GROUTING MATERIALS AND PRACTICES FOR CENTURY-LONG CORROSION PROTECTION OF POST-TENSIONED CONCRETE BRIDGES

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Abstract

Typically, the post-tensioned (PTd) concrete bridges have an anticipated design life or corrosion-free service life of 100+ years. This paper highlights some of the concerns associated with the grouts and grouting practices, which have resulted in a large inventory of inadequately grouted PTd systems. Then, the relevant material properties and associated performance tests to qualify post-tensioning (PT) grouts are discussed. An experimental program on the fluidity, bleed resistance, volume change, and compressive strength of three commercially available PT grouts and one in-house developed PT grout is presented. Then, a compilation of existing standard specifications for PT grouts is presented. Following this, a set of comprehensive, and stringent performance specifications for PT grouts–to enable complete filling of PT ducts–was proposed. Finally, good grouting practices to achieve century-long corrosion protection for PT systems are recommended.

Keywords: Anchorage; Bridges; Concrete; Corrosion; Grout; Post-tensioned; Strand; Tendon; Voids.

1. INTRODUCTION

Grouted post-tensioned (PTd) concrete systems are used worldwide to construct long-span segmental bridges, high-rise buildings, and other major infrastructure systems. This paper focuses on PTd bridges that are designed with the intention to achieve a corrosion-free service life of 100+ years. Nevertheless, the findings in this paper are applicable to various types of grouted PTd concrete systems. The use of inadequate grouting materials and grouting practices have resulted in premature corrosion of strands (say, at about 10 to 20 years of service)–leading to the failure of one or more tendons or the entire PTd structure[1]. This shortfall in achieving quality grouting can be attributed to the lack of awareness, and implementation of the good grouting materials and practices, and their importance to achieve the desired corrosion-free service life of 100+ years. The current practice of qualifying the post-tensioning (PT) grouts using fluidity test alone is not suitable to assess thixotropic grouts [2], because these grouts exhibit low viscosity immediately after high-shear mixing. Thixotropy refers to a time-dependent decrease in the apparent viscosity of the grout when it is subjected to a high shear mixing. Segregation/bleed test is more relevant and must be performed while assessing PT grouts [2]. Also, the performance specifications need to be improved in order to avoid the qualification of inadequate grouts and enable the qualification of only those grouts that are flowable and segregation/bleed resistant to enable complete filling of tendon ducts and thereby help achieve 100+ years of corrosion free service life. It must be noted that the geometry of tendon systems is such that even a small void exposing a few millimeters of strand surface, especially at the anchorage regions, is sufficient to cause severe corrosion and catastrophic failure of PTd systems within 10 to 20 years of service. Hence, complete filling of ducts with grout is very important to achieve the desired corrosion-free service life of 100+ years. This paper provides guidelines on good grout materials and grouting practices to achieve such long service lives.

The remaining paper is arranged as follows: First, the problems due to inadequate grouting materials and grouting practices are presented with an emphasis on the need for good grouting and complete filling of the duct. Then, the desirable material characteristics of grouts are discussed, followed by a list of performance tests. Then, results from an experimental program investigating the performance of various grouts are presented. Then, a set of comprehensive performance specifications and a list of good grouting practices to help achieve century-long corrosion protection for PTd systems are provided.

2. CONCERNS WITH SOME GROUT MATERIALS

Before the early 2000s, plain cement grouts (PCG) and site-batched-grouts (SBG) were used for the majority of PTd bridges worldwide [3]. Moreover, SBGs are still being used in many developing countries. These grouts tend to experience a bleed up to 20 % by volume and the bleedwater rises to the higher points in the ducts [4]. Also, the narrow interstitial

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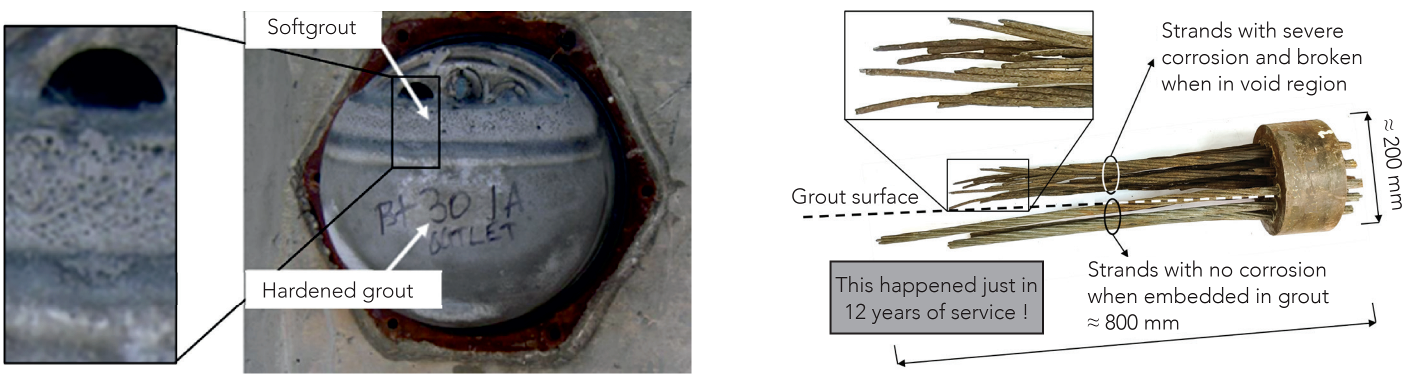
spaces between the seven wires of the strands and between the congested strands can act as capillary pathways, and thereby promote further bleeding. Bleedwater formed in this manner can accumulate and then eventually evaporate or get absorbed into the underlying grout, leading to the formation of air voids (typically at and near the anchorages). Due to these voids and the intentional and unintentional openings in the anchorage regions (say, the grout ports, air vents, and the space between the pieces of wedges), the grout and embedded strands get exposed to oxygen, moisture, chloride, and CO_2. As a result, corrosion of strands can initiate and sustain at the interface of void and grouted regions inside the duct[1]. The formation of bleedwater, and the associated voids have been extensively reduced after the development of pre-packaged thixotropic grouts[5]. However, these prepackaged grouts can also sometimes bleed and segregate, as shown in Figure 1(a) [6]. Also, it is evident that the segregation of grout has led to the formation of pockets of softgrouts [see the zoomed image in Figure 1(a)] – leading to variations in the physical and chemical properties (pH, density, porosity, and chemical composition) of the grout at various locations within the cross-section of the duct. Softgrout represents a layer of low-density material on the grout surface, exhibiting high permeability and low strength. The reason for the formation of softgrout is the segregation of the inert filler particles from the grout system. The grout segregation may lead to grout deficiencies such as high moisture, chloride, and sulfate contents [7]. Therefore, the strands embedded in them will have differences in corrosion potentials, which may accelerate the corrosion of strands due to the formation of macrocells [8]. Figure 1(b) shows a photo of a corroded and broken tendon anchorage collected from a 12-year-old PTd bridge. It can be observed that the top strands were severely corroded; whereas, the bottom strands were not corroded. The root cause for corrosion was the presence of voids at the top region of the duct, resulted from the use of inadequate grout. In addition, chemical analysis revealed the presence of high chlorides (0.12 % bwob) in the grout, possibly because of the chloride-contaminated water used for mixing the grout, which is about 50 % more than the permissible acid-soluble chloride for prestressed concrete of 0.08 % bwob, as per ACI 222R-01 [9].

3. CONCERNS WITH SOME GROUTING PRACTICES

Figure 2 provides photographic evidence and briefs some of the inadequate grouting practices being followed at many construction sites.

1. In some projects, it is still a practice to flush the PT ducts with water. This is done after stressing the strands and before grouting to clean the duct, and to wet the inside surface of the duct (to promote the flow of grout), and/or to assess the watertightness of the duct. However, due to construction delays, water can be left within the duct for many days. Also, it is very challenging to entirely remove the water from the interstitial spaces (between the wires of a strand and between adjacent strands). The remaining water can get mixed with the cementitious grout, lead to increased bleeding, and promote corrosion of strands [10]. Situation can get worsened if this flushing water has more chlorides than the allowable limits. Figure 2(a) shows a case, where water mixed with rust is flowing out of a tendon that was flushed with water. This practice was probably required for ensuring the flow of the plain ordinary Portland cement (OPC) grout, which is not in use today. Today's thixotropic grouts do not need such flushing of ducts with water prior to grouting, and the use of such flushing practices can be detrimental.

2. Figure 2(b) shows a photo of an anchorage region from a PTd concrete element (say, bents or pier caps) of a metro bridge in a coastal city. Note that the schematic shows the half-filled and semi-circular grout face with the bottom strands embedded in the grout and top strands exposed or un-grouted. Also, it is evident that the anchorages are inadequately grouted and not protected with caps;

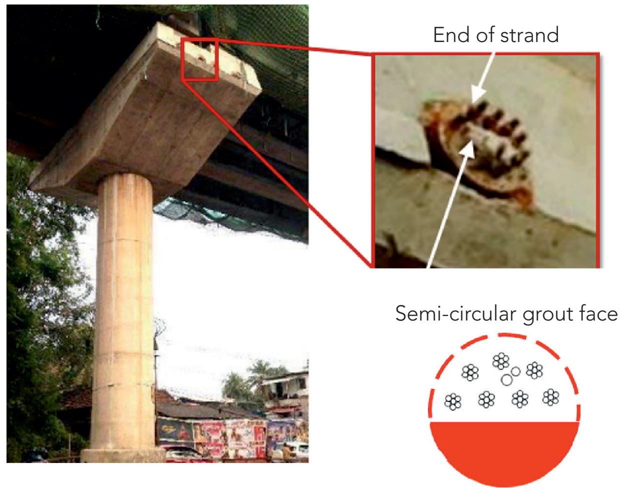


(a) Segregation and softgrout formation at the anchorage– photo taken after removing end cap[6]

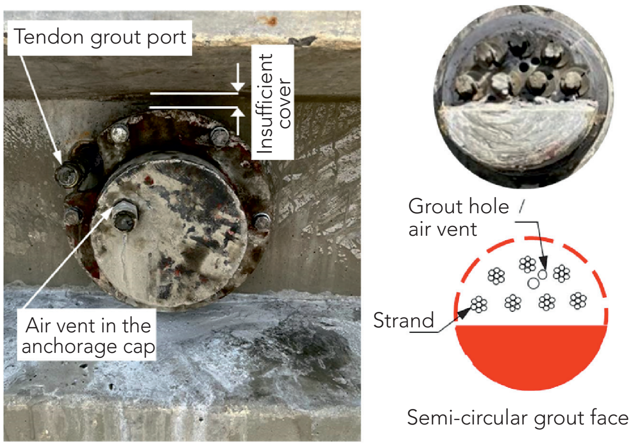
(b) Severely corroded strands within the anchorage of a 12-year-old PTd bridge

Figure 1: Problems in PTd systems due to inadequate grout materials

(a) Corrosion of strands due to flushing the PT ducts with water before grouting



(b) Inadequate sealing of the anchorage exposing the strands



(c) Improper positioning of tendon grout port and air vents due to insufficient width of anchorage recess leading to inadequate grouting

(d) Polymeric coating applied over cementitious caps and exposed to sunlight

(e) Anchorage recess filled with poor-quality concrete

Figure 2: Inadequate grouting practices followed at the site

hence, exposing the metallic components to the corrosive environment during the long construction periods, which is adequate for chloride contamination. Also, these cementitious materials are highly hygroscopic and could attract moisture from the surrounding air and retain humidity [11] – facilitating the corrosion of strands, especially the portions at the voids and the gripped portions inside the wedges.

3. Figure 2(c) shows a situation, where the width of the anchorage recess was insufficient and hence, the grout port was not placed at the top (i.e., 12 o'clock position). This can lead to incomplete filling of the duct [see Figure 2(c)]. Likewise, the air vent in the anchorage cap was positioned at a level lower than the 12 o'clock position of the anchor head – leading to incomplete filling of the anchor head. Both these can result in air voids and associated corrosion well before the target service life.

4. Figure 2(d) shows a case with waterproofing coating applied on cementitious cap at the anchorages and not covered with concrete. Typically, such coatings would develop microcracks and lose their efficiency within a few years (due to exposure to sunlight/UV rays) [12] after which they would allow the ingress of moisture/chlorides and carbonation leading to accelerated corrosion of the wedge-gripped portions of the strands. Also, the coatings must be reapplied every few years (considering their service life of coatings) unless protected from the sunlight (say, by covering with concrete). Considering the change in the maintenance policies and associated personnel, it is very challenging to monitor and ensure routine re-coating of the anchorage caps with waterproofing systems and achieve 100+ years of corrosion-free service life.

5. Figure 2(e) shows the photo of a PTd metro bridge with honey-combed and porous concrete filling at the

anchorage recess, which can provide easy pathways for the moisture and chlorides to ingress, carbonation to occur, and promote the corrosion of strands, especially the wedge-gripped portion.

6. Figure 2(e) also shows that the anchorages are placed at or below the expansion joints without proper detailing for the rainwater runoff – resulting in moisture attack.

7. Filling of tendons from the end anchorages is a common practice. Such practice can often result in incomplete filling of the duct due to the downward flow of grout leading to the formation of entrapped air voids[13].

Ideally, the anchorage can be fully grouted; encased in non-metallic or metallic caps; sealed by a waterproofing membrane; then covered with concrete pour backs[14]. Such practices can prevent the entry of moisture, chlorides, CO_2, and other deleterious elements into the tendon system. Figure 3 shows a good practice of covering the anchorage with non-metallic caps. Metallic caps can be avoided and transparent acrylic caps may be used to ensure good visibility of the grout filling at the anchor heads. Also, metallic caps may corrode in the long run due to possibly less cover concrete. In addition, the deck slab should be designed and constructed to prevent the flow of rainwater into the anchorage region[15]. Providing such multi-level protection will prevent the corrosion of anchorages and tendons. However, it was observed that many of these protection systems are largely neglected on many structures and can lead to severe corrosion of strands within about 10 to 15 years[16,17]. Figure 4 shows a list of PTd bridges that had experienced premature tendon corrosion or failure due to inadequate grouting materials and practices.

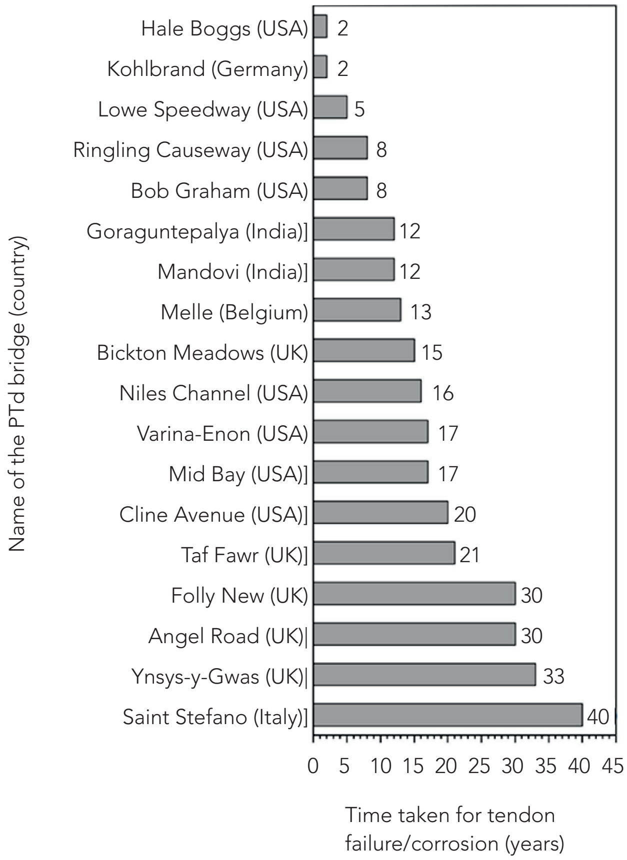


Figure 4: Time taken for tendon failure/corrosion of PTd bridges [adapted from Mohan *et al.* (2021)[16]]

4. RECOMMENDED GROUT MATERIALS AND QUALITY CONTROL TESTS

OPC is the most widely used binder in PT grouts. The surface area and particle size distribution of OPC influence the rheological and hardened properties of the grout. OPC with a

(a) Non-metallic anchorage cap

(b) Non-metallic anchorage caps kept well within the recess to be filled with reinforced concrete

Figure 3: Multi-level corrosion protection system for anchorages[14]

higher surface area can result in higher packing density [18]. PTI recommends OPC with a Blaine's surface area between 300 and 380 m^2/kg for PT grouts [19]. High-performance grouts can be customized by substituting OPC with supplementary cementitious materials (SCMs) such as fly ash, silica fume, metakaolin, and blast furnace slag. The performance of PT grouts depends on the type and fineness of the SCMs used, and hence the combinations and proportions of these materials are paramount [12]. In addition, air entrainers, corrosion inhibitors, expansive agents, superplasticizers, shrinkage-reducing agents, viscosity modifying agents, inert fillers, etc., can be used in a balanced combination to achieve high-quality grout. The quality of PT grouts can be assessed by certain performance tests and is presented next.

A good quality PT grout should possess adequate, i) fluidity and fluidity retention, ii) resistance to bleed water formation, iii) resistance to softgrout formation, iv) resistance to shrinkage or volume change, and v) compressive strength [16]. The quality control test methods and the acceptance criteria should be stringent enough to qualify only good quality grouts. A set of routine qualifying test methods for grouts are discussed in this section, along with the results from an experimental program investigating the performance of four PT grouts on the basis of only the performance tests for routine quality control in the field.

4.1 Materials and methodology

In this study, three commercially available and one in-house developed PT grouts were tested for their fluidity, bleedwater volume, softgrout volume, volume change, and compressive strength. The in-house grout was developed through a research project supported through the IMPRINT India scheme of Government of India and is named as 'TendonFill' (denoted as TF, herein) [20]. Table 1 provides the properties of the various ingredients used in TF [16]. Table 2 shows the mixture proportion of the four PT grouts tested. A custom-made high-shear mixer with a maximum speed of 3000 rpm was used for mixing the grouts as shown in Figure 5. The temperature of the water used for mixing was maintained at ±15°C, and the ambient temperature was maintained at ±25°C.

Table 1: Properties of various ingredients used for making TendonFill (TF)

PROPERTY	HIGH-RANGE WATER REDUCER	VISCOSITY MODIFYING ADMIXTURE	SHRINKAGE REDUCING ADMIXTURE
Form	Powder	Powder	Powder
Colour	Yellow	White	Brown
Odour	None	None	Pungent smell
Chemical family	Polycarboxylic ether (PCE) based	Hydroxyethyl methylcellulose (HMC)	Glycol based
Density (kg/m³)	450	1300	1600
pH (at 20°C)	6.5 - 8.5	6 - 8	6 - 7
Maximum drying loss (%)	2	1	2

Table 2: Composition of four PT grouts used in this study

MATERIAL	QUANTITY (kg/m³)			
	PLAIN CEMENT GROUT (PCG)	SITE-BATCHED GROUT (SBG)	TENDONFILL (TF)	PRE-PACKAGED COMMERCIAL GROUT (PPG)
Ordinary Portland cement	1300	1300	935	Proprietary; Data not available
Class-F fly ash 1	0	0	311	
Class-F fly ash 2	0	0	311	
Water	572	585	420	
High-range water reducer	0	0	1.43	
Viscosity modifying admixture	0	0	0.63	
Plasticized expansive admixture	0	5.85	0	
Shrinkage reducing admixture	0	0	31.7	
Water-to-binder ratio	0.44	0.45	0.27	0.32

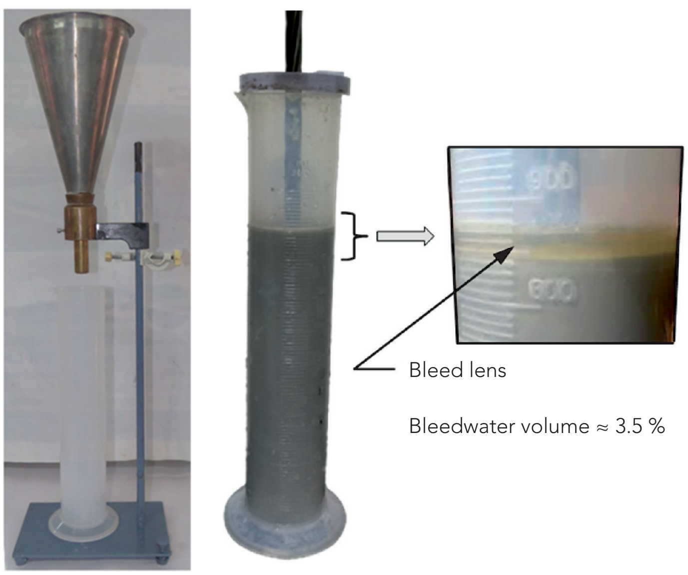
Figure 5: Custom made high-shear mixer

4.1.1 *Marsh cone test as per EN 445:2007* [21]

The selection of grout with suitable viscosity is essential to achieve complete filling of the duct. The fluidity of grouts was assessed by measuring the efflux time using the marsh cone test specified in EN 445:2007 [21]. Efflux time is the time required for a fixed quantity of grout to flow through an orifice and is a function of the viscosity of the grout. Figure 6(a) shows the photograph of the marsh cone test setup. A 1700 ml of grout mix was placed into the marsh cone, and the time required for 1000 ml of grout to flow through the orifice was measured as the efflux time. The efflux time was measured immediately after mixing (say, 1 minute) and after 30 minutes. The drawback of the test is that it qualifies the grouts only based on their fluidity characteristic. For instance, PCG or SBGs exhibiting excellent fluidity could pass the marsh cone test; however, they may exhibit significant bleeding, which is detrimental to the tendon system. So, the marsh cone test alone shall not be used as the screening test for grouts [2]. In addition to fluidity, the bleed resistance of the grouts should be assessed and used for screening the grouts, which is explained in the next section.

4.1.2 *Wick-induced bleed test as per EN 445:2007* [21]

Bleeding refers to the segregation of water from the cement or binder particles of the grout mix. A good grout mix should have adequate resistance against bleeding and can be assessed by the wick-induced bleed test specified in EN 445:2007 [21]. This test gives an estimate of the bleedwater volume taking into account the wicking action through the interstitial space between the wires of the strands. Figure 6(b) shows the photo of the test setup. A 900 ml of grout was placed into a graduated cylinder comprising a 15.2 mm diameter strand placed inside it. The bleedwater accumulated at the top of the grout surface was measured using a micro-pipette after 3 hours. The bleedwater volume was represented in percentage with respect to the initial volume of the grout.



(a) Marsh cone test setup

(b) Wick-induced bleed test setup

Figure 6: (a) Marsh cone test setup to measure fluidity and (b) Wick-induced bleed test setup to measure bleedwater volume

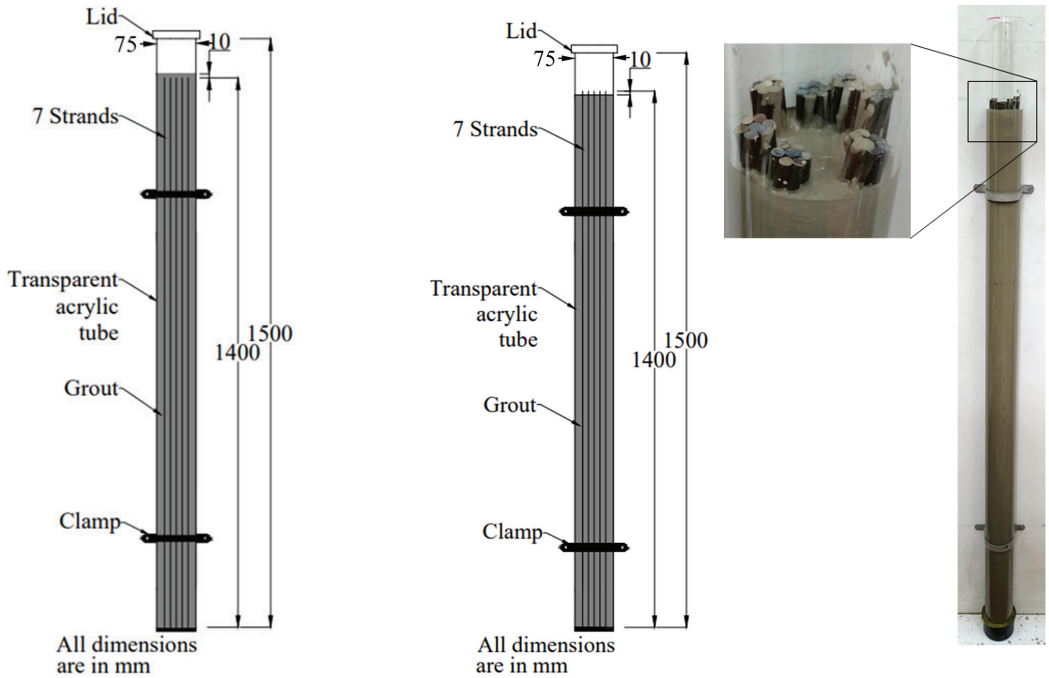
4.1.3 *1.5 m vertical tube test as per fib Bulletin 20:2002* [22]

PT grouts are susceptible to more bleeding in large-scale test setups and can be assessed using the 1.5 m vertical tube test specified in fib Bulletin 20 [22]. Figure 7(a) shows the schematic of the test setup. The grout was placed in the tube at a uniform flow rate using a small diameter tremie up to 1.3 m. The grout filling was then paused for 20 minutes to allow the entrapped air, if any, to escape. Then, the remaining 20 mm of the tube was filled. The bleedwater volume after 3 hours and the volume change after 24 hours was represented in percentage with respect to the initial volume of the grout.

This test method specifies grout filling to be 10 mm above the strand level. But, in a PTd bridge system, the tendons will emerge outside the duct through the anchorages. This shortfall questions the realistic representation of this test method in simulating the field conditions. The issue with this test method is the slow rise of the entrapped air, especially in case of thixotropic grouts, from the interstitial spaces between the wires and the strands. By that time, the grout would have become more viscous and would not allow the air to escape freely – leaving the formation of air bubbles at the top of the grout surface. In fact, this is not the case in the real tendon systems, where the narrow gaps between the wires of the strands provide an easy escape route for the trapped air. This test was recommended in fib Bulletin 20 [21], formulated in the early 2000s (about 20 years ago). During that time, non-thixotropic grouts were commonly used for PT applications. But, nowadays, pre-packaged thixotropic grouts are used, and screening these grouts based on this test method may lead to a false-positive assessment. Hence, this test may not be adopted for testing thixotropic grouts for which the modified test method presented next is recommended.

4.1.4 *Modified 1.5 m vertical tube test*

Figure 7(b) shows the schematic and photo of the modified version of the 1.5 m vertical tube test. The grout was placed into the tube at a uniform flow rate using a small diameter tremie up to 1.3 m. The bleedwater volume after 3 hours and the volume change after 24 hours was represented in percentage with respect to the initial volume of the grout. The modified way of maintaining the grout at a lower level than the strand will allow the entrapped air to escape through the interstitial



(a) 1.5 m vertical tube test setup with immersed strands

(b) Modified 1.5 m vertical tube test setup with strands protruding out of grout surface

Figure 7: Vertical tube test setups to measure the bleedwater volume

space between the wires in strands, preventing the delayed entrapment of air bubbles at the top of the grout surface.

4.1.5 *Softgrout test*

The formation of softgrout was assessed by conducting a wick-induced bleed test, as explained in Section 4.1.2. softgrout (if any) can be visually identified by the presence of a layer of very porous grout material on the grout surface. The height of softgrout lens after 24 hours of placing the grout in the cylinder was measured and represented in percentage with respect to the initial height of grout cylinder, which was then represented as % volume.

4.1.6 *Shrinkage test*

The shrinkage of grouts was determined as per the procedure specified in ASTM C157:2016 [23]. Prisms (25 × 25 × 285 mm) were cast and the total and autogenous shrinkage were monitored until the deformations became negligible. The specimens were covered with a polyethylene sheet immediately after casting to prevent moisture loss. The length of the specimen after 24 hours was taken as the reference length. For determining the autogenous shrinkage, the specimens were wrapped with two layers of aluminium foil tape. The specimens were stored at 25°C and 65 % relative humidity for the entire test duration and shrinkage was measured using an extensometer with a least count of 0.001 mm.

4.1.7 *Compressive strength test*

Compressive strength is predominantly used as one of the qualifying criteria for the selection of grouts, and it was considered to provide an indication of the grout quality with respect to its bond and shear strength. The primary function of grout in a PT system is to provide a protective environment for the strands from corrosion, and only a limited amount of compressive force transfer will occur through the steel-grout interface. Table 3 shows that the recommended compressive strength at 28 days for grouts ranges from 30 to 35 MPa. However, grouts with a compressive strength at 28 days of greater than 80 MPa are being produced and marketed – due to a lack of awareness among the manufacturers on the negative impacts of such grouts. These high-strength grouts will produce high heat of hydration and can adversely affect the shrinkage and later age mechanical properties. For example, the heat of hydration at 24 hours for a M80 grade mix could be twice higher than a M40 grade mix. Cubes of 50 mm were used for measuring the compressive strengths at curing periods of 3, 7, and 28 days to ensure the attainment of minimum compressive strength to carry the in-service compressive loads. Cubes of 50 mm shall be recommended rather than larger ones (say, 100, and 150 mm), as the larger ones are more prone to plastic shrinkage cracking. Figure 8 shows photos of cubes cast to determine the compressive strength of grouts at the site and in the lab. Severe plastic shrinkage cracks can be observed on the surface of the 150 mm cube cast at the site, whereas no cracks were seen on the surface of the 50 mm cube cast in the lab.

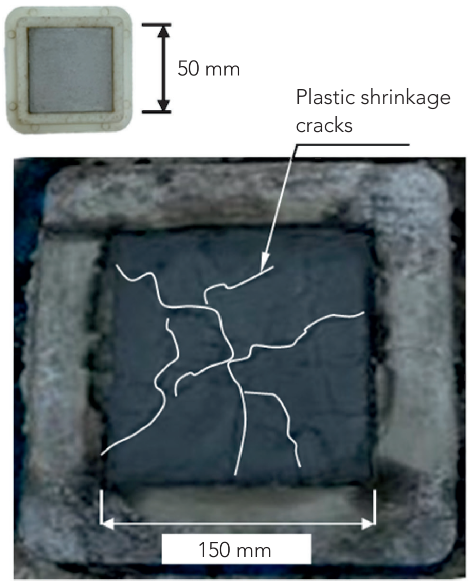


Figure 8: Cubes cast in the lab (50 mm size) and at the site (150 mm size) for compressive strength tests

4.2 RESULTS AND DISCUSSION

4.2.1 *Fluidity and fluidity retention*

Figure 9 compares the efflux time of the grouts measured immediately ($T_{e,1}$) and at 30 minutes ($T_{e,30}$) of grouting. The acceptance criterion specifies that $T_{e,1}$ should not be more than 25 seconds as per EN 447:2007 [24], and all the four grouts have satisfied the criterion. PCG and SBG exhibited sufficient fluidity because of their high w/b ratios. At the same time, TF and PPG showed excellent fluidity despite their low w/b ratios because of their thixotropic property (shear thinning behavior). Also, the enhanced fluidity of TF can be due to the ball bearing action of the spherical flyash particles [16]. When it comes to fluidity retention after 30 minutes of grouting ($T_{e,30}$), PCG and SBG could not satisfy the acceptance criterion specified by EN 447:2007 [24]. This criterion specifies that the percentage change in fluidity should not be more than 20 % from immediately after mixing to 30 minutes after mixing. The $T_{e,30}$ of PCG and SBG are ~25 % and ~33 % more than $T_{e,1}$, possibly due to the thickening of the grout mix due to hydration as time passes. On the other hand, TF showed excellent fluidity retention owing to the incorporation of shrinkage reducing admixture (SRA) in its mix, that decreases the surface tension of the liquid phase. In this experimental program, the fluidity retention of the grouts after 30 minutes only is determined. However, fluidity retention must be checked up to 3 hours after grouting since the grouting operations could last for a couple of hours after mixing.

4.2.2 *Bleed resistance*

Figure 10 compares the bleedwater volume of all four grouts measured after three hours of grouting. The results show that PCG and SBG exhibited severe bleeding in wick-induced and 1.5 m vertical tube tests and failed to comply with the acceptance criteria mentioned in Table 3. However, TF and PPG showed excellent bleed resistance (zero bleedwater volume) in the two tests. The poor performance of PCG and SBG is because of the high w/b ratios (PCG with 0.44 and SBG with 0.45). TF exhibited zero bleeding due to the incorporation of viscosity modifying admixture (VMA) in its mix, which increased the viscosity of the grout and thereby reducing the settling of cementitious phase. Also, it can be observed that the bleedwater volume for the same grout increases from one test to the other. The increase in the bleedwater volume is due to the presence of strands in the test setup. The narrow interstitial spaces between the seven wires of the strand act as capillary pathways and promote additional bleeding. Also, the quantity of bleedwater will be more in large-scale test setups than in small-scale test setups. In addition, it is important to note that PCG and SBG have satisfied the acceptance criterion for fluidity ($T_{e,0} \leq 25$ seconds); however, they exhibited the highest bleed (~ 8 %). Hence, the marsh cone test alone shall not be used as the screening test for grouts. In addition to fluidity, the bleed resistance of the grouts should be assessed and used for screening the grouts.

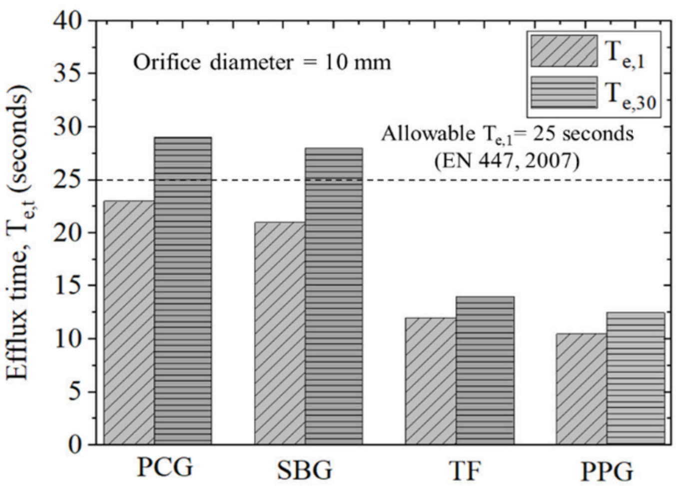


Figure 9: Efflux time of PT grouts

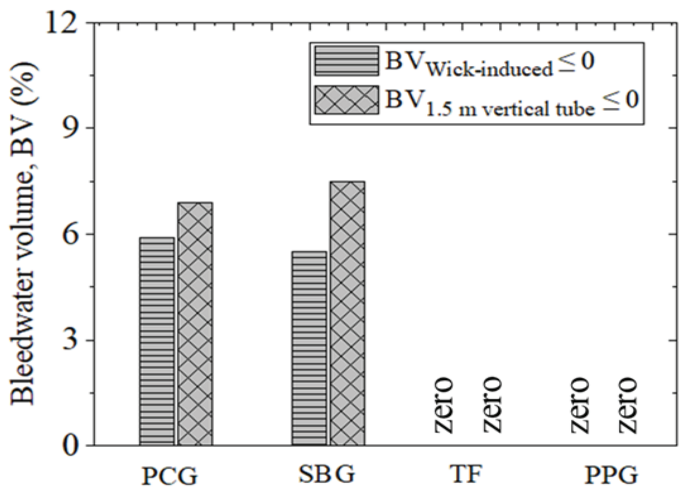


Figure 10: Bleedwater volume of PT grouts

4.2.3 *Volume change and softgrout assessment*

The resistance to volume change is an important property of the grout and is to be maintained within a specified range around zero to completely fill the tendon duct. Figure 11 shows the comparison of volume change determined from the 1.5 m vertical tube test. PCG and SBG exhibited severe negative volume change because of the bleeding and segregation of the constituent ingredients. Also, PCG and SBG failed to comply with the acceptance limit specified in the fib Bulletin 20 [22] (i.e., -1 % ≤ ΔV ≤ +5 %). TF and PPG showed negligible volume change and satisfied the acceptance limit. The negligible volume change of TF and PPG can be attributed to their thixotropic behavior. The viscosity of the mixes increases with time, and hence reducing the settling of the cementitious phase. In addition, the incorporation of VMA in TF increased the viscosity of the grout and thereby reducing the settling of cementitious phase leading to a negligible volume change.

Figure 12 shows the shrinkage of the PT grouts. PTI specifies that shrinkage at the end of 1 day should be less than 0.1 % and at the end of 28 days should lie within -0.2 to +0.2 %.

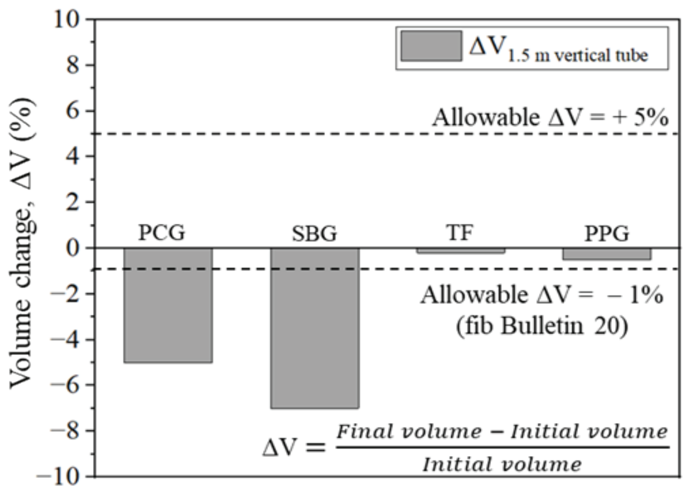


Figure 11: Volume change of PT grouts

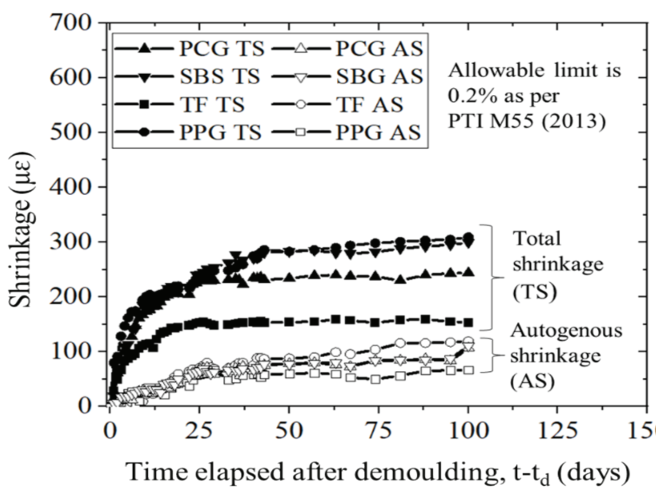


Figure 12: Shrinkage deformation of PT grouts (t_d = 1 day)

All four grouts are within the acceptable limit specified by PTI M55:2013 [19]. PPG exhibited more total and autogenous shrinkage among the grouts. TF showed the least shrinkage among the grouts and the reasoning is due to the use of SRA in its mix. SRA can reduce the surface tension of the liquid phase in the fresh grout resulting in reduced shrinkage. The lesser the surface tension of the liquid phase in the capillary pores, the less will be the shrinkage [16]. All four PT grouts did not exhibit any softgrout formation.

4.2.4 *Compressive strength*

Figure 13 shows the 50 mm cube compressive strength of all grouts at 3, 7 and 28 days of curing. All grouts, except SBG, satisfied the minimum recommended 28 day compressive strength of 35 MPa as per the PTI M55.1-12:2013 [19]. A w/b ratio of about 0.45 and the addition of plasticized expansive admixture have resulted in a porous microstructure with a lower compressive strength at 28 days (see inverse triangular markers in Figure 13).

5. RECOMMENDED PERFORMANCE SPECIFICATIONS FOR GROUTS

Table 3 provides a comparison of the performance specifications proposed by various standards (EN 447: 2007 [24]; PTI M55.1-12: 2013 [19]; fib Bulletin 20: 2002 [22]; MORTH: 2013 [25]; IRS: 2003 [26]; IS: 1343 (2012) [27]; JSCE 2007 [28]) on PT grouts. The present study developed a set of stringent and comprehensive performance specifications and is provided in the last column of Table 3. The dashed line in each column indicates the absence of the specification of that parameter.

The specification for fluidity (efflux time immediately after mixing, $T_{e,1}$) ranges from 5 to 30 seconds and has been recommended in a few standards. However, specifications for fluidity retention is provided only in PTI M55.1-12: 2013 [19]. As mentioned earlier, the PT grouts should not be qualified based

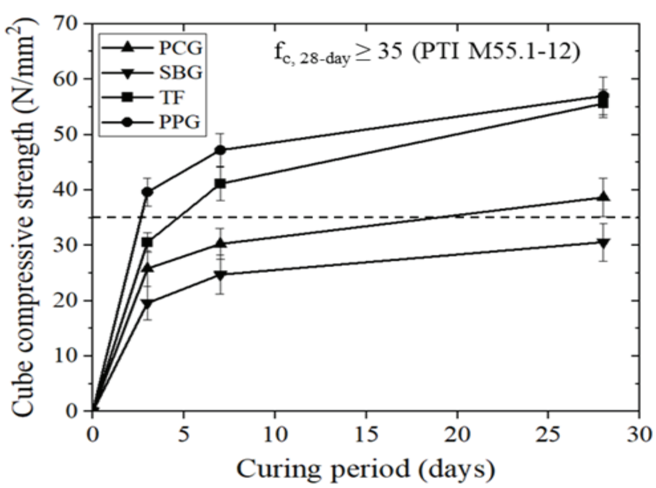


Figure 13: Compressive strength of PT grouts

Table 3: Existing and recommended performance specifications for post-tensioning grouts

PARAMETER	EN 447 (2007) [24]	PTI M55.1-12 (2013) [19]	FIB BULLETIN 20 (2002)[22]	MORTH (2013) [25]	IRS (2003) [26]	IS: 1343 (2012) [27]	JSCE (2007)[28]	RECOMMENDATION BY AUTHORS		
								SPECIFI-CATION	QUALIFI-CATION TEST	QUALITY CONTROL TEST (QC)
Efflux time immediately after mixing, $T_{e,1}$ (s)	≤ 25	5 to 30	≤ 25	-	-	-	-	≤ 25	✓	✓
Efflux time at 30 minutes, $T_{e,30}$ (s)	1.2 $T_{e,1}$ to 0.8 $T_{e,1}$ and ≤ 25	-	-	-	-	-	-	≤ 25	✓	×
Efflux time at 180 minutes, $T_{e,180}$ (s)	1.4 $T_{e,1}$ to 0.8 $T_{e,1}$ and ≤ 25	-	-	-	-	-	-	≤ 30	✓	×
Bleedwater volume at 3 hours, $BV_{Wick\text{-}induced}$ (%)	≤ 0.3	Zero	≤ 0.3	≤ 0.3	-	-	≤ 2.0	Zero	✓	✓
Volume of softgrout at 24 hours, $V_{softgrout}$ (%)	-	-	-	-	-	-	-	Zero	✓	✓
Bleedwater volume at 3 hours, $BV_{1.5\ m\ vertical\ tube}$ (%)	-	-	≤ 0.3	-	-	-	-	Zero	✓	×
Volume change at 24 hours, $\Delta V_{1.5\ m\ vertical\ tube}$ (%)	-	-	-1 to +5	-	-	-	-	-0.2 to 0.2	✓	×
Shrinkage $\Delta L,_{1\ day}$ (%) $\Delta L,_{28\ day}$ (%)	- -	0 to 0.1 -0.2 to 0.2	- -	- -	- -	- -	- -	0 to 0.1 -0.2 to 0.2	✓	×
50 mm cube-compressive strength, $f_{c',\ 7\ day}$ (MPa)	≥ 27	≥ 21	≥ 27	≥ 27	≥ 17	-	≥ 20	≥ 21	✓	×
50 mm cube-compressive strength, $f_{c',\ 28\ day}$ (MPa)	≥ 30	≥ 35	-	≥ 30	-	≥ 27		≥ 35	✓	✓

"-" indicates lack of standard specification; "✓" indicates a test that is required to perform; "×" indicates a test that is not required to perform;
EN - Euronorms; PTI - Post-Tensioning Institute; fib - Federation of Structural Concrete; MORTH - Ministry of Road Transport and Highways;
IRS - Indian Railway Standards concrete bridge code; IS 1343 - Indian Standard for Prestressed Concrete; JSCE - Japan Society of Civil Engineers.

on only the fluidity (efflux time) criterion. As discussed earlier, bleedwater volume is one of the most critical parameters for PT grouts, and MORTH:2013 [25] recommends a maximum allowable bleedwater volume of 2 % - indicating allowing smaller air voids at the anchorage regions. However, allowing smaller the air void means the possibility of smaller anode-to-cathode ratio, which can increase the corrosion rate at the possible anode locations. Hence, no voids should be allowed to form; and hence, bleedwater volume must be maintained at zero. This is in agreement with the PTI M55.1-12: 2013 [19] recommendation of bleedwater volume = 0 %. Another key observation is the formation of softgrout due to the segregation of inert or less reactive materials in grout, the high fluidity of fresh grout, and delayed setting. However, most standards do not recommend any specifications for softgrout. The authors propose to conduct the wick-induced bleed test and measure the volume of softgrout formed, if any, and grouts with softgrout formation should not be used.

Dimensional stability of grout is also very important to consider. For this, the key parameters are volume change and shrinkage.

The fib Bulletin 20 [22] published in 2002 recommends a 1.5 m vertical tube test for PT grouts and an acceptable range of volume change of -1 to +5 %. This was published in 2002 and at that time the use of expansive agents in PT grouts was common. However, such practices have led to significant restraint shrinkage (due to the presence of strands) and cracking of grouts when they are placed in tendons. Nowadays, technology has improved and shrinkage-compensating and non-shrink grout materials are available; and hence, this specification can be made more stringent (say, -0.2 to +0.2) and volume change and shrinkage induced cracking of grout can be reduced.

In terms of mechanical properties, Table 3 shows that the recommended 28 day compressive strength for grouts ranges from 30 to 35 MPa. Note that the primary function of grout in a PT system is to provide a protective alkaline environment for the strands from corrosion, and hence, the strength of the grout need not be more than the adjacent concrete. In addition to good grouting materials, good tendon profiles and grouting practices are equally important to ensure complete filling and hence, the durability of PTd tendons; and are presented next.

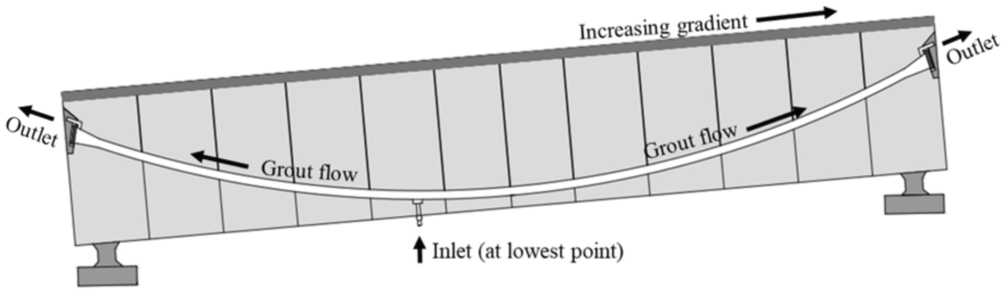
6. RECOMMENDED GROUTING PRACTICES

Good grouting practices ensure complete filling of the ducts and anchorages, preventing unwanted voids and associated corrosion. A few good grouting practices to achieve century-long protection of PTd concrete systems are as follows:

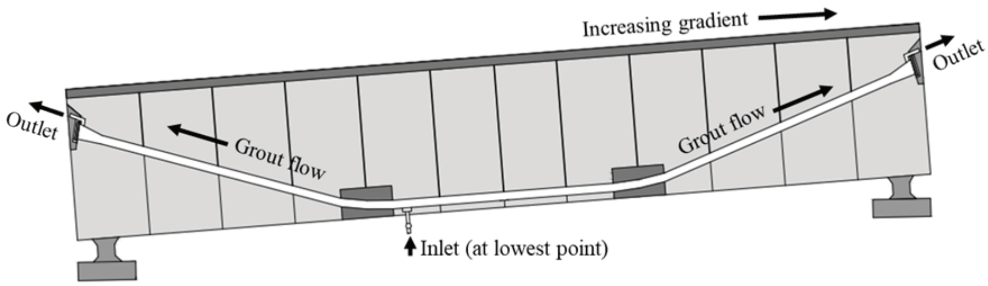
1. The position of grout inlets are crucial in preventing air voids. The grouting of draped or harped tendons shall be in one direction, starting from the lowest point of the tendon profile, as shown in Figure 14(a) and (b). This approach will facilitate the upward movement of grout inside the duct, prevent rolling and entrapment of air, and help ensure complete filling of the duct. Also, an adequate quantity of grout must be discharged from the grout pump to ensure the grout has completely filled the duct[10].

2. Avoid filling the PT ducts with water before grouting, as shown in Figure 14(c). Flushing tendons will leave excess water in the duct, which can adversely affect the grout properties and result in excessive bleeding and segregation. The grouting operation should be carried out by keeping the tendons and ducts in a dry state. If necessary, hot compressed air can be blown through the duct to achieve this [10]; until the relative humidity of the exiting air is sufficiently low (or dry).

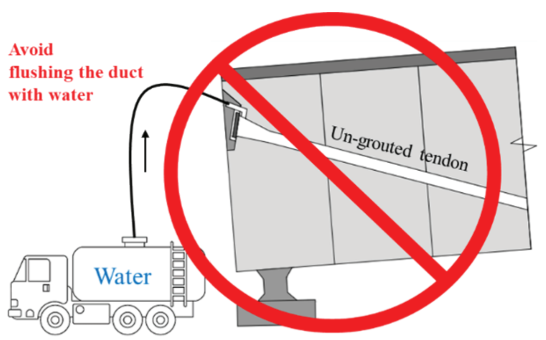
3. Preventing the entry of moisture, mainly from rain and runoff water is important to prevent corrosion and achieve durability. For this, it is recommended to design the anchors/bearing plate at a face-down position rather than keeping them horizontal [10]. The tendons will curve over and head down to the anchor in such an arrangement, as shown in Figure 14(d), and will prevent moisture ingress.



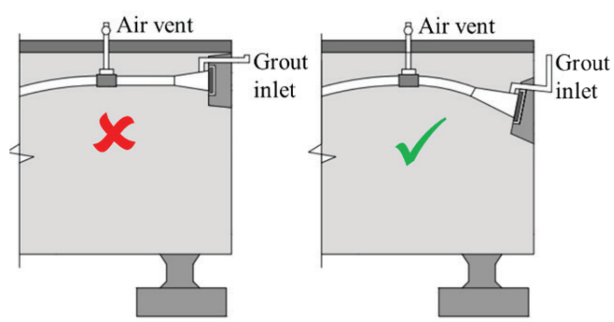
(a) Schematic of PTd bridge with a draped tendon profile depicting the inlet point for grouting



(b) Schematic of PTd bridge with a harped tendon profile depicting the inlet points for grouting



(c) Avoid filling the duct with water before grouting. The grouting operation should be carried out by keeping the tendons and ducts in a dry state



(d) Schematic of diaphragm segment with the anchorage in (i) horizontal position and (ii) inclined position

Figure 14: Recommended practices for PTd tendon grouting [adapted from FHWA-NHI-13-026 (2013) [10]]

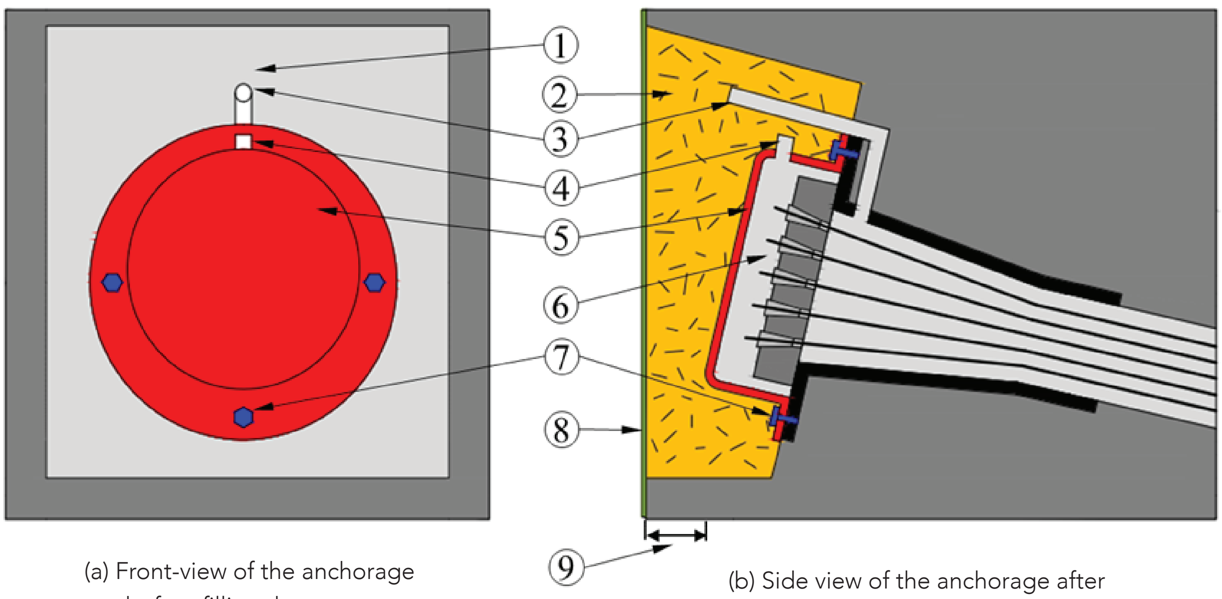
It may also prevent the formation of voids just behind the bearing plates. Also, providing vents at the top-most locations on the ducts will enable the complete filling of duct.

4. The size and positioning of grout ports and vents at anchorages are critical in achieving adequate grout filling. The anchorage recess should be designed and constructed with adequate clearance to fix the tendon grout port over the anchor head (i.e., 12 o'clock position), as shown in Figure 15(a). Such a design will enable the complete filing of the grout inside the duct. The minimum diameter of the grout port shall be 30 mm, to enable faster and continuous grouting, and to prevent clogging of grout inside the tube/port. Providing such a large diameter tendon grout port will also facilitate easier regrouting after a day or after several years. In addition, the anchorage vent shall be positioned at the top of the acrylic cap (i.e., 12 o'clock position) to ensure the complete filling of the grout inside the cap.

5. Figure 15(b) shows the proposed multi-level corrosion protection system for PT anchorages. The anchor head (or bearing plate with wedges) shall be sealed with permanent and transparent acrylic cap. The purpose of the transparent acrylic cap is to inspect if there are any voids and ensure the complete filling of the grout. The acrylic cap should be fastened to the cast iron anchor plate – use non-metallic bolts to reduce galvanic corrosion between the bolts and the anchor plate. Also, acrylic caps can be embedded in the recess concrete and will not corrode; which is not the case with a metallic cap. If the grout materials are good and if the air vents and grout ports are positioned adequately (12 o' clock), then the anchor head will get filled completely. Ideally, a circular grout cap should be formed and all the strands must be covered – unlike in Figure 2(b) and (c).

6. Anchorage recess shall be filled with impervious cover concrete and shall be reinforced with fibres to avoid the occurrence of shrinkage cracks [29]. Also, sufficient surface preparation has to be done on the anchorage recess before placing the cover concrete to enable proper bonding between the substrate and the new material and avoid the ingress of rainwater and air through the joint. A minimum cover of 50 mm shall be ensured between the outer face of the cover concrete and the nearest point of the acrylic cap (in case of inclined anchorages). Also, a waterproofing coating can be applied on the outer surface of recess concrete and parent concrete, especially to cover the joint between them.

7. Grouting is an important and critical activity to ensure century-long service life. It is strongly recommended to avoid grouting during the night-time. Grouting during the daytime would help in better quality control on site.



(a) Front-view of the anchorage before filling the recess

(b) Side view of the anchorage after filling the recess

Note : 1. Clearance for tendon grout port; 2. Fibre-reinforced cover concrete; 3. Tendon grout port (diameter ≥ 30 mm); 4. Air vent; 5. Transparent acrylic cap; 6. Grout filling; 7. Non-metallic screw; 8. Waterproofing layer; 9. Cover ≥ 50 mm

Figure 15: Proposed multi-level corrosion protection system for PTd anchorage

7. SUMMARY AND CONCLUSIONS

The use of good grouting materials and grouting practices are essential to achieve the intended corrosion-free service life (say, 100+ years) of post-tensioned (PTd) concrete systems. However, there exists some concerns in terms of the quality of grouts and grouting practices, which result in inadequately filled tendons/ducts, which in turn lead to premature corrosion of strands. This paper summarizes such concerns with several evidences. Also, an experimental programme assessing the fluidity, fluidity retention, bleedwater volume, softgrout volume, volume change, and compressive strength of four post-tensioning (PT) grouts was conducted. The plain cement grout (PCG) could meet the compressive strength and fluidity requirements but, failed in terms of fluidity retention, bleeding, and volume change. Hence, not recommended for use as PT grouts. Although the widely used site-batched grouts (SBG) showed sufficient fluidity; they exhibited poor fluidity retention, and low resistance to bleeding and volume change, and could not meet the compressive strength requirements; hence, SBGs are not recommended for use as PT grouts. On the other hand, the TendonFill (TF) and a commercially available prepackaged grout (PPG), which are thixotropic in nature, exhibited excellent fluidity, fluidity retention, resistance to bleeding, volume change, and softgrout formation. Hence, both TF and the PPG tested are recommended for use as PT grouts.

Also, a set of performance specifications for the grouts is provided. It must be noted that the PT grouts should not be qualified based on only the fluidity (efflux time) criterion. Other parameters such as fluidity retention, bleed resistance, and volume change must be considered while qualifying the grouts. For routine quality control of grouts, the fluidity, bleed resistance, soft grout, and compressive strength tests are recommended. Then, a compilation of good grouting practices to achieve century-long corrosion-free service life are provided. Such practices can help achieve complete filling of the duct and anchorages and also provide adequate protection against void formation and attack by moisture and other deleterious materials that can accelerate corrosion of strands. The anchorages shall be fully grouted, sealed with permanent transparent acrylic caps, and encased with fibre-reinforced cover concrete to achieve cenury-long corrosion-free service life.

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LIST OF SYMBOLS AND ABBREVIATIONS

ΔL	Change in length
ΔV	Change in volume
ACI	American concrete institute
$BV_{1.5\ m\ vertical\ tube}$	Bleed volume in 1.5 m vertical tube test
$BV_{wick\text{-}induced}$	Bleed volume in wick-induced bleed test
Bwob	by weight of binder
CO_2	Carbon-di-oxide
EN	Euronorms
$f_{c,t}$	Cube compressive strength at 't' days of curing (here t = 3, 7, 28)
Fib	Federation of structural concrete
HRWR	High-range water reducer
IRS	Indian railway standard
IS	Indian standard
JSCE	Japan society of civil engineers
MORTH	Ministry of road transport and highways
OPC	Ordinary Portland cement
PCG	Plain cement grout
PEA	Plasticized expansive admixture
PPG	Pre-packaged commercial grout
PTd	Post-tensioned
PT	Post-tensioning
PTI	Post-tensioning institute
SBG	Site-batched-grout
SCM	Supplementary cementitious material
SRA	Shrinkage reducing admixture
$T_{e,t}$	Efflux time at 't' minutes after mixing
TF	TendonFill
$V_{softgrout}$	Volume of softgrout
VMA	Viscosity modifying admixture
w/b	Water-to-binder ratio

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