 30-40% W/C grouts • Naphthalene-based HRWR • Anti-bleed agent • Corrosion inhibitors (calcium Nitrite)	Silica fume Fine sand	It may contain styrene-Butadiene to improve the open time
Bastien et al., 1997 France [18]	• 30% W/C grout • 3.8%, by mass of cement, melamine sulfonate HRWR	3%, by mass of cement, of precipitated silica	
Bouquet, 1998, [19] Netherland	• 27-30% W/C grouts • 1% addiment EH-NS common injection aid		Ordinary Portland cement CEM I 32.5 R
Khayat et al., 1999, Canada [11]	• 38-42% W/CM air-entrained grout • 1.6% naphthalene-based HRWR • 0.03% welan gum • Coated aluminum powder	8% of silica fume	• Blended silica fume cement • Good durability to frost action

5. Recommended Properties of Grout

Some of the recommended properties of grouts that are generally considered to be suitable in achieving adequate filling of post-tensioned ducts are summarized in Table 3.

Table 3 Recommended properties of grout

Authority	Required Fluidity	Bleeding	Volume change	Strength
Smith, 1961, [1] Canada	Flow of 150 – 225% (flow table)	No visible water after 15 min	Negligible shrinkage	7 d: 22 MPa 28 d: 35 MPa
Polivka, 1961, [1] USA	20 to 24 s flow funnel (funnel with 12.5-mm opening)	Maximum bleeding of 4%	Expansion of 6 to 12%	Not specified
Prestressed Concrete Development Group, 1961, UK [1]	Not specified	Maximum bleeding of 3% after 3 hours	Maximum expansion of 8 to 10%	7d: 18 MPa
Hope and Ip, 1988, Canada [7]	12 to 15 s flow time (ASTM C 939 flow cone)	None (ASTM C 940)	Expansion of 6 to 7% (ASTM C 940)	7d: 45 MPa 28d: 60 MPa
Concrete Society TR No 47, 1994, UK [3, 4]	< 25 s after mixing < 25 s after 90 min (flow cone of 10 mm opening)	No bleeding Density variation < 10%	From 0 to 5%	> 27 MPA after 7 days
Canadian Standard, 1994, Canada [9]	< 11 s flow time (standard flow cone with 13 mm opening)	Maximum bleeding of 1%	Maximum expansion of 5%	> 35 MPa after 28 days (4 to 8% of air)
Bastian et al., 1997, [18]	22-23% flow time (Marsh cone with 10- mm opening)	None	Maximum of 2160 x 10^{-6}	
Khayat et al., 1999, [11] Canada	< 61 s flow time (modified Marsh cone with 4.5-mm opening) < 70 s after 60 min	1) Zero static bleeding 2) Bleeding under pressure < 10%	Maximum expansion of 5%	> 28 MPa after 7 days

6. Conclusions

Considerable advances in grouting materials have been achieved in the last 20 years. In terms of mixture proportion, the trend seems to be toward the design of low W/C grouts to enhance stability and mechanical properties, thanks to the technological advance in high-range water-reducer. However, the autogenous shrinkage that may occur in low W/C grouts constitutes an handicap in producing durable materials. Therefore, one should recognize that advance is needed to establish expertise on materials in order to design durable materials. It is expected that considerable attention will be focused on materials and approaches that can improve the volumetric stability of grouts in the future. The partial replacement of cement by less-reactive materials, development of ternary blended cement can be a promising issue. This help in developing environmentally friendly grouting materials with proper properties and substantial improvement in durability.

Although there is some difference of opinions regarding the suitable properties and the relative importance of these properties, it is shown that grouts with improved placement characteristics as well as higher engineering properties could be designed using admixtures and modifiers that are widely available. The difference of opinion may be due to difference in evaluation methods, which are influenced to some extend by local practices. On the other hand, the suitability of these properties relies on the type of application, grouting equipment and environmental conditions. Hence recommended properties should be regarded as guidance values and the actual properties required should be determined in accordance with the specific application and conditions at hand. It can be suggested that fluidity should be regarded as the key factor for an effective grouting. It is considered more desirable to have the duct completely filled with lower quality grout than have it partly filled with high quality one.

Various quality control test methods are developed and some of them are already included in some standard specifications. However, an urgent need results in developing an curate test method, which can be used at the end of grouting to determine the eventual presence of any voids.

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