DEVELOPING CEMENTITIOUS GROUTS WITH RESISTANCE TO BLEEDING AND SOFTGROUT FORMATION FOR USE IN POST-TENSIONED CONCRETE SYSTEMS AND SPECIFICATIONS

A THESIS

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Dedicated to my parents and my sister

THESIS CERTIFICATE

This is to certify that the thesis titled "**DEVELOPING CEMENTITIOUS GROUTS WITH RESISTANCE TO BLEEDING AND SOFTGROUT FORMATION FOR USE IN POST-TENSIONED CONCRETE SYSTEMS AND SPECIFICATIONS**" submitted by Mr. Manu K. Mohan to the Department of Civil Engineering, Indian Institute of Technology Madras for the award of the degree of Master of Science (by Research) is a bona fide record of research work carried out by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

Grouted, post-tensioned (PT) concrete structures (long span bridges, high-rise buildings, silos, vaults, etc.) are generally designed for a target service life of 100+ years. If not adequately grouted, the entry of water, chlorides, and carbon dioxide into the tendon systems can induce premature corrosion of PT strands. To protect the strands from corrosion, the interstitial space between the tendons and the duct are supposed to be filled with cementitious grouts. To achieve complete filling, the grout must be sufficiently flowable and bleed resistant. However, evidence of poor quality grouts leading to inadequate filling (void formation) and premature corrosion of strands are available. Nowadays, many commercial pre-packaged grouts are available in the market. However, the simulated bleed measurements with prototype tendon grouting tests showed that the pre-packaged grouts tend to form highly permeable softgrout, which poses a serious threat to the corrosion protection. Also, widely used Site-Batched-Grouts (SBGs) in the developing world do not exhibit desired bleed resistance - leading to the formation of fine voids (small anode-large cathode condition), which are probably worse than the situation with large voids. In addition, there is a serious lack of comprehensive and stringent performance specifications to qualify/disqualify poor-quality PT grouts.

In this study, a three-phase experimental program was conducted to develop a flowable, bleed resistant cementitious grout without the tendency to form softgrout and a set of performance specifications for the grouting materials. In Phase-1, all the raw materials were characterized. Then, after several preliminary flow and bleed experiments, six grouts were made with different combinations of binders and admixtures. The binders used were Ordinary portland cement (OPC), two types of fly ash (different particle sizes), and silica fume. The chemical admixtures used were polycarboxylate ether-based high-range-water-reducer (HRWR), cellulose-based viscosity modifying agent (VMA), glycol-based shrinkage reducing admixture (SRA), and nanoclay. All the ingredients were in powder form and blended. The binders were proportioned using the particle packing method and the dosage of HRWR, VMA, nanoclay, and SRA were chosen based on the recommendations on fluidity, wick-induced bleed resistance, and dimensional stability given in EN 447 (2007).

In Phase-2, the performance of the formulated grouts was assessed using fluidity and fluidity retention tests, standard, wick-induced, pressure-induced, and inclined tube bleed tests, rheological tests, and shrinkage tests. Also, the robustness of the grouts with respect to

the changes in the ambient temperature and water-to-binder ratio was studied. The performance of the formulated grouts was assessed with the compliance to the stringent performance specifications from EN and PTI standards. A grout mix with 48% volume replacement of OPC with two fly ashes and appropriate dosages of HRWR, VMA, and SRA yielded a bleed-resistant grout without compromising the fluidity. This grout was identified as the best performing grout and selected for the Phase-3 of the study.

In Phase-3, three tons of the best performing grout material was pre-blended at an industrial blending facility and transported to IIT Madras. The performance of this grout mix was assessed by conducting all the laboratory tests performed in Phase-2. Three cycles of fine-modifications to the mixture proportion, pre-blending, and laboratory tests were conducted. Then, prototype tendon grouting tests were carried out to assess the performance of the grout on a real-scale and compared with widely used SBG. Also, the specifications given in various standards on post-tensioning grouts were critically analyzed. It was found that the existing specifications on fluidity/efflux time are not suitable for qualifying good quality thixotropic grouts. Based on such findings and extensive laboratory experience in testing various properties of grouts, a set of stringent and comprehensive specifications were developed for applications in PT systems. It was also observed that the grout developed in this study met all these stringent specifications. It is proposed to adopt this new set of specifications to qualify the cementitious grouts for PT applications; and thus, help to minimize premature corrosion of strands in PT systems.

Keywords: Prestressed, post-tensioned, concrete, grout, softgrout, strand, tendons, fluidity, bleed, rheology, shrinkage, performance specifications

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ABBREVIATIONS

% bvog	:	% by volume of grout
% bwob	:	% by weight of binder
% bvob	:	% by volume of binder
ASTM	:	American Society of Testing and Standards
AASHTO	:	American Association of State Highway and Transportation Officials
API	:	American Petroleum Institute
ASBI	:	American Segmental Bridge Institute
CMC	:	Critical Micelle Concentration
EN	:	Euro Norms
FaF1	:	Class F Fly ash 1
FaF2	:	Class F Fly ash 2
fib	:	International Federation for Structural Concrete
FTIR	:	Fourier Transform Infrared Spectroscopy
HDPE	:	High-Density Polyethylene
HRWR	:	High Range Water Reducer
IRS	:	Indian Railways Standard
IS	:	Indian Standard
ISO	:	International Standards Organization
JSCE	:	Japan Society of Civil Engineers
MORTH	:	Ministry of Road Transport and Highways
NC	:	Nanoclay
OPC	:	Ordinary Portland Cement
PBG	:	Pre-Blended Grout
PCE	:	Poly Carboxylate Ether
PCG	:	Plain Cement Grout
PNS	:	Poly Naphthalene Sulfonate
PPG	:	Pre-Packaged Grout
PT	:	Post-Tensioned
PTI	:	Post-Tensioning Institute
RH	:	Relative Humidity
SBG	:	Site-Batched-Grout
SF	:	Silica Fume

SRA	:	Shrinkage Reducing Admixture
TxDOT	:	Texas Department of Transportation
VMA	:	Viscosity Modifying Agent
w/b	:	Water-to-binder ratio

NOTATIONS

$AS_{t,\ days}$	:	Autogenous shrinkage strain at ‘t’ days
$BV_{Inclined}$	:	Bleed volume in inclined-tube bleed
$BV_{Pressure,\ P}$	:	Bleed volume at a pressure ‘P’
$BV_{Standard}$	:	Bleed volume due to standard bleed
$BV_{Wick\text{-}induced}$	:	Bleed volume due to wick-induced bleed
$D_{s,\ 0}$	:	Spread diameter, immediately after mixing
$D_{s,\ 30}$	:	Spread diameter, 30 minutes after mixing
$D_{s,\ 180}$	:	Spread diameter, immediately after mixing at an ambient temperature of ‘t’
$D_{s,\ ref}$	:	Spread diameter at a reference water content
$D_{s,\ m}$	:	Spread diameter at a water content of ‘m’
ΔD_s	:	Change in spread diameter
$f_{c,\ 3\text{-}day}$	:	Cube compressive strength after 3 days of curing
$f_{c,\ 7\text{-}day}$	:	Cube compressive strength after 7 days of curing
$f_{c,\ 28\text{-}day}$	:	Cube compressive strength after 28 days of curing
K	:	Consistency
ΔL	:	Change in length
ϕ_P	:	Packing density
$\dot{\gamma}$	:	Shear rate
$ST_{initial}$	:	Initial setting time
ST_{final}	:	Final setting time
τ	:	Shear stress
τ_0	:	Yield stress
$T_{e,\ 0}$	:	Efflux time, immediately after mixing
$T_{e,\ 30}$	:	Efflux time, 30 minutes after mixing
$T_{e,\ 180}$	:	Efflux time, 180 minutes after mixing
$T_{e,\ T}$	:	Efflux time, ‘T’ minutes after mixing
$T_{e,\ t}$	:	Efflux time immediately after mixing, at an ambient temperature of ‘t’
$T_{s,\ ref}$	:	Efflux time at a reference water content
$T_{s,\ m}$	:	Efflux time at a water content of ‘m’
ΔT_e	:	Change in efflux time
$TS_{t,\ days}$	:	Total shrinkage strain at ‘t’ days
$V_{softgrout}$	:	Volume of softgrout

CHAPTER 1

INTRODUCTION

1.1 PRESTRESSED CONCRETE SYSTEMS

The pre-stressing technology is considered as one of the breakthroughs in the concrete construction industry due to the significant advantages associated with it. In the process of pre-stressing, permanent stresses are induced in the concrete element by stressing the tendons. The induced stresses are designed to counteract the external loads coming to the element, and thus, the performance is improved. According to the famous French mathematician Henry Poincare, ‘A method is neither true or false, it is convenient.’ The method of pre-stressing is indeed very convenient and widely used in the concrete construction sector though it is relatively new (Naaman 2004). In the early 1900s, several engineers/researchers had experimented with the prestressing technology to make it practical and economically feasible. However, it was Eugene Freyssinet who successfully used the technology for the construction of a bridge in 1930. Later, the prestressed concrete systems became very popular and have been widely used in the construction of long span segmental bridges, water tanks, tunnels, nuclear vaults, building components such as beams, columns, and slabs, etc.

The prestressed concrete systems are generally classified based on the method of stressing adopted. Those are 1) pre-tensioned systems in which the embedded tendons are stressed before the concrete hardens and gains sufficient strength and 2) post-tensioned systems (‘PT’ herein) where the tendons are stressed after the concrete has attained sufficient strength (say, seven days). The PT concrete systems can be again divided into two categories based on the condition of the tendons in the encasement duct. Such a classification includes 1) bonded/grouted PT concrete systems and 2) unbonded/ungrouted PT concrete systems. Again, based on the location of the tendons, the grouted PT systems can be classified into two categories (external and internal PT systems). If the tendons are placed outside the concrete element, it is called external post-tensioned concrete system. On the other hand, if the tendons are placed inside, it is known as the internal PT concrete system. Even though the practical use of prestressing technology had started in the 1930s, the first grouted/bonded PT concrete structure (a long span segmental bridge) was constructed in 1946 in Spain (Hewson 2011). A decade later, similar long span bridges were constructed in the USA, and slowly the use of PT systems in the concrete industry became manifolded in several parts of the world. Later, the economic viability of PT technology has been well documented. This research study focuses only on the cementitious grouts used to fill the encasement duct of bonded/grouted PT systems (both internal and external).

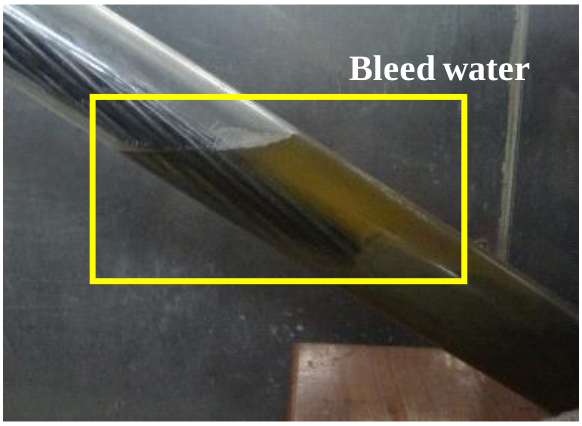
1.2 BACKGROUND OF THE STUDY

In general, grouted PT concrete structures have been considered as highly durable. Therefore, these structures are usually designed for a long target service life of 100+ years. However, the pre-mature corrosion and resulting tendon failure/collapse have raised alarming concerns about the safety and the serviceability of the PT structures (especially PT bridges). Many incidents of the tendon corrosion in PT bridges and sometimes even the failure of the structure have been reported around the world (FDOT 2001a, 2001b, Woodward 1989, Woodward and Williams 1988). A study conducted on 447 bridges in the UK showed that 74 % tendons were corroded and out of this 24 % of the tendons had severe corrosion (Woodward 1981). The major reported reason for the tendon corrosion was the formation of voids near/at the anchorage zones and exposed strands - resulting to the ingress of deleterious materials to the tendons (Trejo et al. 2009). The reason for this void formation is the use of poor-quality grouts and grouting practices. Therefore, the quality of PT grouts is of utmost importance to achieve the long target service life of 100+ years.

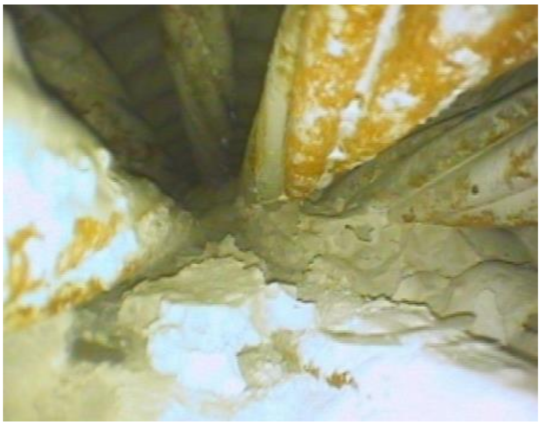
Learning lessons from the past failure incidents, government agencies of different countries published standards with performance specifications to qualify the good quality grouts and the guidelines for the good grouting practices. Later, newly developed cementitious grout mix with all the ingredients pre-packaged in a bag was introduced in the developed world. However, such pre-packaged grouts have not been available/used in developing countries.

1.3 PROBLEM STATEMENT

As discussed in the previous section, in India and several parts of the developing world, high-performance cementitious grouts with excellent flow properties and resistance to bleeding/segregation are not available/used. Instead, indigenous cementitious grouts (also known as site-batched-grout (SBG)) with very low bleed resistance are used for the PT applications (Babu 2016, Kamalakannan et al. 2018, Thirunavukkarasu 2015). Figure 1-2 (a) shows the accumulated bleed water on the surface of SBG in a lab scale inclined tube test. It can be seen that SBG exhibits excessive bleeding at the crown points of the duct. This bleed water later evaporates or reabsorbs to the grout – leaving voids at/near the anchorages. Figure 1-2 (b) shows such voids inside the duct (picture taken using a borescope). These voids facilitate the entry of deleterious materials and trigger corrosion of strands. On the other hand, newly developed pre-packaged grouts with desired levels of flow characteristics and bleed resistance are widely used in the developed world. However, studies conducted to sensitize and critically analyze the performance of these pre-packaged grouts showed that they tend to exhibit a highly permeable layer of hardened grout (known as 'softgrout') at crown/highest points of the PT duct (Babu 2016, Hamilton et al. 2014, Kamalakannan et al. 2018, Randell et al. 2015). Figure 1-2 (c) shows the cross-section of the hardened pre-packaged grout specimen from a prototype tendon grouting study. Similarly, Figure 1-2 (d) shows the porous surface texture in the duct due to the formation of the softgrout. Therefore, the continued use of these PT grouts (both indigenous and pre-packaged) can create voids, exposed stands, and softgrout and result in the tendon corrosion.



a) Lab test showing significant bleed water from a site-batched-grout (SBG) that is widely used in developing countries (Ashokreddy 2016)



b) Inside view of a tendon in an externally post-tensioned bridge with large voids and corroded strands (TxDOT 2009)

Figure 1-1. Excessive bleeding and voids observed in PT structures due to poor-quality grout materials

a) Porous softgrout on a hardened commercially available PPG

b) Porous surface texture in a commercially available PPG

Figure 1-2. Instances of softgrout due to the use of poor-quality grout materials (Hamilton et al. 2014)

Similarly, the currently used grouting practices in the developing countries are not adequate to prevent the corrosion of the PT strands. For instance, Figure 1-3 shows a photograph of a PT bridge from a metro rail project in one of the cities in India. The PT strands are exposed, and the semi-circular grout face indicates the inadequate filling of the duct. Such inadequate grouting and the improper sealing of the anchorage ends will result in the premature corrosion of the PT strands. Similarly, the common practice of covering the PT strands with cementitious end caps is a bad field practice. The cementitious end caps will attract atmospheric moisture and facilitate the corrosion initiation. Therefore, the use of cementitious end caps will facilitate corrosion of PT strands instead of preventing corrosion.

This becomes much more critical in the developing world which witnesses a boom in the large-scale construction projects with PT concrete structures. In India, major infrastructure projects such as metro rails, monorails, smart cities, etc. are planned to construct in metro cities with a large population. Currently, the total length of metro rails will reach about 1000 km, which costs about 11.5 billion rupees in twelve metro cities. In addition, many other large-scale infrastructure projects have been planned by government organizations including nuclear energy programme (NTDPC 2013). Therefore, there a dire need of a durable PT system which can sustain more than 100 years. This can be achieved using highly flowable, bleed resistant cementitious grouts without softgrout formation and a set of comprehensive and stringent performance specifications.

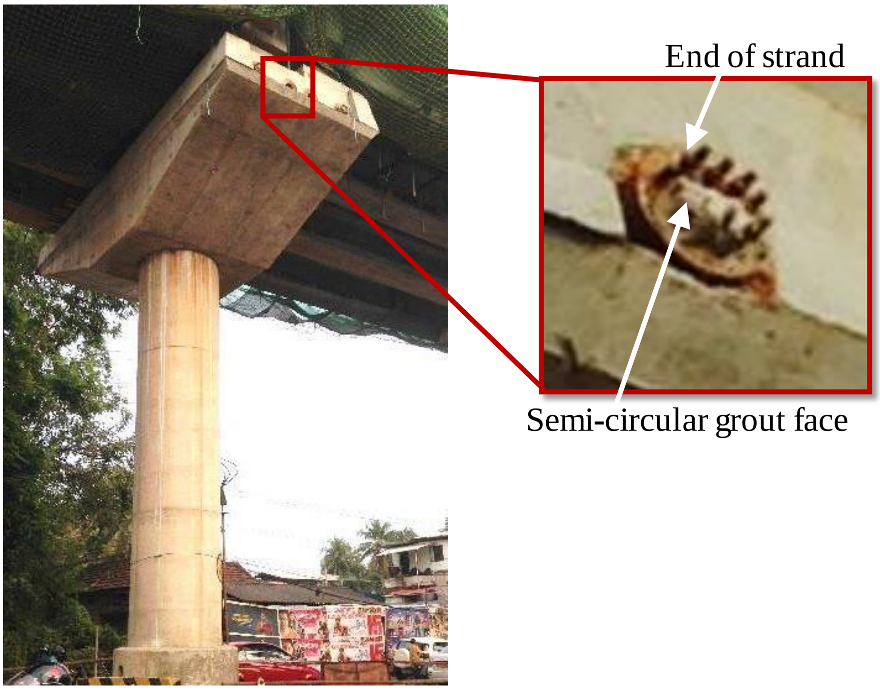


Figure 1-3. Semi-circular grout face at the end of a tendon (indicating a half-filled tendon) in a metro bridge

1.4 RESEARCH OBJECTIVES AND SCOPE

1) To identify suitable indigenous materials for developing cementitious grout and then develop a pre-blended, highly flowable, and bleed-resistant grout with no tendency to form soft grout.

   - Binders: Ordinary Portland Cement (OPC), Class F fly ash (FaF), silica fume (SF).
   - Chemical admixtures: PCE based High range Water Reducer (HRWR), cellulose-based Viscosity Modifying Agent (VMA), nanoclay (NC), and glycol-based Shrinkage Reducing Agent (SRA).

2) To assess the fresh properties (flow, bleed, rheological parameters, robustness) and set/hardened properties (setting time, dimensional stability, compressive strength) of the selected cementitious grouts.

   - Environmental condition: 25°C and 65 % relative humidity for development and performance assessment of grouts
   - Environmental condition: 15 to 35°C for the robustness assessment.

3) To assess and compare the performance of the selected grout with a widely used grout in prototype tendon grouting tests, propose a set of performance specifications (for the grout materials) and a set of guidelines (for good grouting practices).

- Pre-blended grout (PBG) produced at an industrial blending facility and
- Site-batched grout (SBG) using OPC and superplasticized admixture.

1.5 ORGANIZATION OF THE THESIS

The thesis is organized in the following way

- Chapter 1 gives an introduction about the prestressing technology especially the grouted PT concrete systems, the background of the study, problem statement, the objectives and scope of the research work.
- Chapter 2 presents a detailed review of the literature, the historical overview of the corrosion incidents of PT concrete systems, the mechanism of corrosion on grouted PT concrete systems. Also, the details of the grout system, the factors affecting the grout performance are discussed. Also, the current scenario of the grouting practices followed in India and on a global scale is explained. Eventually, the specifications proposed in standards and codes are critically evaluated.
- Chapter 3 deals with the experimental methodology adopted for the study. The details about the experimental procedure such as mixture designing methodology, mixing procedure and methods to assess the performance of the PT grouts on a lab scale as well as a field are discussed in detail.
- Chapter 4 gives a detailed overview of the results and main findings from the study. The results are critically analyzed, and the conclusions are drawn.
- Chapter 5 presents the conclusions from the study. The general and specific conclusions are separately explained. Also, the recommendations from the current study and the possible scope for the future study are explained in this chapter.
- The final portions of this thesis comprise a list of references that were reviewed for this study. Proposed modifications on the performance specifications MORTH standard and elaborative procedure of the large-scale prototype tendon grouting tests are given in the appendices.

CHAPTER 2

REVIEW OF LITERATURE AND FIELD PRACTICES

2.1 INTRODUCTION

This section gives a detailed review of the literature on the historical overview of corrosion incidents in grouted post-tensioned (PT) concrete structures, cementitious grout used in the PT structures, desired properties of the PT grout, and the factors affecting the performance of grout. Then, a detailed overview of grout materials and grouting practices followed in India and around the world are discussed. Finally, the specifications and acceptance criteria according to the various standards/codes are critically analysed.

2.2 GROUTED POST-TENSIONED CONCRETE SYSTEM

Grouted PT concrete structures have been considered as highly durable for a long period. Also, the enhanced constructability, cost effectiveness, increased construction speed, and reduction in beam depth makes these structures a suitable choice for the construction of long span bridges, nuclear vaults, high-rise buildings, water retaining structures, etc. Thus, today's construction industry uses the full potential of PT concrete systems in large-scale infrastructure projects. Also, it's worth noting that the use of PT concrete systems in the developing countries gaining huge momentum. These PT concrete structures are generally designed for a target corrosion free service life of 100+ years. The seven-wire strands embedded in the plastic duct inside the concrete acts like a backbone to the PT structures. Thus, it is important to protect the PT strands from the pre-mature corrosion to achieve such a long service life.

Figure 2-1 represents a typical grouted, internally post-tensioned, segmental concrete bridge. From the figure, it is apparent that the tendons inside the concrete elements are highly congested and eccentric at various locations. At the anchorage ends (i.e., at section A-A), the strands are aligned concentrically to the duct as they are fastened by the anchor heads at the ends. However, at the locations where sudden changes in the profile occur, the strands stay close together due to the induced stresses acting on it. One such location is section B-B of the PT bridge. The strands are raised to the top portion of the cross-section of the duct at section B-B. It is challenging to fill the cementitious grout at these locations due to the presence of congested strands. In order to achieve complete filling of all the interstitial spaces between the strands and the duct, the cementitious grout must be highly flowable. At the same time, the grout must be resistant against bleeding/segregation. If not, the liquid phase from the cementitious grouts will separate during the grouting pumping and when the grout flows through the small interstitial spaces.

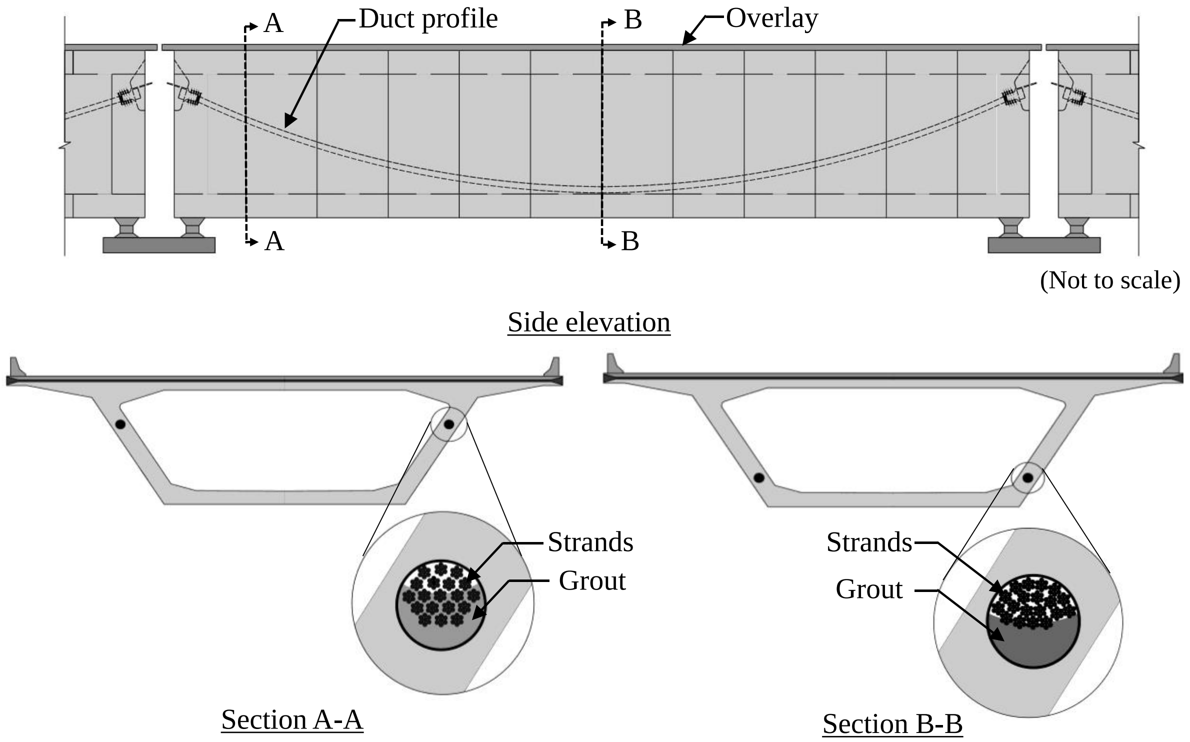


Figure 2-1. Schematic representation of tendon profile in a post-tensioned bridge – showing the possible void conditions at various locations

2.3 HISTORICAL OVERVIEW OF CORROSION IN PT SYSTEMS

As discussed in the previous section, the PT concrete structures are typically designed for a service life of 100+ years and have been considered as highly durable in the last few decades. However, several tendon corrosion/failure incidents changed the mindset of engineers and researchers. The first reported the collapse of a PT structure was Bickton Meadow Bridge in the UK; 15 years after the construction (Concrete Society 1996). Later, several tendon corrosion/failure incidents were reported around the world. Such reported incidents of tendon corrosion/structural failure are tabulated in Table 2-2 and Table 2-1. It can be observed that the majority of the incidents are reported in the USA and UK. This does not mean that the tendon corrosion incidents have been confined only in USA and UK. Most of the PT structures around the world have experienced similar problems. However, the lack of availability of the well documented and comprehensive list of tendon corrosion/failure incidents or associated forensic analysis in most of the developing world created such a pretense.

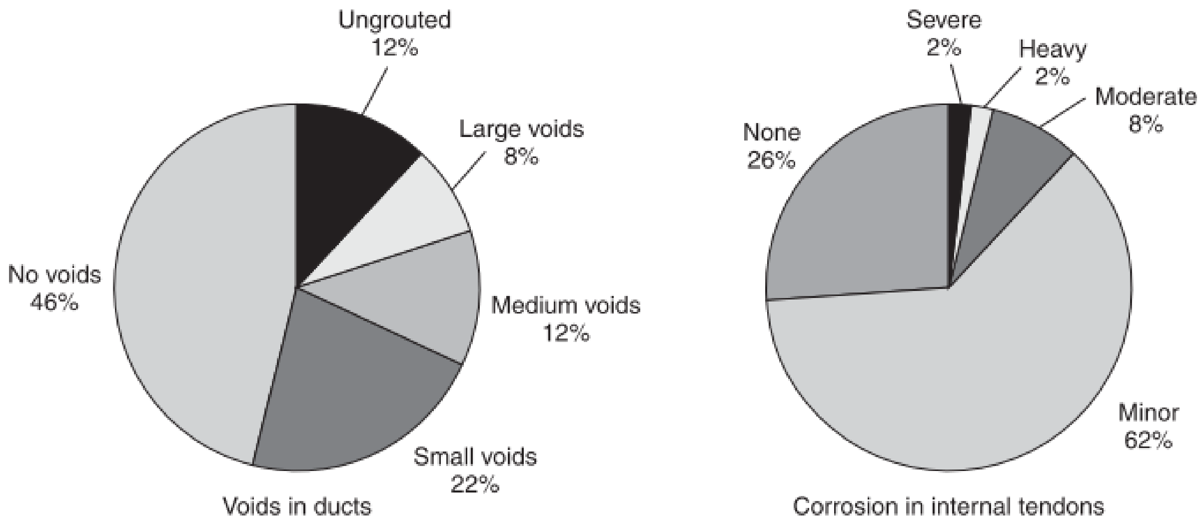
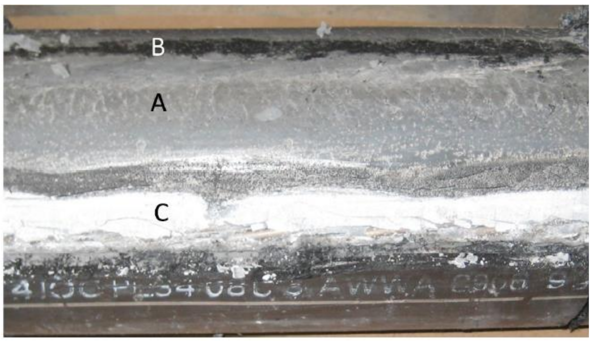


Figure 2-2. Results of the survey conducted in 447 bridges in the UK (Woodward 1988)

From the mid-1980s to late 1990s, several studies were conducted in the UK to assess the corrosion resistance of the tendons inside the PT bridges. Figure 2-2 shows the results of the study conducted on 447 PT bridges in the UK. This extensive survey showed that a significant number of corroded strands are present inside the existing PT bridges in the UK (Hewson, 2011, Woodward 1988). Woodward (1988) reported that out of the 447 PT bridges surveyed, 74% had corroded tendons. Out of this, 24% of the tendons had severe corrosion (more than 40% loss in cross-sectional area due to corrosion), 52% of the tendons had small to moderate corrosion (10 - 40% loss in cross-sectional area due to corrosion). The reason for the corrosion of the tendons was later identified as the use of the poor-quality grout (Powers, 1999, Trejo et al. 2009). The poor-quality grouts with very low bleed resistance create voids at/near the anchorages which facilitate the ingress of deleterious materials and eventually the corrosion of the strands (Trejo et al. 2009). Based on such survey results of the PT concrete systems, the concrete society in the UK banned the construction of the PT bridges by stating that the PT concrete systems are not durable due to the use of poor-quality grout and grouting practices (Concrete Society 1996). The ban was lifted in 1996 after the publication of a standard (draft of EN445 published in 1996, designated as prEN 445 (1996)) which included a set of specifications to choose proper grout materials and guidelines for good grouting practices. Similar standards were later published by post-tensioning institute (PTI M55: 2002) in USA and *fib* (fib bulletin 20: 2002) in Europe, which give a detailed overview of the specifications to assess the quality of the grout material and guidelines for good grouting practices. However, most of these standards are not used/available in the developing world due to the lack of awareness of the engineers/contractors (Kamalakkanan et al. 2018, Clark 2013)

Similar forensic studies were held in the USA in the late 1990s after the tendon failure incidents at Mid-bay bridge, Verina Enon bridge, Niles Channel Bridge, Midbay Bridge, Sunshine Skyway Bridge, etc. in Florida and Virginia. From the forensic studies, the reason for corrosion of strands was reported as the presence of voids throughout the duct (FDOT 1999, FDOT 2001a, 2001b, Hansen 2007). Later it was identified that these voids were formed due to re-absorption or evaporation of the accumulated bleed water. The corrosion has been initiated in the exposed strands and later propagated through the galvanic action between the corroded strands and the un-corroded strand portion. Another reported reason for tendon corrosion was the formation of the highly permeable layer of grout known as 'softgrout'. Lau et al. (2016) conducted extensive forensic studies on the corroded/failed tendons in the PT bridges located in Florida, USA. He observed two different layers (segregated and non-segregated) of grout from the petrographic studies. Figure 2-3 shows the cross-section of the hardened grout from the study conducted by Lau et al. (2016). From Figure 2-3, it is apparent that the segregated grout has white colour while the non-segregated grout has a dark grey colour. Also, the segregated layer contains a large amount of fine limestone powder. The major reason for the corrosion of tendon was the formation of the layer of softgrout due to the settling of the inert filler materials and subsequent ingress of moisture (Lau et al. 2016).

a) Cross-section of segregated grout



b) Portion A is wet plastic grout, B is a dark band of sedimented silica fume, and C is chalky grout

Figure 2-3. Segregated grout from Ringling Causeway Bridge, USA (Lau et al. 2016)

Table 2-1. Tendon failure incidents in grouted PT concrete bridges

Bridge name & Country	Reason	T*	T_{corr} * (years)
Kohlbrand, Germany (Saul et al. 1998)	Corrosion due to the ingress of de-icing salts through the construction joints.	1976	2
Angel road, UK (Concrete Society 1996)	Wires were broken due to corrosion of the steel at anchorages.	1980	30
Taf Fawr, UK (Porter 1985)	Severe corrosion of the prestressing steel	1982	21
Hale Boggs, UK (Mehrabi et al. 2006)	Corrosion cracks were observed along the tendons. The reason was identified as voids formation due to the use of poor-quality grout material.	1985	2
Folly new, UK (Concrete Society 1996)	More than half the tendons had corroded near the anchorages	1988	30
Niles channel, USA (FDOT 1999)	Corrosion caused by bleeding water, and there was general evidence of inadequate grouting	1999	16
Saint Stefano, Italy (Proverbio and Ricciardi 2000)	Corrosion of prestressing steel	1999	40
Lowe's motor speedway, USA (Sly 2001)	Corrosion of prestressing steel	2000	5
Mid-bay, USA (FDOT 2001a)	Strand corrosion exposed strand along a bleed water trail and cracked PT ducts. Severe corrosion was present in a total of 11 out of 846 tendons.	2001	9
Bob Graham sunshine skyway, USA (FDOT 2001a)	Voids formed due to bleed water evaporation near anchorage zones; infiltration of saltwater or surface drainage water into the PT ducts through the poorly sealed joints between the segments, openings at anchorages, cracks on ducts, etc.	1995	8
Varina Enon, USA (Hansen 2007)	Location of tendon failure was at the interface between two different grouts and created a galvanic corrosion cell and lead to corrosion of tendons	2007	17
Cline Avenue, USA (Frost 2006)	Many strands were exposed and had a high degree of corrosion	2009	20
Ringling Causeway, USA (Lau et al. 2016)	Corrosion of strands due to the softgrout formation	2011	8

*T_{corr} is the time taken (in years) for tendon corrosion to occur

**T is the year at which the corrosion was observed/failure occurred.

Table 2-2. Structural failures in grouted PT concrete structures

PT structure and Country (Reference)	Reason	T*	T_{corr} * (years)
Bickton Meadows, UK (Concrete Society 1996)	Thin mortar joints connecting the segments allowed the ingress of moisture, chlorides, and oxygen to the tendons-resulting in the premature corrosion.	1967	15
Berlin Congress Hall, Germany (Helmerich and Zunkel 2014)	Voids were observed inside the duct due to the use of poor-quality grout.	1980	23
Ynsys-y-Gwas, UK (Woodward 1988)	Pitting corrosion of the strands due to the ingress of chlorides near the segmental joints. Chlorides, from de-icing salt, were present in the grout collected PT from the ducts. Exposed wires in partially grouted ducts were also severely corroded.	1985	33
Mandovi, India (Arullappan 2010)	The use of poor-quality grout resulted in excessive bleeding and later voids	1986	12
Malle, Belgium (Mathy 1996	Corrosion of the post-tensioning through the hinged joint of the end tie-down member	1992	13

*T_{corr} is the time taken (in years) for tendon corrosion to occur
**T is the year at which the corrosion was observed/failure occurred.

Figure 2-1 indicates the timeline of the life of the grouted PT tendon/bridge and the time taken for the tendon corrosion to occur. Form Figure 2-1, it is apparent that most of these PT bridges had experienced the tendon corrosion or failure within 30 years after the construction.

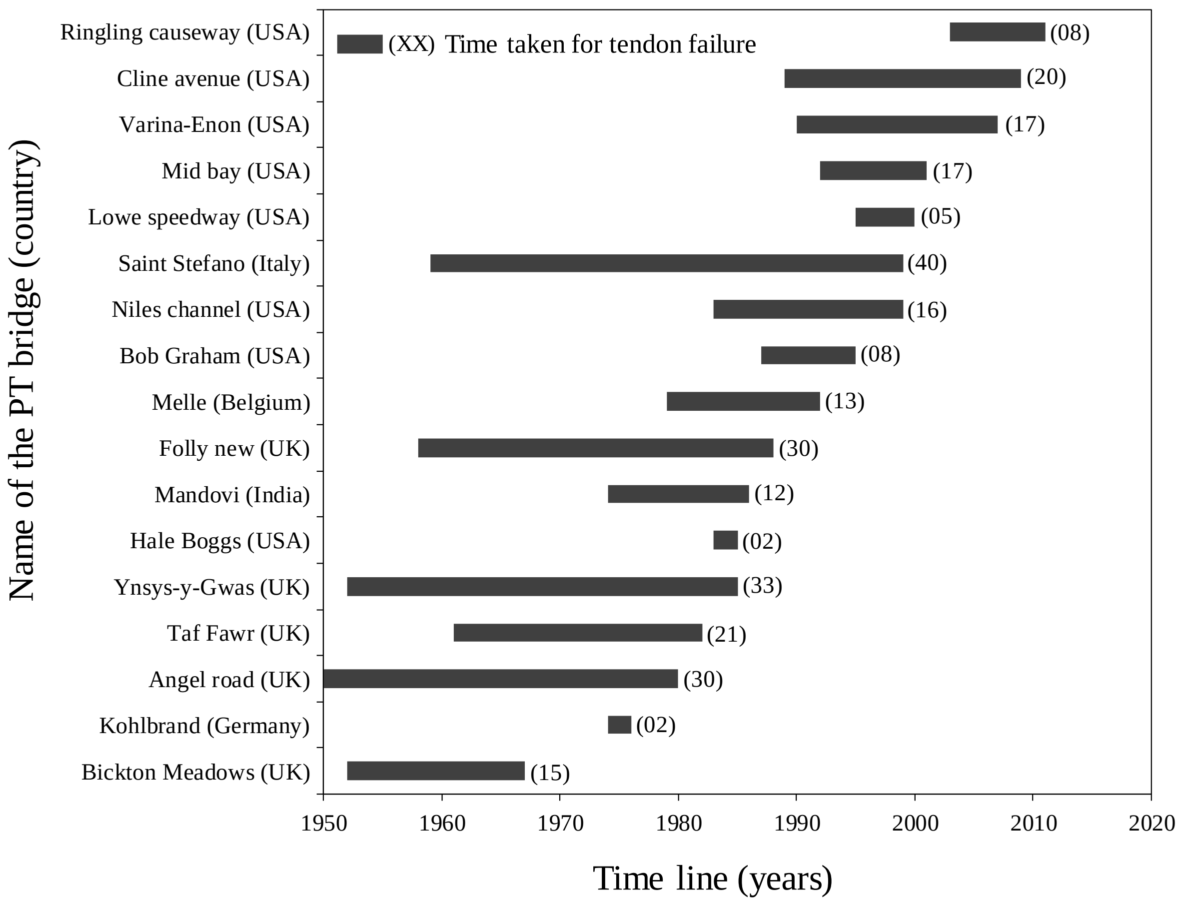


Figure 2-4. Time taken for the tendon failure/corrosion in PT concrete bridges

2.4 CORROSION MECHANISMS IN VOIDED PT CONCRETE SYSTEMS

As discussed in the previous section, grouted, post-tensioned (PT) concrete systems are commonly used in large-scale structures such as bridges and high-rise buildings. Generally, these structures are designed for a target service life of about 100+ years. Many of these structures are exposed to the chloride-rich environment and other aggressive conditions (say seepage of water and de-icing salts through joints, carbonation of grout, etc.). These aggressive conditions can cause corrosion of the pre-stressing strands if not protected adequately (Wang et al. 2005). In general, multiple levels of protection systems are used to protect strands from corrosion (Concrete Society 1996). Among these, the cementitious grouts (PT grouts) are considered as the last and most important level of protection (Schokker et al. 1999). As discussed in the previous section, many PT concrete structures around the world have experienced premature corrosion and resulted in the failure of strands/tendons (say, within a few years after the construction). The major reported reason for the strand corrosion was the presence of voids inside the ducts, especially at/near the anchorages. This void formation is mainly due to the use of grouts with low bleed resistance - resulting in the accumulation of bleed water at high points of the tendons (say, anchorages and crest of the tendons). Later, this bleed water gets re-absorbed to the hardened grout or evaporated - creating unwanted voids at/near the anchorage zones and other high points and expose the strands. Such voids facilitate the entry of moisture, oxygen, chloride, and/or carbon dioxide, etc. to the tendons – leading to the onset of strand corrosion (Sagues et al. 2003; Trejo et al. 2009). Once initiated, corrosion can propagate due to the formation of electrochemical cells between the small anodic regions (exposed and corroding strand surface) and the large cathodic regions (strand covered with cementitious grout) (Moreno and Sagues 1998; Sagues et al. 2003). When the anode-to-cathode ratio is smaller (i.e., with the presence of small voids), the corrosion rate will be severe – resulting in the localized reduction in the cross-section of the strand. Hence, to achieve the desired corrosion protection of strands, even the smallest interstitial spaces (say, millimeters in size) between the strands and duct must be filled with cementitious grout. For this, the PT grouts must have high fluidity and bleed resistance. Therefore, the quality of PT grout is of utmost importance for achieving the corrosion free service life of 100+ years.

2.5 GROUT SYSTEM IN PT CONCRETE ELEMENTS

Cementitious grout is a mixture of cement, supplementary cementitious materials, inert fillers, chemical admixtures, and water. Although some standards are allowing the use of fine aggregates with a maximum size of 1 mm, it is not always recommended. The principal reason for using cementitious grout to fill the ducts is to provide an alkaline medium around the tendons. This will improve the passivity of the steel tendons. In addition, the hardened grout will resist the ingress of deleterious materials from the atmosphere. Also, in some cases where the HDPE/Galvanized iron ducts are not present, the hardened grout can contribute to the bond between the tendons and the surrounding concrete element.

2.5.1 PT grout classification

PT grouts have been classified based on the exposure conditions or ingredient present in the grout and based on the texture/appearances of the hardened grout. The former classification allows the site engineer to choose the PT grout best suited for the application based on the site conditions. Similarly, the latter classification helps in determining the reason for the tendon corrosion at the time of forensic analysis.

2.5.1.1 Based on the exposure conditions

PTI M55.1-12 (2013) classifies the PT grout into four categories based on the exposure condition. Table 2-3 enlists the classification of such classification.

Table 2-3. PT grout classification as per PTI M55. 1-12

Classification	Description	Exposure condition
Class A	Cementitious grout prepared with OPC and water without chemical admixtures	Nonaggressive: indoor or nonaggressive outdoor.
Class B	Grout designed by the manufacturer and mixed and construction site	Aggressive: subject to wet/dry cycles, marine environment, de-icing salts
Class C	Pre-packaged grout material proportioned and packaged in a factory and mixed with water at the construction site	Nonaggressive or aggressive
Class D	Special grout designed by the engineer at a construction site	Specific exposure conditions determined by the engineer

2.5.1.2 Based on the texture of hardened PT grout

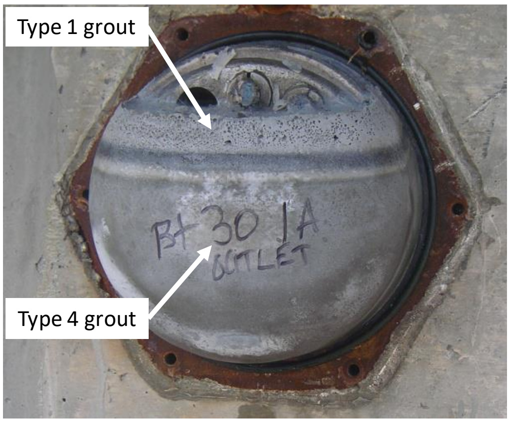
The hardened grout can be classified into four categories based on the appearances/texture. This classification was put forward by FHWA (2013) based on the extensive forensic studies conducted on the PT bridges where severe tendon corrosion/failure was observed. Table 2-4 shows the classification of the PT grout based on appearances/texture.

Table 2-4. Classification of the hardened PT grout as per FHWA (2013)

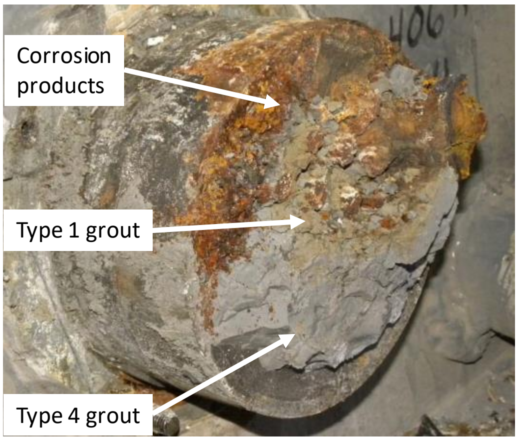
Classification	Description
Type 1	Segregated wet plastic (soft) grout with a clay-like consistency.
Type 2	Segregated grout with black striated layers.
Type 3	Segregated dry grout with a chalky white consistency.
Type 4	Hardened, gray, dry grout.

Ideally, the tendons should be covered with Type 4 grout to achieve the desired level of corrosion protection. However, the forensic analysis showed that in most of the cases, all the four types of grouts would be present in the same duct itself (FHWA 2013). Figure 2-5 (a) shows an opened anchorage end from a PT bridge in the USA. A clear demarcation between the Type 1 grout at the top and Type 4 grout at the bottom can be visible from Figure 2-5 (a).

The strands are exposed to the atmosphere where the Type 1 grout is present. Similarly, Figure 2-5 (b) shows an opened anchorage head from another PT bridge in the USA. Type 1 grout and Type 4 grout are present in the system, and near the Type 1 grout, the corrosion products are formed (FHWA 2013)



a) Opened anchorage end (Courtesy: Parsons Brinckerhoff)



b) Opened anchorage end (Courtesy: Parsons Brinckerhoff)

Figure 2-5. Different types of grouts observed in PT bridges in the USA (FHWA 2013)

2.5.2 Properties of the PT grout

The desired properties of good-quality PT grout are listed below. The details of the experimental test methods to determine these parameters and the desired level (set by different standards) of these parameters are explained in Section 3.3.

2.5.2.1 Fluidity

The fluidity of PT grout is a general term which indicates how easily the cementitious grout flows inside the PT duct when it is in the fresh state. The grout must be fluid enough to fill even the smallest interstitial space between the tendons and duct. Also, the fluidity of the PT grout is the deciding factor for the determination of the pumping pressure. As the fluidity decreases, the pressure needed will become more. The fluidity of the PT grouts is usually assessed by measuring the ‘efflux time’ using Marsh cone conforming to EN 445 (2007) or ASTM C 939 (2010). Similarly, the fluidity often assessed by measuring the ‘spread diameter’ of the freshly prepared grout with spread test as per EN 445 (2007).

Efflux time and spread diameter can be used as the indication of the fluidity of the PT grout. These test methods are widely used in the construction field as a quality check due to its simplicity and the cost-effectiveness. Thus, the Marsh cone and spread tests are simple empirical methods to characterize the fluidity of PT grout whereas rheological tests with a viscometer/dynamic shear rheometer provide more fundamental understanding about flow behaviour of the PT grout; however, require more complex equipment and skilled operators.

The type of cement, admixtures, particle size, and shape, etc. affect the fluidity of the cementitious systems. Also, the fluidity can change with the changes in ambient temperature, water content, HRWR dosage and addition method, relative humidity, mixing energy (Jayasree 2008, John 2014).

2.5.2.2 Fluidity retention

PT grout should retain its fluidity throughout the entire period of grouting operation. Usually, the grouting continues up to 3 hours depending on the length of the duct. If the PT grout does not have desired levels of fluidity retention, it can affect the pumping and flow through the duct. Fluidity retention can be evaluated by measuring the change in efflux time or spread diameter up to the desired period (say, three hours).

2.5.2.3 Viscosity

Viscosity is the measure of the resistance offered by layers of the fresh grout to the deformation by shear stress (Hackley and Ferraris 2001). As the freshly prepared cementitious grout is a non-Newtonian, thixotropic fluid, the viscosity will vary with respect to shear rate as well as with time (Papo 1988; Roussel 2005; Yahia and Khayat 2003). The time-dependent variation of viscosity happens from the non-reversible changes due to the hydration reaction and the reversible changes due to the thixotropy. Also, the PT grout will experience a wide range of shear rate at the time of mixing, pumping to the duct, and while flowing through the tortuous path between the tendon and the duct (Ferrara et al. 2012). However, if the w/b is high (more than 0.4) or at the saturated dosages of HRWR, generally, the constituent particles will be in the highly dispersed state and will behave like a near-Newtonian fluid (Agullo et al. 1999, Jayasree 2008, Roy and Roussel 2005). Thus, at highly dispersed state, viscosity in terms of efflux time can be understood from Marsh cone test with reasonable accuracy. However, the accurate measurements of viscosity of the grout can be obtained from shear rate sweeping experiments using a viscometer/dynamic shear rheometer.

2.5.2.4 Yield stress

Yield stress can be defined as the minimum shear stress required to initiate the flow of a non-Newtonian fluid (here, the PT grout in the fresh state). Although there are considerable debates going on "on the existence of yield stress," in the rheology community, experimental evidence suggests that the cement grout exhibits definite yield stress. The yield stress can be a crucial factor for the design of the PT grout because it is indirectly related to the bleed resistance of the grout (Perrot, 2009). Also, before the motion of the grout impends during pumping and flow through the duct, the amount of yield stress present in the material determines the pumping pressure required.

The yield stress of the cement grout can be measured by both rotational and oscillatory rheometry. Rotational methods include: 1) fitting the flow curve to a suitable rheological model and then extrapolating the flow curve to the shear stress axis and determining the shear stress corresponding to zero shear rate. 2) measuring the creep compliance for increasing stress levels and determining the transition from a solid like to a liquid-like material (Christopoulou et al. 2009; Qian and Kawashima 2016). Oscillatory methods include 1) estimating the crossing point of loss and storage modulus (Kugge et al. 2011) 2) fitting the behavior well above the yield point with a power-law function and defining the yield point by the intersection of this line with the horizontal line through the linear storage modulus data (Graef et al. 2011) 3) by plotting shear stress vs shear strain curve on logarithmic scale, and then determining the intersection of a line with unit slope at low strains with a power-law equation at high strains (Christopoulou et al. 2009).

The yield stress if the cementitious grouts can be determined with reasonable accuracy by fitting to the Herschel-Bulkley model and extrapolating to the shear stress axis (Ferraris 1998, Jayasree 2008, Nguyan 2011). However, this method is not as accurate as the creep compliance method, which requires highly sensitive rheometer/viscometer.

2.5.2.5 Bleed resistance

Bleed resistance is an important quality defining a parameter of the PT grouts. PT grout should be in a stable state throughout the time whole operation of grouting (Khayat 1999, 2008, Kamalakkanan et al. 2018). The bleeding can be defined as the separation of cementitious phase from the grout due to the difference in the density between the constituent particles. A good quality PT grout should be resistant to bleeding/segregation during the grouting operation.

Bleed resistance of the PT grouts can be assessed in several simulated field conditions. The details of the test methods to evaluate the bleed resistance are given in Section 3.3.1. The good quality grout should exhibit zero bleed water volume 3 hours after mixing.

2.5.2.6 Setting time

The setting time of PT grout is important as the setting of the grout will cause problems at the time of pumping and the flow through the duct. Setting time can be determined by using the Vicat apparatus ASTM C953 (2010). Typically, PT grouts will have higher setting time due to the presence of the chemical admixtures such as viscosity modifying agents (Khayat and Yahia 1997),

2.5.2.7 Dimensional stability

The dimensional stability refers to the changes in the volume of the hardened grout. If the hardened grout has volume changes more than the limits (0.1% of initial volume as per PTI M55.1-12), cracks can form and through which deleterious ions ingress and lead to the corrosion of strands.

Typically, PT grouts are prepared with low w/b (say 0.25 - 0.30), and fine materials for achieving an increased bleed resistance. Therefore, the PT grouts with low w/b without any inert fillers can experience and high autogenous shrinkage (Bentz, 2006). This high autogenous shrinkage is due to the presence of very fine capillary pores and the relatively high volume of paste. When the water in these capillary pores is progressively used up for the hydration reaction, a negative capillary pressure will be formed. This negative capillary pressure is directly proportional to the surface tension of the pore solution and inversely proportional to the pore size (Folliard and Berke 1997). Thus, the higher the negative capillary pressure, the higher will be the autogenous shrinkage. One of the best methods to reduce this shrinkage deformation is the addition of shrinkage reducing admixtures (SRA) which reduces the surface tension of the mixing water and thus reducing the shrinkage. Several researchers have investigated the effects of SRAs in the autogenous shrinkage of pure and blended cement paste (Bentz 2006; Rakesh G. 2010, Sant et al. 2010). However, the studies to mitigate the shrinkage deformations in PT grouts are very limited. Yoo et al. (2017) reported that the addition of 2% SRA (glycol based) by weight of binders reduced the shrinkage nearly by 56% (Yoo et al. 2017). However, the concentration of SRA should be optimized to get the maximum possible reduction in surface tension. The addition of SRA beyond a certain dosage will not help in reducing surface tension but creates micelles. Therefore, the concentration of SRA in pore solution should not exceed the CMC (Evans and Wennerström 1999). Thus, the surface tension measurements can help in optimizing the SRA dosage. For conventional concrete systems, drying and carbonation shrinkages are also very important dimensional stability parameters. However, for PT systems, those are negligible because the PT grout will not be in contact with the atmosphere to cause drying.

Cementitious systems are inherently shrinking in nature. Expansion of the PT grout can cause distress on the PT ducts. The use of aluminum powder can significantly increase the pumping pressure needed for the PT grouts. Also, the sensitivity of the aluminum powder to the variations in ambient temperature, water content, time of addition to the grout mix less robust (Hope and Ip 1989; Khayat et al. 1999; Lankard et al. 1993; Schupack 1970). Later, researchers started incorporating the shrinkage reducing agents which primarily works by decreasing the surface tension of the water/liquid phase.

2.5.2.8 Compressive strength

The compressive strength of the PT grout is essential as it is directly proportional to the durability of the system. The more durable grout system can resist the ingress of harmful materials and thus the corrosion of the tendons.

2.5.3 Factors affecting the performance of PT grout

Several factors can influence the performance of the PT grout. Although the grout is mix design is carried out usually based on the fluidity and the bleed resistance, the hardened properties are also important to consider. The essential factors that influence grout performance are listed below.

2.5.3.1 Cement

Ordinary portland cement is the most widely used binder in the design of PT grouts and generally will have more than 50% of the volume of the total binders. The surface area and particle size distribution of cement are important as it can change the fluidity of the freshly prepared grout mix. The cement with the higher surface area can result in higher packing density and when combined with fly ash will exhibit enhanced fluidity (Nanthagopalan and Santhanam 2008). Mizra et al. (2013) observed that the viscosity of the grout mix increases as the surface area of the cement increases (i.e., mean diameter reduces) at low w/c ratios. The author deduced that the grout viscosity is directly proportional to the fineness of the cement based on the study conducted on 16 different types of cements (Mirza et al. 2013). Also, the type of cement with higher surface area and the and cellulose-based VMA will result in enhanced bleed resistance. This can be attributed to the higher rate of adsorption of the VMA molecules on to the cement particles and the resulting intertwined, agglomerated particulates (Khayat 1998).

The composition of the cement used for the preparation of the grout also influences the flow and bleed characteristics. As the concentration of C_3A increases, the grout mix becomes more and more viscous in general. This could be because of the increase in the rate of the hydration reaction and the formation of the new bonds that results in the enhanced viscosity (Mirza et al. 2013). Another aspect is the reaction of the cement with the superplasticizer and VMA. Kim et al. (2000) studied the effect of the cement composition on the fluidity of cement paste with polynaphthalene sulfonate (PNS) based superplasticizer. The rate of adsorption of PNS admixtures on the cement particles found to depend on the amount of C_3A, C_4AF, and C_3S. The cement is having a low amount of soluble alkalis were incompatible with PNS superplasticizer and vice versa. Although these incompatible cements adsorb more superplasticizer, there is no significant change in fluidity and fluidity retention (Kim et al. 2000).

Similarly, studies conducted with polycarboxylate ether (PCE) and PNS based superplasticizers, it was observed that the OPC required less amount of PNS superplasticizer to reach the fully dispersed system with high fluidity compared to low heat of hydration cement. However, the grouts formulated with PCE based superplasticizer have high initial fluidity irrespective of the cement type and w/c ratio. Also, the retention of fluidity was more compared to grouts made with PNS superplasticizer (Yahia 2011). A similar study conducted by with different types viscosity modifying agents (VMA), PCE based HRWR, and OPC it was observed that the dosages of VMA and HRWR highly influences the fluidity and bleed resistance of the cement grouts. There exists two compensating mechanisms of dispersion and agglomeration/intertwining by the actions of HRWR and VMA (Khayat et al. 2008; Khayat and Yahia 1997; Saric-Coric et al. 2003). Therefore, the selection of cement and the appropriate chemical admixture is very important to achieve the desired levels of flow and bleed resistance.

2.5.3.2 Water-to-binder ratio (w/b)

The water-to-binder (w/b) ratio is important as it is directly proportional to the fluidity as well as the amount of bleed water. As the w/b ration increase, the grout mix shows excellent fluidity; however, the bleed resistance will decrease. Thus, PT grouts should have very low w/b to achieve excellent bleed resistance; however, very low w/b ratio will result in enhanced autogenous shrinkage. Therefore, a balanced w/b is desired to achieve a highly flowable grout with better bleed resistance. As discussed in Section 2.5.2.3 the fluidity can be estimated using the Marsh cone if the PT grout is behaving like a Newtonian fluid (Agullo et al. 1999; Jayasree 2008, Khayat and Yahia 1998; Roy and Roussel 2005). But, at very low w/b ratios, the PT grout will have non-Newtonian characteristics such as shear thickening and pseudo-plasticity (Jayasree et al. 2011; Khayat et al. 2002; Yahia and Khayat 2001). However, the fluidity can be estimated by using the Flow/Marsh cone at the saturation dosage of superplasticizer as the particles will be dispersed entirely (Jayasree and Gettu 2008).

Another aspect associated with the w/b ratio is the susceptibility of autogenous shrinkage. The autogenous shrinkage is significant for cement grouts incorporating the very fine supplementary cementitious materials at low w/c ratios. The autogenous shrinkage will be significant if the w/c is less than 0.42 and concrete with very low w/c of 0.17, the autogenous shrinkage strain was reported as 700×10^{-6} at 28 days of age (Aitcin et al. 1997, Tazawa and Miyazawa, 1994).

2.5.3.3 Mineral admixtures and inert fillers

PT grouts with tailor-made properties can be prepared by replacing OPC with supplementary cementitious materials such as fly ash, silica fume, blast furnace slag, and metakaolin. The type and fineness of the mineral admixtures will influence the fluidity and the bleed resistance. Thus, great care must be given while choosing the combination and proportion of these materials. The effect of these materials on the fresh and hardened properties has been studied to a great extent in the past four decades.

Hope et al. studied the effect of silica fume on the fluidity and the bleed resistance of the PT grouts. He observed that a replacement of 10-15% silica fume by weight of binders (% bwob) could reduce the bleed to zero. However, this level of replacement of silica fume can reduce the fluidity considerably. Also, the incorporation of silica fume can result in a very dense and impermeable grout mix compared to the control gout having only OPC. The results of accelerated chloride permeability tests showed that the charge passing through the grout with 10% silica fume was about ten times less than that with control grout (Hope et al. 1988). The reason for the enhanced bleed resistance can be attributed to the higher surface area of the silica fume particle and resulting in higher packing density. Deidrichs et al. (1989) conducted studied on the effect of temperature, and relative humidity with silica fume replaced grouts. He observed that when OPC replaced with silica fume by 5% bwob, the bleed resistance can the bleed resistance can enhance 40% more than the control mixes at a w/c of 0.4 (Deidrichs et al. 1989). Similarly, the grout with OPC replaced by 8% silica fume bwob with combinations of PNS based HRWR and welan gum VMA, can exhibit excellent fluidity and fluidity retention. The bleed resistance under standard and pressure-induced conditions were also excellent compared to the OPC control mix (Khayat et al. 1999). Thus, the use of silica fume in the formulation of PT grouts can be very effective provided to use adequate dosages of HRWR to achieve desired levels of fluidity.

The effect of fly ash particles in the cementitious systems is well studied and documented. The replacement of fly ash (up to 40%) increases the fluidity, corrosion protection by chloride binding, enhanced long-term strength gain, etc. (Cheewaket et al. 2009, Lee et al. 2003, Khayat et al. 2008). Krishnamurty et al. (2002) studied the effect of Class F fly ash on the fresh and hardened properties of the cementitious grout with different w/b ratio ranging from 0.25 - 0.40. Grouts made with 40% replacement of Class C fly ash by volume of binders (bvob) can exhibit the enhanced bleed resistance in the investigated range of w/b (Krishnamurty et al. 2002). Khayat et al. (2008) observed that the replacement of Class F fly ash bvob up to 30% and with low dosages of PNS based HRWR increases the viscosity of the grout. Such an increase may be due to the formation of a less dispersed system even though the HRWR was present in the system (Khayat et al. 2008). However, with an increase (up to 40%) of the replacement level of fly ash can further enhance flow properties. This may be due to the effect of ball bearing action by fly ash particles become dominant and reduce the interparticle friction when the high replacement level (Khayat et al. 2008). Therefore, the dosage of fly ash particles is very important to achieve the desired level of fluidity.

The grouts made by replacing OPC up to 40% ground granulated blast furnace slag (bwob) shows enhanced fluidity with increased water demand. The ternary blended grouts with fly ash and slag (replaced up to 50%) need relatively more amount of HRWR than binary blended OPC and slag system. This can be due to the increased water demand from the more packed ternary blend. However, the resulting well-dispersed ternary blend has shown better bleed resistance, lower yield stress, and higher viscosity. The increase in viscosity (up to 90%) can adversely affect the smooth flow of grout inside the duct (Khayat et al. 2008).

The replacement of OPC with metakaolin in the range of 6% to 20% bwob decreases the fluidity significantly. The yield stress and viscosity were also found to increase. This is due to the high surface area of metakaolin particles and high-water demand. Also, the compressive strength increases significantly which can be due to the reaction of calcium hydroxide to produce more CSH (Sonebi et al. 2013). Another study conducted by replacing the OPC with natural zeolite has shown that the replacement of zeolite up to 40% increases the viscosity and yield stress significantly. However, the grout had more compressive strength (about 20%) (Sahamaran et al. 2008). The reason could be the enhanced adsorption of water by zeolite particles due to its high surface area and a large number of micro-passages and cavities on the crystalline surface (Chan et al. 1999)

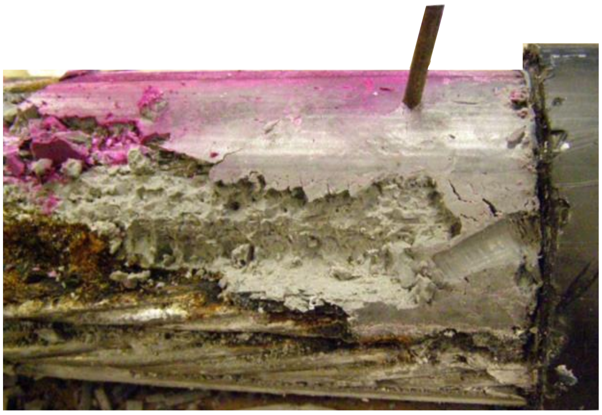
The cementitious grouts incorporating inert fillers can reduce the plastic and autogenous shrinkage strains to a great extent. Besides, as the amount of reactive binder content is reduced, the heat of hydration will be less. This way can reduce the thermal cracks due to the high heat generation. Almost all the commercially available grouts have 30 - 40% of inert fillers by weight of total binder content (Hamilton et al. 2014). However, there are some adverse effects like the formation of soft grout due to the addition of inert fillers. Softgrout can be defined as the layer of low-density grout on the surface of the grout with high permeability and low strength (Hamilton et al. 2014). The softgrout will have low pH and can retain moisture. The formation of soft grout can accelerate the corrosion initiation of PT tendons (Hamilton et al. 2014). The principal reason for the formation of the soft grout is the segregation of the inert filler particle from the grout system.

(a) A layer of softgrout on an opened anchorage zone (FHWA 2013)

(b) A layer of highly permeable softgrout with a ruler pierced into it (FDOT 2016)

Figure 2-6. Softgrout formed at the anchorage zone of the PT duct (from literature)

b) A scarpable layer of highly permeable softgrout (Hamilton et al. 2014)



a) Softgrout/segregation (Babu 2016)

c) A layer of softgrout with a screwdriver inserted into it (Lau et al. 2016)

Figure 2-7. Softgrout/segregation exhibited by commercially available PPGs (from literature)

If the filler material has low specific gravity than the binders in the grout, it can create a layer of softgrout at the top surface. The grout mixes with 35-45% filler material such as limestone powder generated twice the amount of soft grout than the control mix without filler (Randell et al. 2015). Thus, utmost care should be taken while selecting the filler material and the level of replacement. Also, the softgrout layer was observed on the commercially available pre-packaged grouts tested at IIT Madras (Babu 2016).

It is worth noting that even though a handful of studies have done on the grouts containing mineral admixtures, in most of the studies, the researchers have used high water content to enhance the fluidity, which adversely affected the bleed resistance. Also, most of the studies were not exclusively for the PT grouts where the bleed resistance is of paramount importance.

2.5.3.4 Chemical admixtures

The chemical admixtures like superplasticizer, viscosity modifying agents, air entrainers, and corrosion inhibitors, expansive agents, shrinkage reducing agents, etc. are widely used in the formulation of the PT grouts. The balanced combinations of compatible admixtures are always necessary to achieve a highly flowable, bleed resistant grout, and dimensionally stable grout.

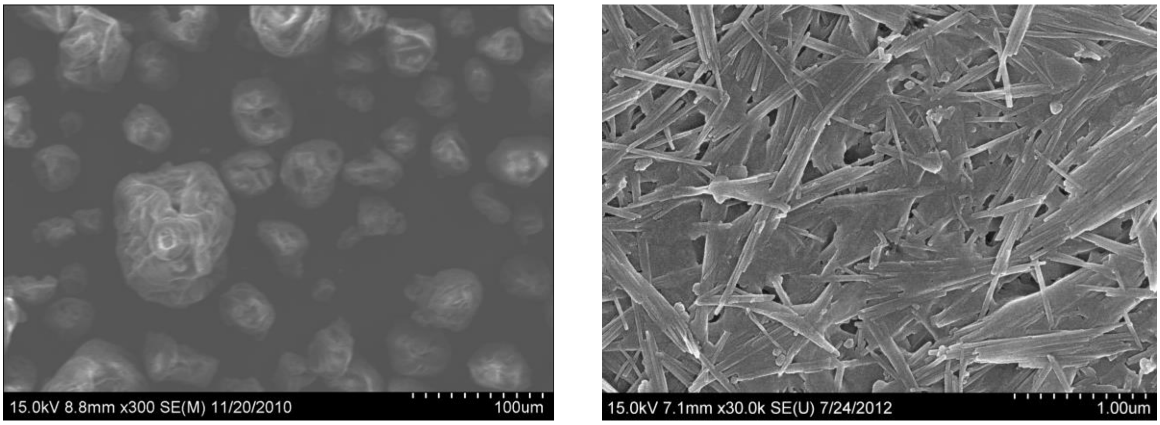
Addition of HRWR generally increases the fluidity of the PT grout regardless of the w/b ratio. When the HRWR is at the saturation dosage, the constituent particles in the system disperse completely. Also, at the saturation dosage, the grout mix behaves like a near-Newtonian fluid and exhibit the highest fluidity (Gettu et al. 1999, Roussel et al. 2005). After the saturation dosage, the liquid phase of the grout separates out. When the added to the cement the HRWR particles will adsorb on to the cement particles and dispersion of the cementitious particles will depend upon the degree of the adsorption of the superplasticizer molecules on the cementitious particles. Generally, the adsorption of superplasticizer can depend on several factors like ingredients of the grout mix, type of HRWR, nature of the aqueous solution, alkali content, presence and concentration of other chemical admixtures and the type of sulfates (Flatt et al. 2001). The initial fluidity of the cement grout generally increases with the degree of adsorption of PCE based HRWR. On the other hand, the degree of adsorption of SNF (Sulphonated Naphthalene Formaldehyde) based superplasticizer is inversely proportional to the fluidity of the grout. This can be due to the low amount of polymer chains in the system to disperse cement particles. The PNS based superplasticizers will be strongly adsorbed to the aluminates than the hydration products of the silicate phase. The hemihydrates and alkalis can be used to reduce the rate of adsorption and can increase the initial fluidity (Khayat et al. 2008).

Another aspect is the sequence of addition of superplasticizer to the grout mix. The SNF based superplasticizers have a strong affinity towards the C_3A and will compete with gypsum. Therefore, the reaction between gypsum and C_3A will be retarded. The incompatibility issues may arise due to the variation of the chemical composition. Therefore, SNF based admixtures are not suitable for the pre-packaged grouts where all the ingredients are pre-blended. The use of PCE based superplasticizers has fewer incompatibility issues and can be successfully used for the formulation of the pre-packaged grouts.

Shupack (1971) started using chemical admixtures such as viscosity modifying agents (VMA) in the PT grout formulation to increase the bleed resistance. From the large-scale prototype tendon grouting tests using draped ducts and tendons, he showed that the (VMAs) could drastically reduce the bleed water (Schupack 1974). VMA generally increases the viscosity of the mixing water which in turn reduces the settling of the particles – resulting in improved bleed resistance (Schupack 1971). Hence, different classes of VMAs such as cellulose ethers, natural gums are widely used in PT grouts (Khayat 1998, Khayat and Yahia 1997).

Highly purified palygorskite clay (also known as nanoclay) particles has been used in specific applications like self-compacting concretes and 3D printable concrete, there was only a handful of studies which gives a practical insight to the fluidity of the cement pastes incorporating nanoclay particles (Ferron 2008, Kawashima 2012, Kawashima et al. 2013a, 2013b, Tregger et al. 2010). The nanoclay particles create flocs and increase the flocculation strength and thus enhances the stiffness rapidly when kept rest (Ferron 2008, Tregger et al. 2010). These flocs are highly stable with strong inter particles bonds. Ferron et al. (2013) used the focused beam reflectance measurements and observed that the addition of small dosages (up to 1%) creates a highly agglomerated system with bigger chord lengths (Ferron et al. 2013). The increase in the flocculation strength and resulting stiffness can be best utilized in the PT grouts as these systems need a compromise between the fluidity (i.e., should have sufficiently low viscosity) and stability at the time of pumping and flow through the tortuous path in the PT duct with congested strand system. In addition, the nanoclay particles can accelerate the rate of hydration and can improve the fresh properties of the cementitious systems by acting as a seeding agent or as a filler material. With the small dosages of nanoclay itself (about 1%), the rate of structural rebuilding at rest was found to be much higher than the plain cement pastes without the nanoclay. This can be due to the rate of rebuilding (aging) is much higher as the clays make the system in a highly jammed state immediately after shear (Kawashima et al. 2013a). In addition, the highly purified attapulgite clays exhibit high stability in the colloidal systems and forms gel in the liquid phase of the matrix and thus, increase the rate of the rebuilding of the system.

The nanoclay particles are chemically exfoliated to remove the swelling characteristics. Generally, the nanoclay particles will be in highly agglomerated form (by the manufacturer) for the ease of transport. However, in its original form, it has a particle size of 1.75 μm in length and 3 nm in diameter and needle-like shape (Kawashima 2013). Figure 2-8 shows the SEM images of the nanoclay particles in highly agglomerated and dispersed states. From Figure 2-8 (b), it is apparent that the nanoclay particles have a needle-like shape.



a) Highly agglomerated state **b) Well-dispersed state**

Figure 2-8. Scanning electron micrographs of nanoclay particles (Kawashima et al. 2012)

2.5.3.5 Method of mixing and mixing procedure

The mixing of binder phase with water is important to achieve a grout mix with good homogeneity. The type of mixing, mixing speed, mixing time, and the sequence of addition of ingredients in the mixing significantly influence the properties of the resulting grout. Also, the variations in these factors can affect the fresh properties of the PT grout (Han and Ferron 2015)

To disperse the binders and chemical admixtures in PT grouts with low water content, high-shear colloidal mixers must be used. The high shear mixer can properly disperse all the ingredients due to high mixing energy. However, the low-speed paddle mixer may not disperse the particles completely. ASTM C1738 (2018) specifies the method (high-shear mixing) of mixing of cement pastes (AST C 1738: 2018).

2.5.4 Particle packing method for the mixture proportion

The cementitious PT grouts can be prepared with different ways by combining the OPC and SCMs. Several researchers have carried out the parametric studies to understand the rheology, bleed resistance, shrinkage, etc. of the PT grouts by replacing OPC with different dosages of SCMs and chemical admixtures (Khayat et al. 1999, 2008; Krishnamoorthy et al. 2002; Schupack 1974). As the fresh properties of the PT grouts greatly affected by the combination and proportion of the binders, it is very important to optimize the proportions of the binders.

The role of the particle packing on the flow properties of the cement paste has been investigated previously. Bentz et al. (2012) observed that the total particle density has a linear correlation with the plastic viscosity of the cement paste replaced with fly ash (Bentz et al. 2012). Similar studies have shown that as the particle packing density of the system increases, the yield stress reduces (Nanthagopalan et al. 2008). Therefore, the system will exhibit good fluidity when the particles are packed in their maximum possible packing density. One of the easiest methods to measure the packing density is by Puntke test – which is based on the concept of filling of the gaps between the particles in the system with a fluid (say, water or kerosene). The packing density and the volume of the liquid needed to fill the gaps are in inversely proportional. By using the particle packing method, the proportioning of the binders used in the grout mix design can be optimized. (Nanthagopalan et al. 2008).

In the last century, several studies were conducted in the concept of particle packing, and all of them revolves around the same concept; the smaller particles will fill up the voids between the larger particles. This concept of particle packing in concrete technology helped in the design of high-performance concrete, self-compacting concrete, fiber-reinforced concrete, etc. (Fennis and Walraven 2012). Fuller in 1907 introduced an exponential grading curve that gives the greatest packing density for the aggregates alone (Fuller and Thompson 1907). Later, Andreasson has proposed a model by assuming that the smallest particles in the system would be infinitesimally small (Kumar and Santhanam 2003). However, in real materials, the finest particles have a finite size and the model will not give an accurate estimation of the ideal packing. Thus, Diner and Funk modified the Andreasson model by linking the Furnas distributions and termed as modified Andreasson model (Kumar and Santhanam 2003). The model is described the given in Equation 5.1

$$CFPT = 100\left[\frac{d^q - {d_m}^q}{D^q - {d_m}^q}\right] \qquad \text{Eq. 5.1}$$

where,

CFPT	=	Cumulative (volume) Percent Finer Than
q	=	Distribution coefficient;
d	=	Particle size
d_m	=	Minimum particle size of the distribution
D	=	Maximum particle size

The distribution coefficient (q) in the modified Andreasson equation can be varied in the range of 0.21 to 0.37, depending on the different required levels of workability. As the value of q increases, the system will accommodate coarser particles, and as the value of q decreases, the volume of finer particles will increase (Banerjee 1998). The packing theories consider the packing of elements by volume basis. If all the constituent particles are of the same density, the respective volume would be proportional to the weight. However, the experiments involving several particles with different densities, it is important to convert the weights to corresponding volumes (Elkem 2016).

The mixture proportioning of the PBGs in this study was carried out with the particle packing method. A detailed description of the mixture proportioning methodology is given in Section 4.1.1.

2.6 GLOBAL AND INDIAN SCENARIO OF GROUT MATERIALS AND GROUTING PRACTICES

In the developed world, the grouting operations are carried out with utmost care. A handful of standards and guidelines have been published by agencies such as PTI, ASBI, ACI, and *fib* to ensure that the grouting operations are carried out with utmost care with good quality grout materials. Also, other state agencies in USA such as FDOT, TxDOT, and FHWA have been published guidelines for good grouting practices and periodically conducts training programs for the engineers, contractors, and workforce who works in the PT concrete field. On the other hand, the engineers/contractors, even the authorities do not give proper importance to the grouting operations in most of the developing countries. Also, there exists a serious lack of awareness about good grout materials and grouting practices in those countries (Babu 2016, Kamalakkanan et al. 2018).

2.6.1 Grout material

High-performance prepacked grouts are used in the developed world from the early 2000s onwards (PTI Technical note 2015). As these new grouts are properly engineered and made in a factory with controlled conditions, it is anticipated that they show desired flow properties and resistance to bleeding/segregation. However, recently, there were reported incidents of the higher levels of chloride content in the PPGs and tendency to form highly permeable softgrout at the crown points of the PT duct. The improper mixture design, inadequate selection of ingredients without proper technical know-how are the main reasons for these problems (Neff 2012, FHWA Memorandum 2011 & 2012, Hamilton et al. 2014, Randell et al. 2015, Babu 2016). On the other hand, the developing countries use indigenous grout materials (also known as site-batched-grout, (SBG) for the PT applications (Kamalakannan et al. 2018).

Studies have been conducted at IIT Madras to sensitize the PT grouts available in the Indian/foreign market and widely used indigenous grouts. Figure 2-9 shows the efflux time of some of the widely used PCG, SBGs, and PPGs. These grouts are made according to the water content prescribed by the manufacturer or the water content used at the construction site. PPGs have high efflux time compared to the SBGs and PCG indicating low fluidity. Similarly,

Figure 2-10 shows the volume of bleed water exhibited by same grouts (PCG, SBGs, and PPGs). From Figure 2-9, it is apparent that commercially available PPGs have high bleed resistance compared to PCG and SBGs even though their fluidity is relatively low. The reason for low fluidity and high bleed resistance can be due to the presence of chemical admixtures in the PPGs and the low water content respectively.

Generally, there is the practice of using Marsh cone test only for the selection/rejection of good/poor-quality grouts at the construction site. However, it can result in the selection of very low bleed resistant PCGs and SBGs and rejection of bleed-resistant PPGs. Therefore, Marsh cone test alone should not be used as a screening test for the PT grouts; all the different bleed tests also should be assessed for the section/rejection (Kamalakannan et al. 2018).

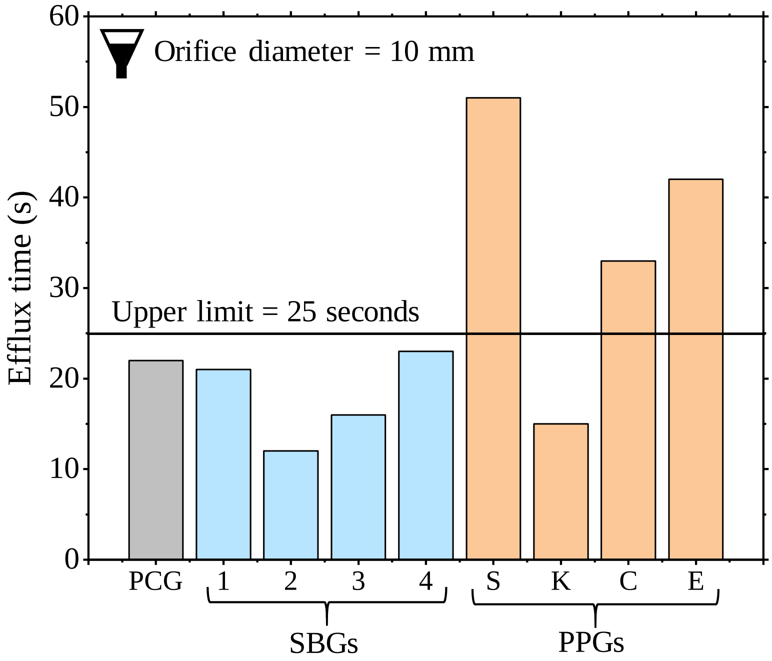


Figure 2-9. Efflux time of the PCG, SBGs, and PPGs (Kamalakannan et al. 2018, Babu 2016, Dutta 2017)

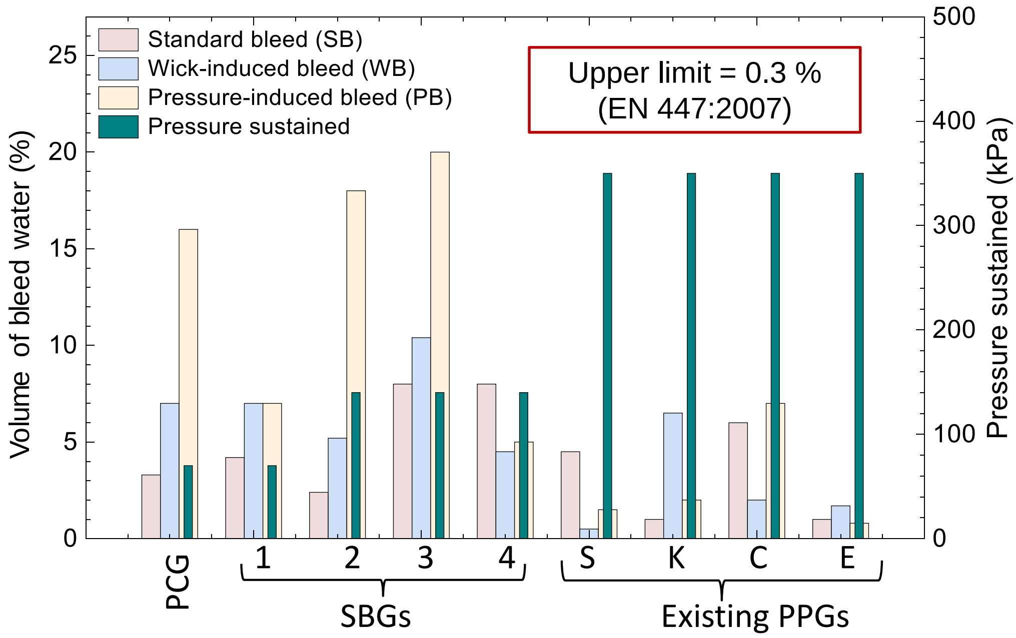


Figure 2-10. Bleed volume of PCG, SBGs, and PPGs under three different simulated real bleed test conditions (Kamalakannan et al. 2018, Babu 2016, Dutta 2017)

2.6.2 Grouting practices

The grouting practices are equally important as the grouting materials to achieve complete filling of PT ducts. However, in several parts of the world, the grouting operations are carried out with least care, and thus, voids are formed throughout the duct – leading to the exposed strands and eventually corrosion of strands. As discussed in Section 2.6, different agencies have published guidelines for good grouting practices.

A few good grouting practices are as follows:

1) Grouted PT tendon ends must be covered with fiber-reinforced plastic with an anti-oxidant coating. The grout caps must have a service life of at least 75 years with an environmental stress endurance of 192 hours as per ASTM D 1693 (2015). The end caps must be attached to anchor plates with stainless steel bolts. The use of proper end caps will arrest the ingress of moisture to the tendons (FHWA 2004).

2) The grouting of draped or horizontal tendons should be carried out from the lowest points of the tendon profile. The inlet points can be initial anchorage zone or at the intermediate lower points. To ensure the grout has completely filled the duct, a fixed quantity of grout must be discharged through the outlet (FHWA 2013).

3) The grouting operation should be carried out by keeping the tendons and ducts in the dry state. However, there exists a common practice of flushing the PT ducts with water or oil to remove the impurities on the surface of PT tendons (say sand, dust, etc.). However, this is not a good practice as it is impossible to remove the flushed water completely. Water should not be pumped inside the duct prior to pumping. The pumping of water prior to grout injection will facilitate the corrosion of the tendons (FHWA 2004, PTI M55.1-12: 2013).

Some of the poor grouting practices can be enumerated as follows:

1) One of the bad grouting practice is to fill the grout from the elevated points (crown points) of the duct. This will result in the incomplete filling of the duct and thus, the formation of the voids later.

2) It is very common in many developing countries to seal the anchorage ends with quick setting mortar (dry packing) or by concreting the anchorage recess before grouting (fib bulletin 33: 2006). The cementitious end caps are highly hygroscopic and attracts moisture to the tendons and thus, facilitates the onset of corrosion.

3) Flushing the PT ducts with water before pumping of the grout can also be a poor grouting practice. The corrosion can be initiated in the strands due to the pumping of water. Also, the water flushed inside the duct can mix with the cementitious grout and can facilitate bleeding. The corrosion incidents were observed in PT tendons which were flushed with water before grouting (Babu 2016).

a) High quality plastic grout caps should be used as end caps (Courtesy VSL, Switzerland)

b) Good quality polymer based end cap at blister of a PT bridge (fib bulletin 33, 2005)

Figure 2-11. Examples of good grouting/grouting practices

a) Cementitious end-caps used in a metro bridge **b) Cementitious end-caps used in a girder**

Figure 2-12. Examples of poor grouting/construction practices

2.7 SPECIFICATIONS FROM STANDARDS/CODES

The grouting is a complex process involving various tasks. Those tasks range from proper material selection to the pumping of the fresh grout. To achieve good quality grouting, the different tasks involved in the process must be systematic. As discussed in Section 2.6, various standards have been published by different national agencies for this purpose contains the specifications from these standards on grout properties (EN 445:2007, EN447: 2007; fib bulletin 20: 2002; IRC 2003; JSCE 2007; PTI M55.1-12: 2002). Table 2-5 enlists the detailed description of different quality defining parameters mentioned in various standards. The dashed line in each column indicates the absence of the specification pertaining to that parameter/property. From Table 2-5, it is apparent that most of the standards are not complete/comprehensive and stringent enough to differentiate good and poor-quality PT grouts. Similarly, Table 2-6 shows the specifications on the materials used for the grout formulation specified in various standards. EN 447 (2007), ISO 14824-1 (2012), PTI M55.1 12 (2013) standards give more comprehensive and stringent specifications for the grout materials.

Table 2-7 enlists the specifications on the duct materials and grouting operations to be adopted to achieve avoid free grout system. EN447 (2007), fib bulletin no. 20 (2002), PTI M55.1-12 (2013, and MORTH standards give more exacting specifications, and other national standards do not specify on the duct materials and grouting operations.

Over the last two decades, state agencies like FHWA, FDOT, TxDOT in USA have published technical documents and detailed manuals/guidelines on PT tendon installation, selection of grout materials, test methods to assess the grout properties, grouting operations, etc. (FHWA 2004, 2013a, 2013b, FDOT 2016, TxDOT 2009). Several similar documents were published mostly in Europe and the USA VSL international (a for-profit company specializes in installation and grouting of PT system) aiming to improve the quality of the PT grouts (Misra et al. 2004; Somerville 2002; TxDOT 2004). To achieve the expected level of corrosion protection using the PT grouts, the specifications must be comprehensive and stringent. By proper following of these specifications can qualify/disqualify the good/poor quality grouts and can help in achieving required corrosion protection.

Table 2-5. Specifications for PT grouts mentioned in various standards

Parameter	EN 447 (2007) & ISO 14824 – 1 (2012)	PTI M55.1-12 (2013)	*fib* bulletin no. 20 (2002)	MORTH (2013)	IRS (2003)	IS 1343 (2012)	JSCE (2007)
$T_{e,0}$ (s)	≤ 25	$5 \leq T_{e,0} \leq 30$	≤ 25	-	-	-	-
$T_{e,30}$	$1.2\ T_{e,0} \geq T_{e,30} \geq 0.8\ T_{e,0}$ & $T_{e,30} \leq 25$	-	-	-	-	-	-
$D_{s,0}$ (mm)	≥ 140	-	-	-	-	-	-
$D_{s,30}$ (mm)	$1.2\ D_{s,0} \geq D_{s,30} \geq 0.8\ D_{s,0}$ & $D_{s,30} \geq 140$	-	-	-	-	-	-
$BV_{Standard}$ (%) BV_{Wick} (%) $BV_{Pressure,\ 350kPa}$ (%) $BV_{Inclined}$ (%)	 ≤ 0.3 - ≤ 0.3	- ≤ 0.0 ≤ 0.0 ≤ 0.3	- ≤ 0.3 - ≤ 0.3	- ≤ 0.3 - -	- - - -	- - - -	- ≤ 2.0 - -
ST_i (hour) ST_f (hour)	≥ 3 ≤ 24	$3 \leq ST_i \leq 12$ -	> 3 < 24	$3 \leq ST_i \leq 12$ ≤ 24	- -	- -	- -
Compressive strength (MPa) 7-day 28-day	- ≥ 27 ≥ 30	- ≥ 21 ≥ 35	- ≥ 27 -	 ≥ 27 ≥ 30	 ≥ 17 -	- - ≥ 27	- ≥ 20
Volume change (%) At 24 hrs. At 28 days	 - –1 to 5	- $\leq +0.1$ $\geq +0.2$	- –0.5 to +5.0 -	 - 1-5	- - -	 - -	 –0.5 to + 0.5
Deleterious materials (%) Chloride (Cl^-) Sulphate (SO_3^{2-}) Sulphide (S^{2-})	- 0.1 4.5 0.01	- 0.08 - -	- ≤ 4.1 ≤ 4.5 ≤ 0.01	- 0.1 4 0.01	- - - -	- 0.1 - -	- - - -

EN - Euronorms; ISO - International Organization for Standardization; PTI - Post-Tensioning Institute; *fib* - Federation of Structural Concrete; MORTH - Ministry of Road Transport and Highways by Govt. of India; IRS - Indian Railway Standards concrete bridge code; IS 1343 - Indian Standard for prestressed concrete; JSCE - Japan Society of Civil Engineers

Table 2-6. Specifications on the ingredients for PT grouts mentioned in various standards.

	Parameter	EN 447 (2007) & ISO 14824 – 1 (2012)	PTI M55.1-12 (2013)	*fib* bulletin no. 20 (2002)	MORTH (2013)	IRS (2003)	IS 1343 (2012)	JSCE (2007)
Grout materials	Type of cement	OPC and blended cements are allowed	OPC with Blaine's surface area of 300 - 380 m^2/kg and blended cements are allowed	OPC and blended cements are allowed	Only OPC is allowed. Blended cements are not permitted to use	-	-	-
	Mineral admixtures	Mineral admixtures are allowed	Mineral admixtures such as fly ash, slag, and undensified silica fume are allowed	Mineral admixtures are allowed	No mineral admixtures are allowed	-	-	-
	Chemical admixtures	Admixtures compatible with cement and mineral admixtures are allowed	Admixtures compatible with cement and mineral admixtures are allowed	Admixtures compatible with cement and mineral admixtures are allowed	Admixtures compatible with cement and mineral admixtures are allowed	-	-	-
	Water	Clean potable water	Clean, potable water with a concentration of Cl^{-1} ions ≤ 500 ppm & no organic matter	Clean water	Clean potable water	-	-	-
	w/b ratio	-	-		< 0.45	-	-	-
	Grout temperature, T (°C)	-	≤ 32	10 ≤ T ≤ 40	≤ 25	-	-	-
	Allowable aggregate size	Not allowed	≤ 1 mm		≤ 150 μm	-	-	-

EN - Euronorms; ISO - International Organization for Standardization; PTI - Post-Tensioning Institute; *fib* - Federation of Structural Concrete; MORTH - Ministry of Road Transport and Highways by Govt. of India; IRS - Indian Railway Standards concrete bridge code; IS 1343 - Indian Standard for prestressed concrete; JSCE - Japan Society of Civil Engineers

Table 2-7. Specifications on the duct materials and grouting operations mentioned in various standards.

Parameter		EN 447 (2007) & ISO 14824 – 1 (2012)	PTI M55.1-12 (2013)	*fib* bulletin no. 20 (2002)	MORTH (2013)	IRS (2003)	IS 1343 (2012)	JSCE (2007)
Duct	Duct material	Galvanized steel or smooth/corrugated HDPE pipes	Galvanized steel or smooth/corrugated HDPE pipes	Galvanized steel or smooth/corrugated HDPE pipes	Galvanized or smooth/corrugated HDPE pipes	-	-	-
	Cross-sectional area of the duct	≤ 2 to 3 times the area of steel present inside	≤ 2 times the area of steel present inside	≤ 2 to 3 times the area of steel present inside	≤ 2 times the area of steel present inside	-	-	-
Operation	Grouting time	≤ 30 minutes after mixing	≤ 30 minutes after mixing		No hand mixing	-	-	-
	Grout mixer & pump	Colloidal mixer to produce homogenous and stable grout mix. Positive displace pump must be used	Colloidal mixer to produce homogenous and stable grout mix. Positive displacement pump must be used	Colloidal/vane mixer can be used. Positive displacement pump to inject the grout.	Colloidal mixer to produce homogenous and stable grout mix. Positive displacement pump must be used	-	-	-
	Mixing time	≤ 5 minutes	≤ 2 minutes	-	-	-	-	-
	Grout pump pressure	≤ 1 MPa	≤ 1 MPa	≤ 1 MPa	≤ 0.3 MPa	-	-	-
	Grout injection	-	Should be done from the lowest end	-	-	-	-	-

EN - Euronorms; ISO - International Organization for Standardization; PTI - Post-Tensioning Institute; *fib* - Federation of Structural Concrete; MORTH - Ministry of Road Transport and Highways by Govt. of India; IRS - Indian Railway Standards concrete bridge code; IS 1343 - Indian Standard for prestressed concrete; JSCE - Japan Society of Civil Engineers

2.8 NEED FOR COMPREHENSIVE PERFORMANCE SPECIFICATIONS

The grouting of PT tendons is one of the most important operations to protect the strands from the premature corrosion. Unfortunately, in India and several developing countries, the grout materials and grouting operations of PT concrete systems are not given needed importance. To achieve corrosion free service life of 100+ years, it is very crucial to critically analyze the various standards available different parts of the world. Instead of doing that, there is a trend of adopting the specifications mentioned various standard as such without sensitizing the specifications present in them.

The widely used standard in India for the construction of PT bridges is the standard published by the Ministry of Road Transport and Highways (MORTH) by the Government of India (MORTH 2013). However, the specifications for grout materials and grouting operations are not comprehensive in the MORTH standard. For instance, MORTH standard specifies that only ordinary portland cement must be used for the grout formulation and pozzolanic cement is not allowed (MORTH 2013). However, the advantages associated with the pozzolanic materials are well established and documented. Realizing such potential of SCMs, various other standards permit to use them in the formulation of grout material (PTI M55.1-12: 2013). Similarly, the specifications mentioned in MORTH standard or standard published by Indian Railways (IRS 2003) are not stringent enough to screen out poor-quality grouts. On the other hand, even though the PTI and EN standards are fairly comprehensive, they are not able to screen out a grout with a tendency to form softgrout. This situation will result in the continued use of the poor-quality grouts and thus the segregation/bleeding – leading to the premature corrosion of the strands.

From the critical analysis of Table 2-5 toTable 2-7, a set of quantitative requirements for the grout materials can be defined. Many of the standards do not give the needed emphasis on the bleed properties of the PT grouts. Thus, this study focuses on proposing a set of stringent and comprehensive specifications for the grout materials. The acceptance criteria for all the quality defining parameters should be considered for that.

2.9 SUMMARY AND RESEARCH NEEDS

The review of literature spans from the history of PT tendon corrosion incidents, mechanism of corrosion in grouted PT concrete systems, factors affecting the grout performance, desired properties for PT grout to the analysis of specifications from various standards. Also, a brief outline of test methods for assessing these properties was explained. From the discussion, it can be inferred that there is a dire need for a durable post-tensioned concrete system and comprehensive and stringent performance specifications. Otherwise, we will end up in spending huge amount of money in unavoidable repair and maintenance. This becomes more crucial in the developing countries which are currently witnessing a boom in the construction of large-scale PT concrete systems.

The research needs can be categorized as:

- The specifications for grouting materials and the guidelines for grouting practices from the currently available standards/codes published by a handful of agencies such as PTI, EN, MORTH, IRS, etc. are not comprehensive/stringent enough to differentiate good and poor-quality PT grouts. For instance, none of the above-mentioned standards gives specification on the volume of softgrout; and thus, fails to disqualify the grouts with tendency to form softgrout. Therefore, there is a need for comprehensive and stringent performance specifications to qualify/disqualify good/poor quality grouts.
- Currently, in India and other developing countries, indigenous grouts (SBGs) with very low bleed resistance are used for the PT applications. On the other hand, newly developed pre-packaged grouts (PPGs) with excellent flow and bleed characteristics are used in the developed world for the past two decades. However, the literature indicates that most of these PPGs exhibit a frothy layer in the fresh state and softgrout in the hardened state. The continued use of these grouts for PT applications can result in the ingress of deleterious materials and eventually corrosion of tendons. Therefore, there is a need for developing a good quality flowable, bleed resistant cementitious grout without the formation of softgrout for PT applications.

2.10 MOTIVATION AND SIGNIFICANCE OF CURRENT RESEARCH

As discussed in the previous sections, PT concrete systems are widely used in today's construction sector and are expected to have a corrosion-free service life of 100+ years. Achieving such a long corrosion free service life is very crucial to minimize the large repair and maintenance costs. In order to achieve this, a durable and permanent protection system for tendons is required. Literature indicates that the grouts used in PT industry in India and many developing countries are not meeting the required specifications and can lead to the formation of significant amount voids and exposed strands, which in turn can lead to premature corrosion. Also, in the developed world, the newly developed pre-packaged grouts pose a threat of premature corrosion due to the formation of soft grout (frothy layer). Therefore, this research is motivated by the need of a pre-blended (high accuracy batching and blending of ingredients), highly flowable and bleed-resistant cementitious grouts without the tendency to form softgrout, and a set of stringent performance specifications to avoid premature corrosion of tendon systems in PT concrete structures.

Following points explains the significance of this study:

- A systematic methodology of the mixture proportion of a pre-blended, flowable, bleed resistant cementitious grout without softgrout formation grout using indigenous materials. Such a high-performance pre-blended PT grout (which is currently not available/used in India and many parts of the developing world) can be a viable solution for the preventing the pre-mature corrosion of PT strands.
- The performance of the PT grouts needs to be assessed by large-scale production using an industrial blending facility and subsequent large-scale prototype tendon grouting studies which can closely simulate the performance of the developed grout on a real scale.
- a set of performance specifications (for the grout materials) and a set of guidelines (for good grouting practices to achieve a void-free duct system for PT structures.

CHAPTER 3

METHODOLOGY

3.1 EXPERIMENTAL DESIGN

The overall methodology of the experimental program is shown in Figure 3-1. The study starts with a detailed literature review. The performance of the commercially available and indigenous PT grouts was assessed based on the results of past studies done at IIT Madras. Later, a suitable set of binders and chemical admixtures were identified based on the literature review. The experimental procedure was started with optimizing the combinations and proportions of the binders. After that, the dosages of chemical admixtures were optimized for a pre-defined w/b ratio. Then, the fresh and hardened properties of the formulated PT grouts were evaluated using laboratory test methods. Later, a grout with desired levels of fluidity, bleed resistance, and dimensional stability (as per EN 447:2007) was identified as best performing grout. This grout was selected for further performance assessment. Then, the robustness of the chosen grout with respect to variations in water content and ambient temperature of mixing was assessed. Later, the best performing grout has been blended in an industrial blending facility, and the properties were evaluated on a lab scale. The mixture proportion was fine-tuned further based on the performance of the industrial blended grout. Then, the bleed resistance of the final grout mix has been assessed with large-scale prototype tendon tests. The details of each phase have been explained in the next section.

3.1.1 Overview of experimental program

- Phase-1: Identification, characterization of suitable raw materials and mixture proportioning of pre-blended grouts (PBGs).
- Phase-2: Assessment of the fluidity, fluidity retention, bleed resistance under simulated real conditions, rheological parameters, robustness with respect to mixing variables, dimensional stability, and set/hardened properties of the developed grouts in Phase I.
- Phase-3: Large scale blending of best-performing grout from Phase-2 using an industrial blender, and then the performance assessment on lab scale. All the tests conducted in Phase-2 was repeated in Phase-3 to assess the performance of the PBGs produced on a

large scale. The mixture proportion was further fine-tuned based on the performance, and the large-scale blending was repeated. Prototype tendon grouting tests were conducted with the best performing grout, and the site-batched-grout (SBG). Then, the performance of both the grouts was compared. Finally, a set of performance specifications were developed.

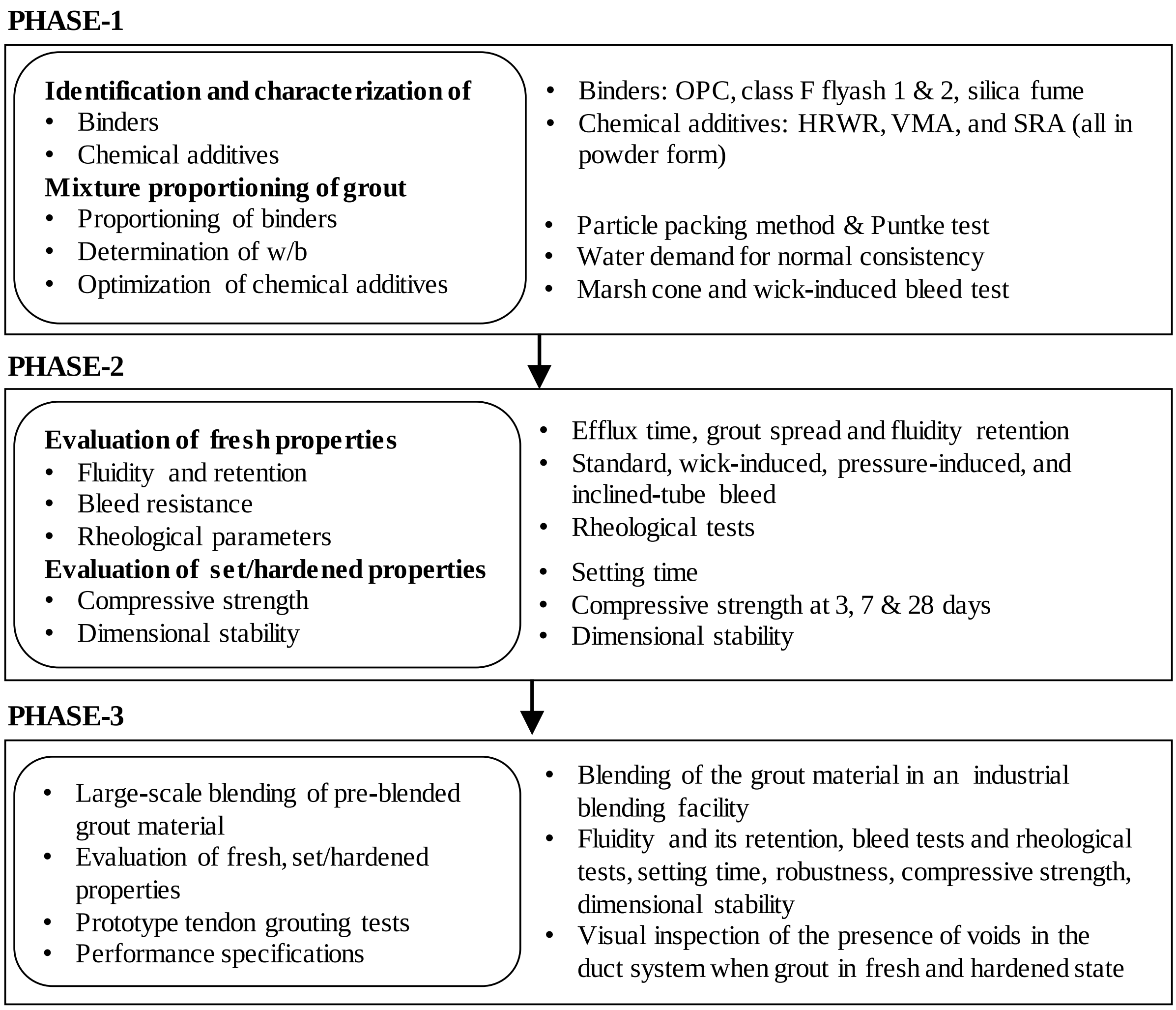


Figure 3-1. Methodology of the experimental program

All the experiments in the first phase were conducted in a controlled environmental condition of 25°C ambient temperature and 65% relative humidity. The experiments were repeated with five replicas of each grout mix to obtain statistically consistent and reproducible results

3.2 PHASE-1: DEVELOPMENT OF PBGS

3.2.1 Materials

The materials used of the grout formulation were identified based on the review of the previous similar studies conducted at IIT Madras and elsewhere (Babu 2016, Kamalakkanan et al. 2018, Dutta 2017). The selection criteria of the ingredients were the ease of availability of the material, the performance, and the cost-effectiveness. All the chemical admixtures were in powder form. Table 3-1 shows the list of identified binders and chemical admixtures.

Table 3-1. Binders and chemical admixtures

Binder	Chemical admixture
• Ordinary portland cement, OPC (53 grade) • Class F fly ash 1 (FaF1) • Class F fly ash 2 (FaF2) • Silica fume	• PCE based high range water reducer • Cellulose-based viscosity modifying agent (Hydroxy ethyl methyl Cellulose) • Nanoclay (Purified palygorskite clay) • Glycol based Shrinkage reducing agent

Ordinary 53-grade portland cement satisfying the requirements of IS 12269 (2013) was used in the study. Two different Class F fly ashes conforming to ASTM C 618 (2019) taken from two from different sources were used. The particle size distribution and fineness of these two fly ashes were different. The silica fume was in the densified form when arrived. The chemical properties of the binders are given in Table 3-2, as determined by X-Ray Fluorescence spectroscopy.

Similarly, Table 3-3 shows the physical properties of the binders used. The water demand for normal consistency of OPC was determined by the Vicat apparatus as per ASTM C187 (2016). The initial and final setting times were determined with Vicat apparatus using a cement paste at its normal consistency. A penetration depth of 25 mm was chosen to determine the initial setting time (ASTM C191: 2018). Then, the test was continued with a standard needle with an annular attachment for determining the final setting time. The time elapsed between the time when water was added to the cement and the time at which the needle fails to make an impression on the surface of the test specimen is taken as the final setting time (ASTM C191: 2018).

Table 3-2. Chemical composition of the binders

Chemical composition	Quantity (by mass %)			
	OPC	FaF1	FaF2	Silica fume
SiO_2	20.88	59.32	60.56	96.8
Al_2O_3	5.54	29.95	32.67	-
Fe_2O_3	4.71	4.32	4.44	-
CaO	61.70	1.28	1.41	0.4
MgO	1.06	0.61	0.23	-
$(Na2O)_{eq..}$	0.20	0.16	0.12	-
LOI	2.27	-	-	-

The specific surface area of the binders was determined by Blain's air permeability apparatus ASTM C204 (2018). As the silica fume particles were in densified form, the Blain's method was not suitable. Therefore, the specific surface area was taken from the manufacturer's specification which was determined by the BET method.

Table 3-3. Physical properties the binders

Parameter	Mean value			
	OPC	FaF1	FaF2	Silica fume
Water demand for normal consistency of cement paste (%)	30	-	-	-
Initial setting time (minutes)	175	-	-	-
Final setting time (hours)	275	-	-	-
Blaine specific surface area (m^2/kg)	310	536	628	15000
Specific gravity	3.15	2.3	2.4	2.2
Mean diameter (µm)	15	4.5	3.0	0.41

The particle size distributions of the OPC and fly ash were determined by laser diffraction method as per ISO 13320 (2009). It was not possible to determine the particle size distribution of the silica fume particles accurately as they were in the densified form. Also, the prolonged ultra-sonification (up to 30 minutes) prior to laser diffraction did not break down the densified silica fume particles to its original size. Therefore, the particle size distribution was taken from the manufactures specification. The particle size distribution curves are shown in Figure 3-2.

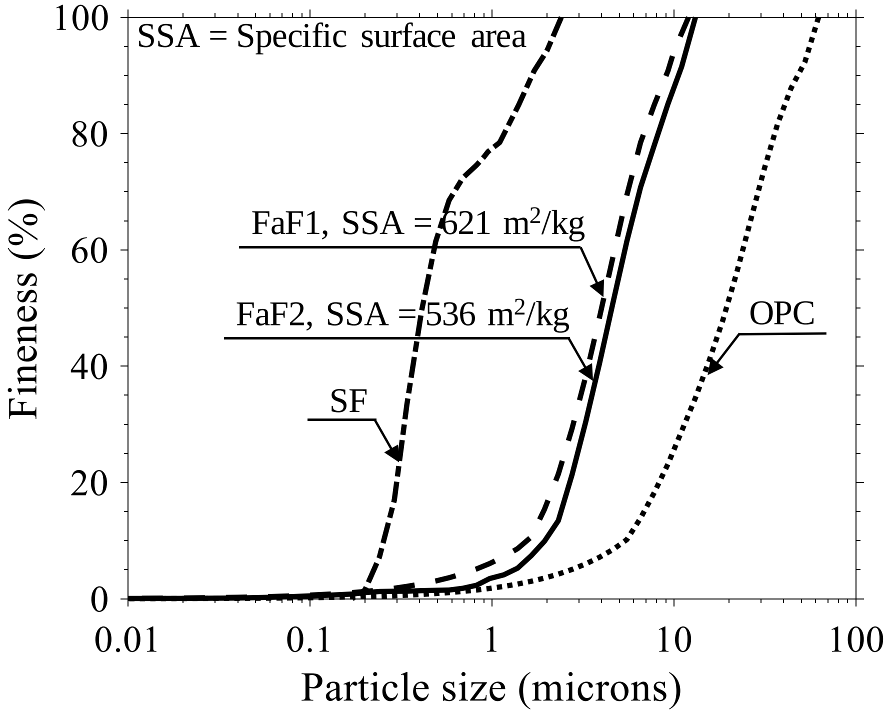


Figure 3-2. Particle size distribution curve of all the binders used for the study

Similarly, the physical properties of the chemical admixtures are tabulated in Table 3-4. The drying loss of the chemical admixtures was determined by heating the powder admixtures in an oven for 24 hours as per ASTM E 1868 (2015). To determine the molecular composition of the chemical admixtures, the Fourier transform infrared spectroscopy (FTIR) studies were carried out. The functional groups present in the compounds were determined by analyzing the functional group region. After the analysis of the fingerprint region of the FTIR spectra, the chemical compounds present in the admixtures were determined.

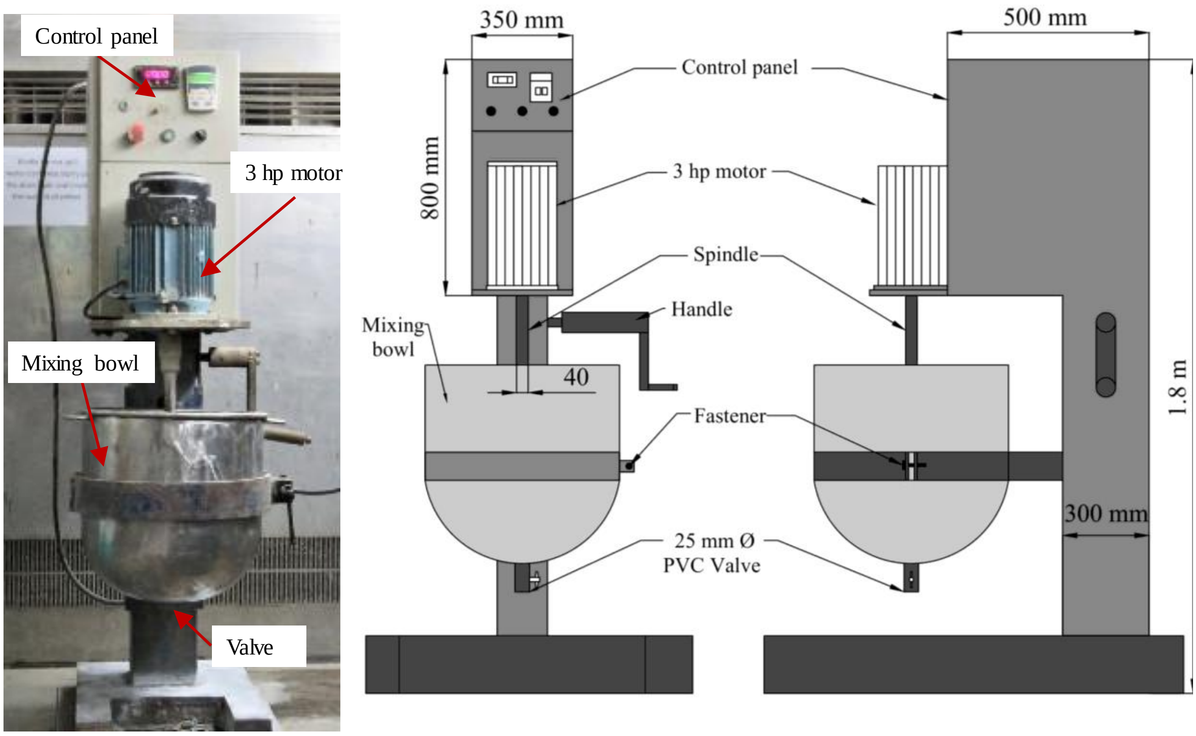
Polycarboxylate ether based high range water reducer (HRWR) was used to disperse the binders effectively and to increase the fluidity. Hydroxyethyl methyl cellulose and a commercial form of purified palygorskite clay (nanoclay) were used as viscosity modifying agents.

Table 3-4. Physical properties of the chemical admixtures

Property	HRWR	Viscosity modifying agent	Nanoclay	SRA
Form	Powder	Powder	Powder	Powder
Colour	Yellow	White	Yellow	Brown
Odour	None	None	None	Pungent smell
Density (kg/m^3)	450	1300	2290	1600
pH (at 20° C)	6.5 - 8.5	6 - 8	6 - 7	6 - 7
Drying loss	Maximum 2%	Maximum 1%	Maximum 1%	Maximum 1%

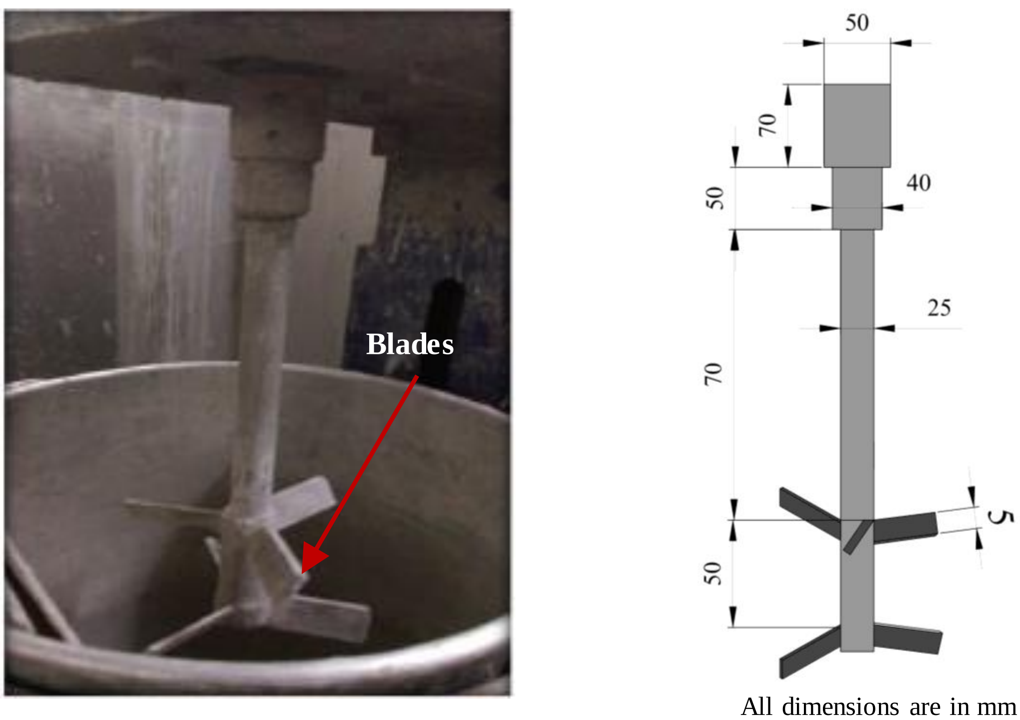
3.2.2 High shear grout mixer

As discussed in the previous chapter, mixing operation of grout materials is very important to achieve a homogenous grout mix. A custom made high shear mixer was fabricated at IIT Madras for that (Kamalakkanan S. 2015, Thirunavukkarasu R. 2015). The high-shear mixer has a capacity of 20 liters and a maximum angular velocity of 3000 rpm. A variable frequency oscillator was attached to the mixer to control the mixing speed with a least count of 5 rpm. Figure 3-3 shows the front view and the schematic representation of the custom-made high-shear grout mixer. Figure 3-5 (a) and (b) show the alignment of the mixing blade and spindle system and configuration of the blades respectively. The blades and spindle are made of single pieces of mild steel. The blades are arranged 120° with each other and are arranged in two levels to have better mixing. The spindle has a has a very smooth surface texture and aligned perfectly vertical to reduce the wobbling at higher speeds. A ball valve is attached at the bottom of the mixing bowl to collect the grout after mixing operation (Kamalakkanan 2015).



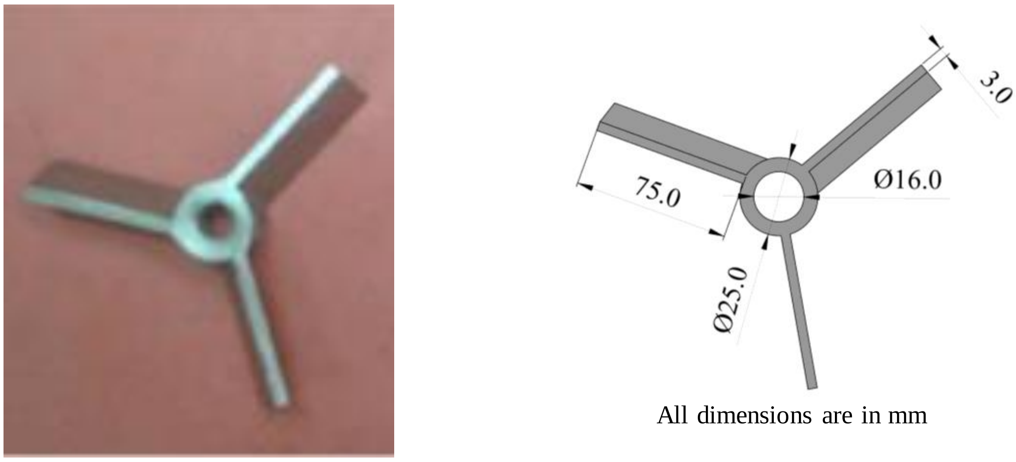
a)Front view **b) Schematic representation**

Figure 3-3. Custom-made high-shear grout mixer



a) Blade and spindle alignment

Figure 3-4. Details of the spindle used in the high-shear grout mixer



All dimensions are in mm

b) Blade configuration

Figure 3-5. Details of the blade used in the high-shear grout mixer

3.2.3 Mixing procedure

A custom-made mixing procedure has been devised based on the recommendations from the previous studies conducted at IIT Madras, ASTM/ PTI procedures and the literature (ASTM C 1738: 2018 Ferron et al. 2013, Han and Ferron 2015Kamalakkanan et al. 2018, PTI M55.1-12: 2013). This mixing procedure has been adopted to completely disperse all the ingredients in the grout mix.

The mixing procedure has two stages. The details of the mixing procedure and duration are as follows:

<u>Stage 1: Pre-blending</u>

1) Dry blend the binders and chemical admixtures using a planetary mixer at 250 rpm for 60 seconds

2) Condition the pre-blended material in the environmental chamber at standard temperature and humidity for a specified time (say, 24 hours)

<u>Stage 1: Wet mixing</u>

1) Add potable water to the high-shear mixer

2) Add the pre-blended, pre-conditioned grout material to the high-shear mixer while the blades are rotating at 300 rpm

3) Increase the mixing speed to 1500 rpm and continue mixing for 300 seconds

Initially, the binders and chemical admixtures were dry-blended in variable speed planetary mixer (say, Hobart mixer) of 17 L capacity as per ASTM C 305 (2018). The duration of mixing was set in such a way to obtain a uniform distribution of the ingredients. After the dry-blending stage, the uniformity of the blended grout material was ensured by visual observation. Then, the pre-blended material was kept inside the environmental chamber for 24 hours for conditioning at a temperature of 25° C. The conditioning process is also very important in order to ensure the temperatures of the pre-blended material and mixing water equilibrated with the ambient temperature of mixing. The grout mixing and testing were carried out at 25° C and a relative humidity of 65 %. The quantity of grout material, mixing speed and mixing procedure was kept uniform throughout the experiment. Thus, for every trial, 25 kg of dry-blended grout material was taken to avoid the variability due to the mixing volume. This yielded a quantity of grout approximately 15 to 17 liters when mixed with a pre-defined amount of water. After the mixing, the grout was kept in constant agitation until the testing was completed (say, 3 hours). The mixing bowl was covered with acrylic glass plates to avoid moisture loss due to evaporation.

3.3 PHASE-2: PERFORMANCE EVALUATION OF PBGS ON LAB SCALE

This section contains the details of the laboratory scale tests conducted to assess the performance of the formulated grouts. The fresh and hardened properties were determined on five batches of each grout mix to achieve statistically valid results. The formulated grouts named as PBG1 to PBG6; abbreviation for pre-blended grout. Similarly, the factory blended grouts were named as PBG7 to PBG9

3.3.1 Tests to assess the fresh properties of the PT grouts

Over the last few decades, simple and field-oriented test methods were developed to evaluate the fresh properties of the PT grouts by several researchers. Those test methods are designed in such a way to assess the properties quickly without the necessity for time-consuming laboratory test methods which require technical expertise.

Marsh cone test originally devised by H. N. Marsh in 1930s for the drilling fluids (Marsh and Calif 1931). Later, the Mash cone has been used widely for the quick assessment of fluidity without the reference to rheological parameters (Agullo et al. 1999; Khayat and Yahia 1998; Roussel and Le Roy 2005; Roy and Roussel 2005). Nevertheless, the Marsh cone test gives a reasonably accurate indication of viscosity when the ingredients of the grout are in the well-dispersed state (other words, when the superplasticizer dosage is optimum) (Agullo et al. 1999). Thus, the Marsh cone test has been widely used for the determination of the saturation dosage of superplasticizer and to assess the fluidity of the flowable grouts.

The fluidity of the PT grout can be assessed by a Marsh cone conforming to EN 445 (2007) or ASTM C939 (2010). However, both the Marsh cones are geometrically different, and the procedure of testing is also slightly different. Figure 3-6 shows the photograph and the schematic representation of the Marsh cone test setup conforming to EN 447 (2007). As per EN 445 (2007), the grout mix of 1700 ml should be poured into the Marsh cone and the time required for 1000 ml of grout to flow through the orifice is called efflux time (EN 445:2007). On the other hand, as per the ASTM C 939 (2010) efflux time is defined as the time required for the grout mix of 1725 ± 5 ml to flow through the orifice is called efflux time (ASTM C939: 2010). To assess the fluidity of the PT grout, the test should be carried out immediately after the mixing as the rest time, and pre-shear can affect the fluidity of the grout mix (Roussel et al. 2010) and after each 30-minute interval up to 3 hours.

Similar to Marsh cone test, the spread test also can be used as a simple way to measure the fluidity. From the spread diameter, an indication to yield stress of the cement grout can be obtained with reasonable accuracy. The grout spread test can be conducted on the fresh grout mix as per EN 445 (2007). Figure 3-7 shows the picture and schematic representation of the apparatus. The cylinder has an inner diameter of 40 mm and a height of 60 mm. The cylinder should be completely filled with the fresh grout and must be kept stagnant for 30 seconds. Then, the cylinder can be raised without trapping any air bubbles inside the grout. After 30 seconds, the diameter of the grout should be measured. This test can also be repeated up to 3 hours to monitor the change in the spread with respect to time.

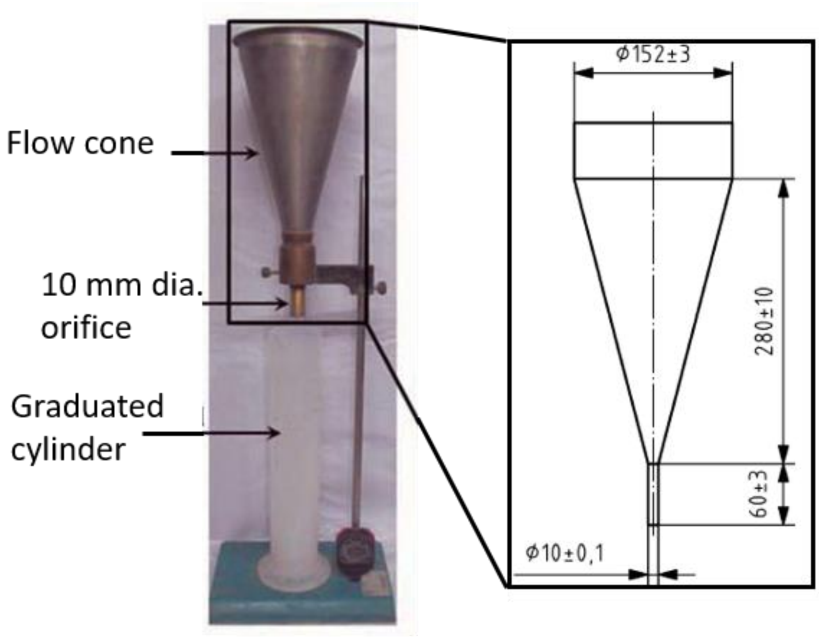


Figure 3-6. Marsh cone test setup to measure fluidity

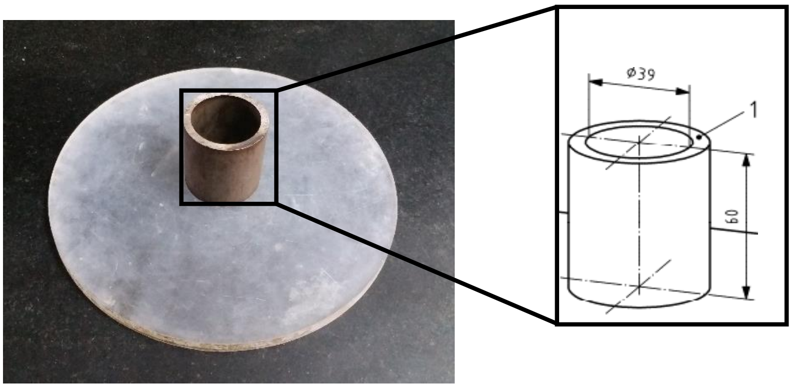
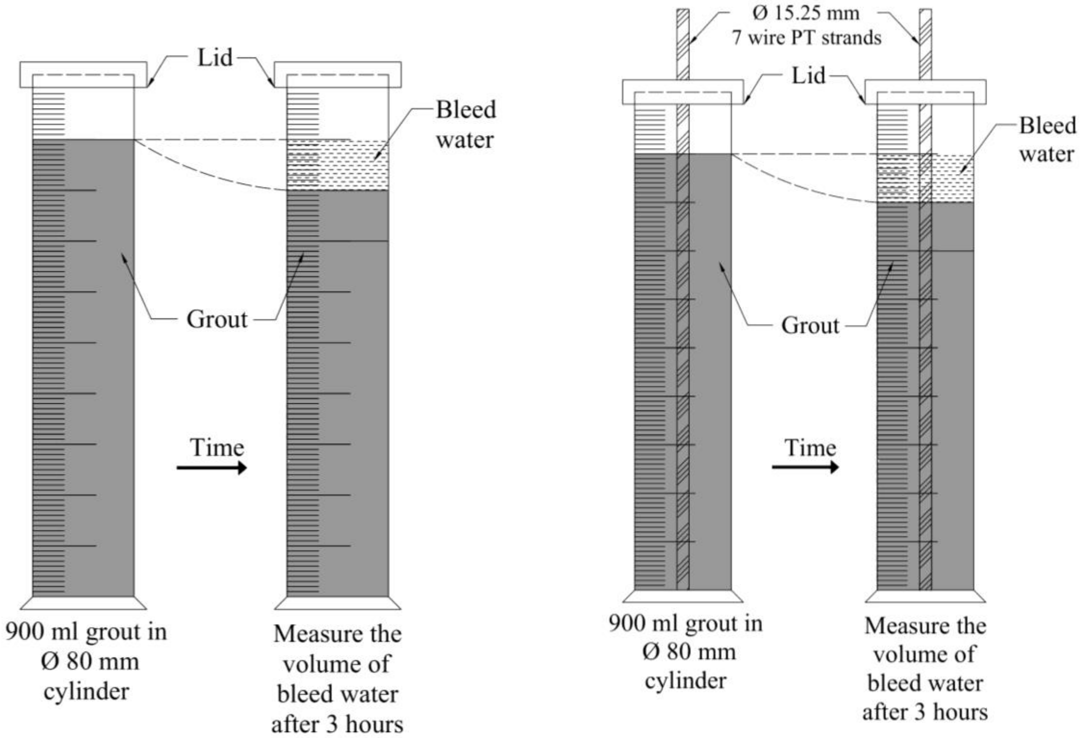


Figure 3-7. Spread test setup to measure fluidity

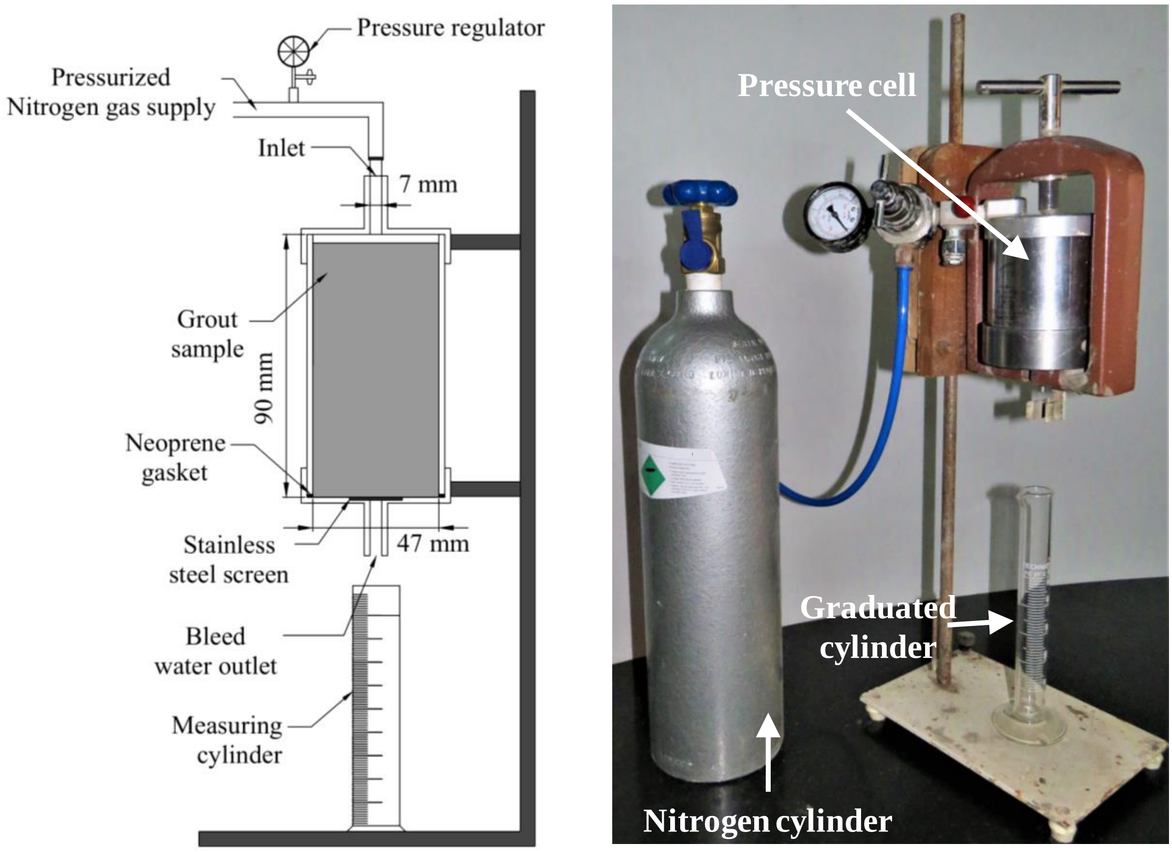
The bleed resistance of the PT grouts can be measured under four different simulated real conditions. The standard bleed test (ASTM C940: 2016) gives the amount of bleed water on the surface of the grout after keeping the fresh grout for stagnant for 3 hours in a graduated cylinder. Due to the strong density difference between the constituent particles and the water, the particles will settle down at the bottom. The test can be carried out as per ASTM C 940 (2016). Figure 3-8 (a) shows the schematic representation of the standard bleed test setup. About 900 ml of grout should be poured into a graduated cylinder, and the top surface should be covered to avoid moisture loss due to evaporation. After 3 hours, the amount of accumulated bleed water at the surface can be measured by a micro-pipette. Generally, the bleed water volume is expressed in percentage relative to the initial volume of the grout taken (say, one liter). Though the standard bleed test gives a quick estimation of the bleed resistance of the PT grouts, it fails to capture the accumulated bleed water volume due to the presence of PT strands.



a) Standard induced bleed **b) Wick-induced bleed**

Figure 3-8. Schematic representation of the.test setups for the bleed measurement

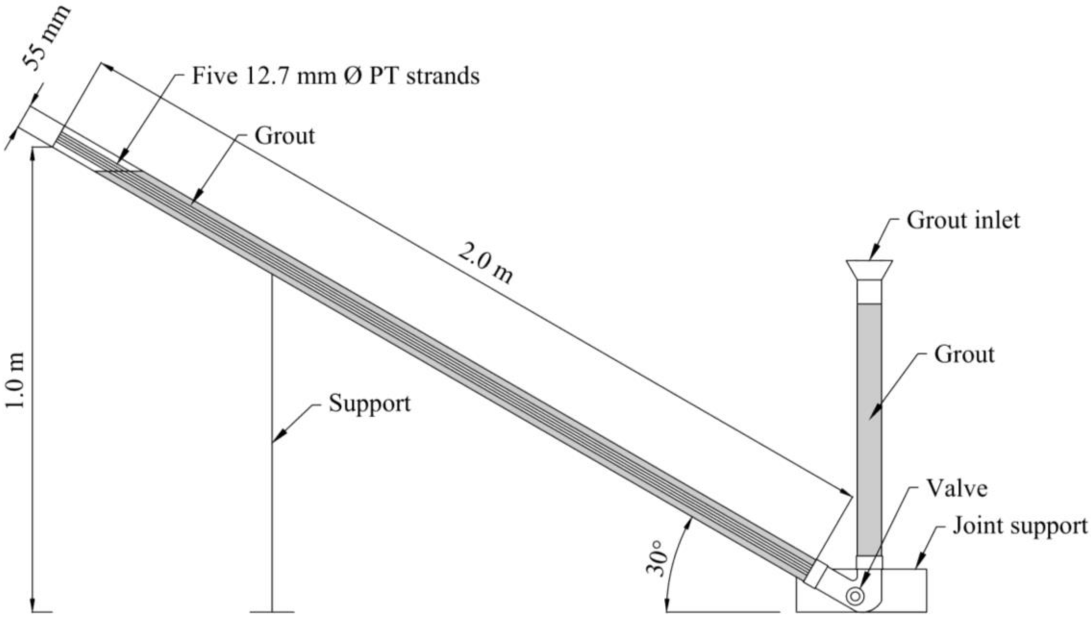
In reality, the PT concrete system contains seven-wire strands, and the interstitial space between these wires acts as a bleed channel. Therefore, to get a realistic estimate of bleed water volume due to the wick-action present through these channels, the wick-induced bleed test should be carried out a per EN 445 (2007). The wick-induced bleed test can be conducted by inserting a seven-wire strand in the graduated cylinder. Figure 3-8 (a) shows the schematic illustration of the test setup. About 900 ml of freshly prepare grout was poured into the graduated cylinder with one 15.6 mm diameter seven-wire strand inside it. The bleed water can be expressed in percentage with respect to the initial volume of grout taken (EN 445:2007).



a) Schematic illustration **b) Actual test setup**

Figure 3-9. Pressure-induced bleed test setup

As discussed in the previous chapter, the PT concrete elements are widely used in the construction of long span segmental bridges, nuclear vaults, etc. Most of the cases, the tendon profile will be inclined (up to 30° with the horizontal) and sometimes vertical (in columns and nuclear vaults). When the tendon profile is not horizontal, bleeding will be manifolded by the action of gravity as well as the self-weight of the grout above. To simulate these critical situations, the pressure-bleed test was developed. Originally devised by Schupack in the 1970s (Schupack 1970) and later adopted by ASTM as a standard (ASTM C 1741: (2018)). The pressure cell in the apparatus is known as Gelman pressure filter cell. Figure 3-9 (a) shows the schematic representation of the pressure-bleed apparatus and Figure 3-9 (b) represents the actual apparatus. A stainless-steel filter screen and neoprene gasket are present at the bottom of the pressure cell; to avoid the passage of cementitious particles. About 200 ml of freshly mixed grout should be slowly filled into the pressure cell without entrapping air bubbles. After filling, the grout must be kept stagnant for 5 minutes. Then, the pressure can be increased by 50 kPa intervals up to 350 kPa. This induced pressure will be equivalent to a grout column of 6 m height; based on the density of grout mix. The induced pressure should be sustained for 3 minutes at each pressure increment. The bleed water coming through the opening at the bottom can be collected in a graduated cylinder. Then, the cumulative bleed water after the experiment can be expressed in percentage relative to the initial volume of the grout taken.



a) Schematic representation of the inclined tube test set-up

b) Inclined tube test set-up

Figure 3-10. Modified inclined tube test set-up

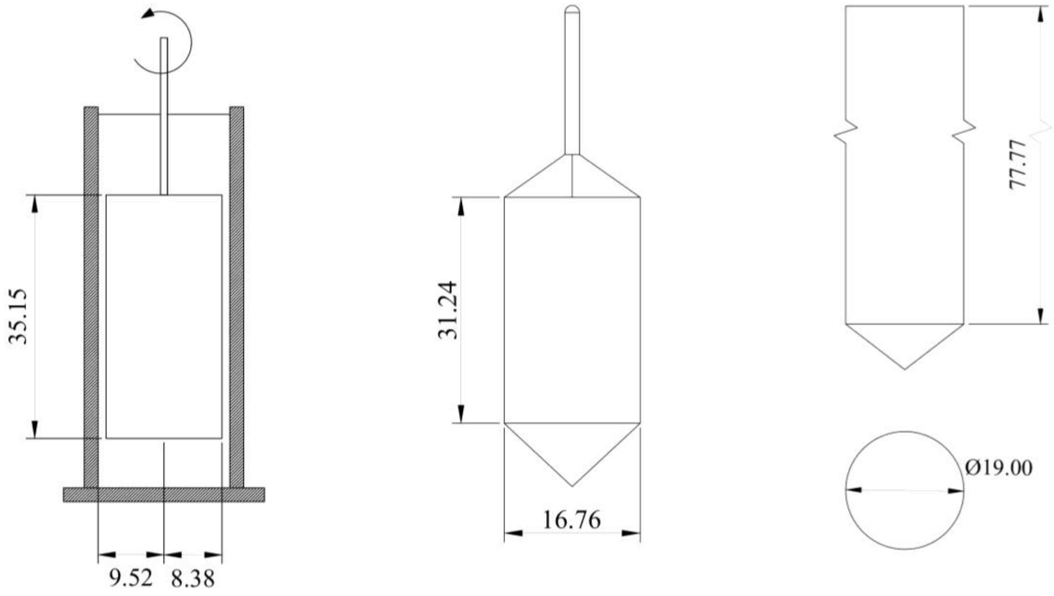
As shown in Figure 2-1 in Chapter 2, the long span segmental bridges have highly congested strand system inside the duct; where the wick action will be very high. A good quality PT grout is expected to be bleed resistant even in such adverse conditions also. To simulate such a highly congested strand system with inclination, inclined tube test was developed (as shown in Figure 3-10). EN 445 (2007) standard specifies to use 5 m long ducts with 80 mm diameter and twelve, 15 mm diameter, seven-wire strands with a strand area to duct area ratio 0.5. These specifications can best represent the congested strand system in an actual PT system. However, the test has been slightly modified by keeping the strand to duct area ratio as constant to fit the test setup inside the environmental chamber. This modification reduced the length of the duct to 2 m and the number of strands to 5.

As per EN 445 (2007), the freshly prepared grout should be filled in the inclined tubes with the strand system. Then, the open ends should be covered to avoid moisture losses due to evaporation. The volume of accumulated bleed water should be measured after 15, 30, 60, and 180 minutes. The cumulative volume of bleed water can be expressed in percentage relative to the initial amount of grout taken.

As discussed in Chapter 2, the cementitious grouts with chemical admixtures exhibit non-uniform rheological characteristics. Therefore, it is important to assess the rheological behaviour of the developed cementitious grouts. For that, a rotational viscometer (Brookfield HAIII) with a co-axial cylinder geometry (inner cylinder radius = 16.77 mm, gap width = 1.14 mm). Figure 3-11 shows the rotational viscometer and the attachments. The details of the coaxial cylinder set up are shown in Figure 3-12.

a) Brookfield HA III rotational viscometer **b) Co-axial cylinder and spindle attachment**

Figure 3-11. Brookfield HAIII rotational viscometer



All dimensions are in millimeters

a) Co-axial cylinder **b) SC4-21 Spindle** **c) HT-2 sample chamber**

Figure 3-12. Details of co-axial cylinder set-up

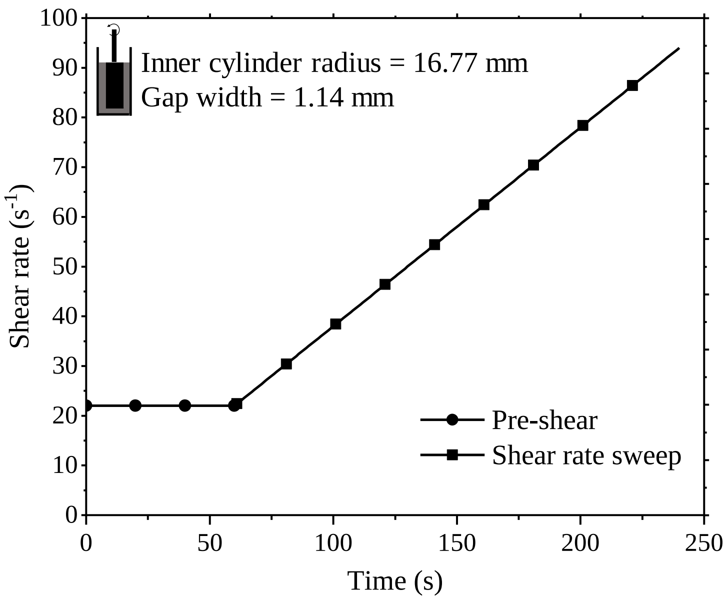


Figure 3-13. Shear rate sweep protocol used in the rheological study

The rheological behaviour depends on the type of spindle, shear rate, the gap between the cylinders and environmental conditions. The basic principle of the rheological experiment is to apply a known shear rate to the grout through the spindle and measure the corresponding shear stress produced (Jayasree 2007). The spindle corrugated with 0.5 mm deep grooves which helped in reducing wall slip during the shearing stage. The bob was covered with a plastic cap for the entire test duration to avoid the solvent drying due to the evaporation of mixing water.

The shear protocol was chosen based on several trial experiments. From the time depending on the variation of torque measurements, the time required for torque to become steady was determined for different shear rates. Also, the shearing for longer durations induced gravitational settling of constituent particles. Therefore, the protocol for shear rate sweep was selected based on the torque vs. time measurements and the time of the settling of grout ingredients. The grout was sheared very slowly to capture the uniform rheological response of the material without causing segregation of the particles. The shear rate sweep was carried out in a range of 24 to 90 s^{-1}, which can correspond to the shear rate during the mixing, pumping, and flow through the duct (Ferrara et al. 2012). The shear rate was limited to 100 s^{-1}, since the shearing the material above 100 s^{-1} can induce instabilities due to secondary flows. Also, the spindle started wobbling beyond a shear rate of 100 s^{-1}. Before the shear rate sweeping, the grout was pre-sheared for 50 $^{-1}$ for 3 minutes to avoid the past shear histories (Jayasree and Gettu 2008; Nguyen et al. 2011; Roussel 2005). After the pre-shear stage, the shear rate was swept from 24 to 90 s^{-1} with an increment of 0.1 s^{-1} for 7 minutes. Figure 3-13 shows the shear rate sweeping protocol used for the rheological experiments.

3.3.2 Tests to assess the set/hardened properties

The set/hardened properties are also important for PT grouts. According to various standards, the setting time of the PT grouts should be more than 3 hours. If the setting time is very low, the grout will not flow easily through the duct and fill all the interstitial spaces (Khayat et al. 2008). Setting time can be determined by the Vicat apparatus as per ASTM C953 (2010). The penetration depth can be determined with respect to time and the depth corresponding to 35 mm penetration can be reported as the initial setting time. Similarly, the final setting time is the time after the ring needle of the Vicat apparatus fails to make an impression on the grout surface (ASTM C 953: 2010).

The compressive strength of the formulated grouts can be determined by strain controlled universal testing machine as per ASTM C942 (2017). The rate of loading for the experiment is 5 N/s. The compressive strengths of the 50 mm cube specimens at curing periods of 3-day, 7-day and 28-day can be determined.

The shrinkage strains can be determined as per ASTM C157 (2016) method by casting 25 mm × 25 mm × 285 mm prism specimens. Immediately after casting, the specimens should be covered with a polyethylene sheet to prevent moisture loss from the specimen. The specimens should be demoulded after 24 hours and length should be measured. This length can be taken as the reference length from which the shrinkage can be measured. The specimens need to stored at standard atmospheric conditions as the changes in ambient temperature and humidity can affect the shrinkage of the cementitious systems (Bentz 2006). The specimens were stored at 25°C and 65% relative humidity for the entire test duration in this study. For determining the autogenous shrinkage, the specimens should be wrapped with two layers of aluminium foil tape. The autogenous and total shrinkage deformations can be measured using an extensometer with a least count of 0.001 mm, until the changes in the shrinkage deformations are negligible.

3.4 PHASE-3: PROTOTYPE TENDON GROUTING TESTS

This phase describes the details of the large-scale production of the best performing grout at an industrial blending facility, test methods to assess the performance of the produced grout.

3.4.1 Large-scale production of pre-blended grout

Out of the six formulated grouts, one grout was identified as best performing grout based on the fluidity, bleed resistance and dimensional stability. Then the best performing grout was produced by blending at an industrial blender of 3 metric ton capacity. Figure 3-14 shows the industrial blending facility and with the dosing system. The binders and chemical admixtures were fed into the dry blender, and the blending was carried out. The duration of blending was 3 minutes at an angular velocity of 500 rpm. The homogeneity of the dry blending was evaluated by visual inspection. After the blending, the grout material was packaged in 25 kg bags. Then, the bags were transported to IIT Madras, and the performance of the preblended grouts was assessed at the laboratory. The mixture proportioning was further fine-tuned based on the performance of the pre-blended grout. Three such large-scale productions were carried out each time refining the mix design.

a) Dosing of ingredients **b) Blending of ingredients of PBG**

Figure 3-14. Industrial blender used for pre-blending the grout materials (Courtesy: Ultratech Cements Ltd.)

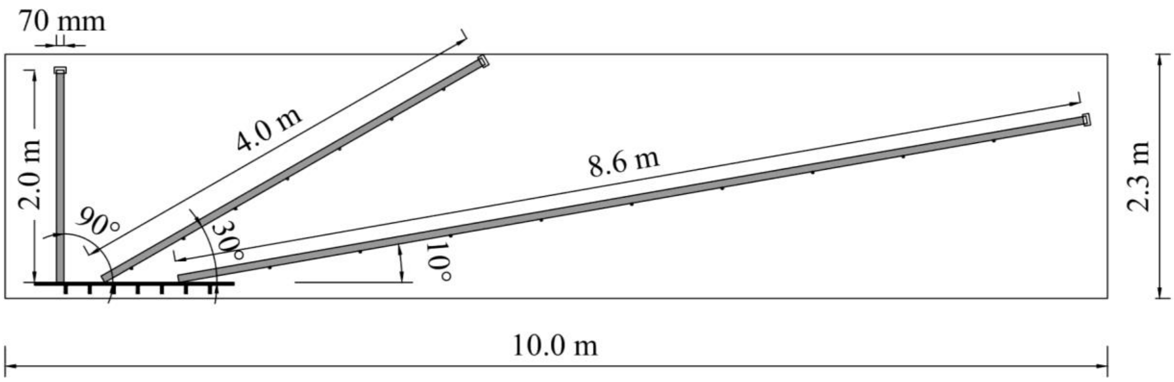
The performance of the pre-blended grout was assessed based on the results of the fresh and set/hardened properties. The experiments were conducted as discussed in section.

3.4.2 Prototype tendon grouting tests

Prototype tendon grouting experiments were conducted to critically assess the bleed resistance the best performing from Phase-2. Therefore, the prototype tendon grouting tests were carried out on the best performing grout and the Site-batched-grout (SBG). Then, the bleed resistance best performing grout was compared with the SBG.

Figure 3-15 shows the schematic diagram of the prototype tendon grouting test setup. Three different profiles (inclined 10°, 30°, and 90° with the horizontal) of duct and tendon system was assembled on a vertical wall. Each duct has an inner diameter of 70 mm and a wall thickness of 3 mm. Twelve, seven-wire (ϕ 12.7 mm) strands were inserted in each duct. AASHTO LRFD specifies that the strand area to duct area ratio should not be more than 0.5 while the PTI, ASBI and EN standards specifies that the ratio should not be more than 0.4 (AASHTO LRFD 1998, PTI M50.3-12: 2013, EN 523: 2003). To test the bleed resistance of the grout in the most critically congested strands and duct system, the ratio between cross-sectional areas of strand and duct was fixed as 0.4. Such a ratio is chosen in order to realistically assess the amount of bleed water due to congested tendon system usually present in segmental PT bridges.

Figure3-16shows the details of the 30° angle (with respect to horizontal) tendon grout system. Transparent acrylic tubes are used as ducts for better visual observation. The prototype tendon grouting tests were conducted with the best performing grout from Phase-2. The performance of the best performing grout was then compared with a widely used grout composition (site-batched-grout, SBG). The SBG contains OPC and plasticized expansive admixture. Grout mixing operation was carried by an industrial grout mixer with a maximum mixing speed of 1450 rpm. For each trial, 45 liters of grout was needed to fill the ducts. Based on the yield from 1 bag of best performing grout, the number of bags required to completely fill the duct was determined.

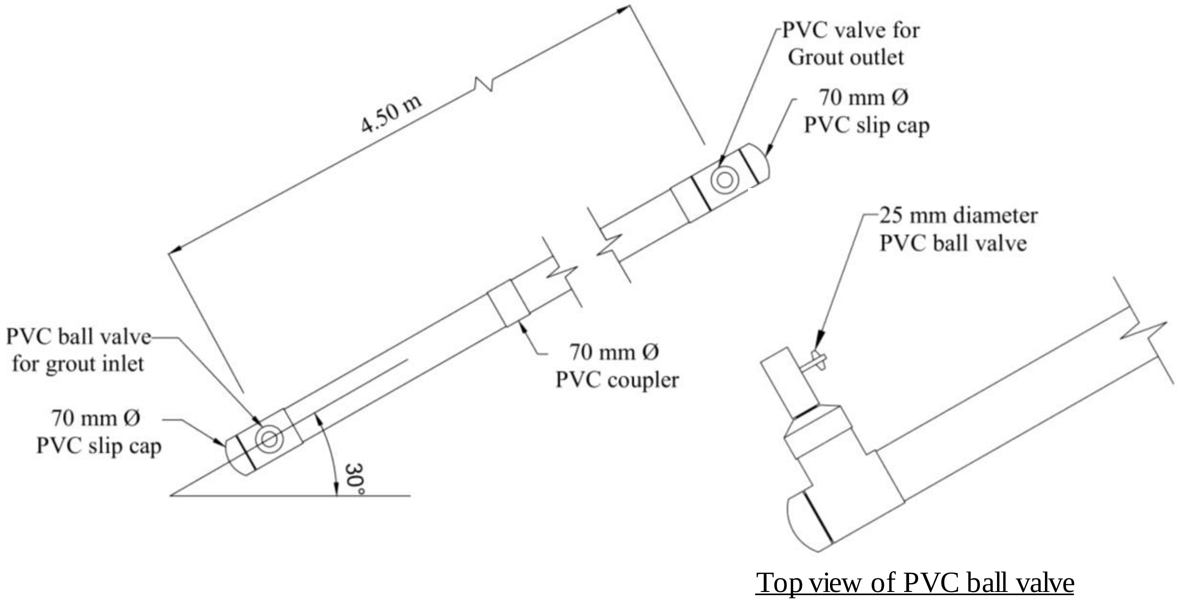


a) Schematic diagram of the tendon and duct system used in the prototype tendon grouting tests

b) Prototype tendon-duct system after grouting

Figure 3-15. Schematic diagram of the tendon and duct system used in the prototype tendon grouting tests.

Two trials were conducted with best performing grout and the SBG to get statically consistent and reproducible results. After grouting, the ducts were covered with cotton cloths, and the was watered intermittently to keep the temperature of the grout in the range of 20 - 25° C. After three days, the tendon duct system was disassembled and cut at each 2 m sections to check the presence of voids in the hardened grout.



a) Schematic illustration

b) Actual test setup in 30° inclination

c) Actual test setup in 10° inclination

Figure 3-16. Schematic illustration and photographs of the duct system

a) Grout mixer **b) Mixer blade configuration**

Figure 3-17. Grout mixer and the blade configuration used in the typical sites in India (Courtesy: Utracon Structural Systems)

The details of the mixing procedure for PBG is given below. Mixing of PBG should be done very carefully since it has very low water content. The grout material should be transferred to the mixer very slowly with the mixer blades rotating to avoid the formation of lumps. Also, after the prescribed mixing period, the consistency of the grout mix should be assessed by visual inspection or with efflux time test. The mixing should be continued until a homogenous grout mix without any lumps is obtained.

<u>Mixing procedure for PBG</u>

1) Add potable water to the high-shear mixer

2) Transfer the bags of to the grout mixer slowly, while the mixer blades are rotating

3) Continue mixing speed to 1500 rpm and continue mixing for 300 seconds

The details of the mixing procedure for SBG is given below.

Mixing procedure for SBG

1) Add potable water to the grout mixer

2) Transfer the bags of ordinary portland cement to the grout mixer slowly, while the mixer blades are rotating

3) Add the pre-defined amount of expansive admixture to the grout mix

4) Continue mixing at an angular speed of 1500 rpm for 300 seconds

Table 3-5 lists the parameters or assessment methods that can be used for the assessment of the performance of the grouts in prototype tendon grouting test. Table 3-5 also gives the acceptance criteria for each parameter; which can be used to screen out poor-quality grout materials.

Table 3-5. Assessment of the performance of grout in prototype tendon grouting tests

Parameter/assessment tool	Test method	Acceptance criteria
Efflux time, $T_{e,0}$	Flow cone test as per EN 445 (2007)	$T_{e,0} \leq 25$ seconds
Volume of bleed water, $BV_{wick\text{-}induced}$ (%)	Wick-induced bleed test as per EN 445 (2007)	$BV_{wick\text{-}induced}$ (%) ≤ 0.3
Volume of softgrout $V_{softgrout}$ (%)	Measure the volume of the softgrout layer 24 hours after grouting	$V_{softgrout}$ (%) = 0
Volume of bleed water, $BV_{Prototype\text{-}grouting}$ (%)	Measure the volume of accumulated bleed water 3 hours after grouting	$BV_{Prototype\text{-}grouting}$ (%) = 0
Visual inspection	Visual inspection on the cross-sections of the dissected tendon-duct system	There should not be any voids throughout the cross section

CHAPTER 4

RESULTS AND DISCUSSION

This section contains the results of the Phases 1 to 3. Six different grouts (PBG1-6) were developed with several flow and bleed tests in Phase-1. Out of the six different grouts, a grout with desired levels of fluidity and bleed resistance (as per EN 447:2007) was identified as best performing grout and was selected for further studies. At this stage, the selected grout exhibited excellent fluidity and excellent bleed resistance without the tendency to form softgrout. Then, the shrinkage of the selected grout was determined by adding different dosages of shrinkage reducing admixture (SRA). After optimizing the SRA dosage, the best performing grout material combination was blended on a large scale (3 metric tons) using an industrial blending facility and packaged in 25 kg bags. Then, the blended and packaged grout bags were transported to IIT Madras laboratory, and the fresh and hardened properties were assessed. Based on the performance of this grout, the mixture proportion was further fine-tuned to achieve desired levels of flow, bleed resistance, and dimensional stability. Three such fine-tuning and pre-blending in the industrial blender was carried out (PBG7-9). Then, in Phase-3, the performance of the best performing grout was assessed using prototype tendon-grouting tests. Finally, a set of stringent and comprehensive performance specifications were developed

4.1 PHASE-1: DEVELOPMENT OF PBGS

The grouts were designed for desired levels of fluidity, bleed resistance and dimensional stability. The specifications from EN 447 (2007) were taken as the reference for deciding the desired levels of the properties. The following section gives a detailed description of the mixture proportioning of the pre-blended grout material.

4.1.1 Mixture proportioning of PBGs

As discussed in Section 3.2.1, the PBGs were prepared with different combinations of OPC, SCMs, and chemical admixtures. The combination and proportion of the binders were decided by the particle packing method. The basic idea for binder proportioning was to choose the volume proportion of binders exhibiting highest packing density.

A commercially available particle packing software (EMMA, Elkem 2016) was used for this purpose. The particle size distribution of each of the binders, specific gravity, the proportion of the binders, and distribution ratio were the input for the software. The software calculates the idealized distribution curve based on the modified Andreasson model and compares with the actual particle size distribution curve. The input parameters required for the calculation are the value of distribution coefficient (q), particle size distributions of the ingredients, and the sizes of the minimum and maximum particles present in the mixture. As the grout mix should have very good fluidity, the distribution coefficient should be as low as possible. From the previous similar studies conducted at IIT Madras, a distribution coefficient of 0.23 was chosen for obtaining the ideal gradation curves (Babu 2016, Dutta 2017). In the software, the user can select a range of binder combinations. From different iterations, the user can pin down the range of volume proportions of the binders to a narrow window. The volume of the binders which can provide a gradation curve which is close enough to the ideal gradation curve with the pre-defined distribution coefficient. Figure 4-1 shows the output plot from the software which shows the ideal gradation curve and the particle size distribution curve of OPC and FaF1 combination.

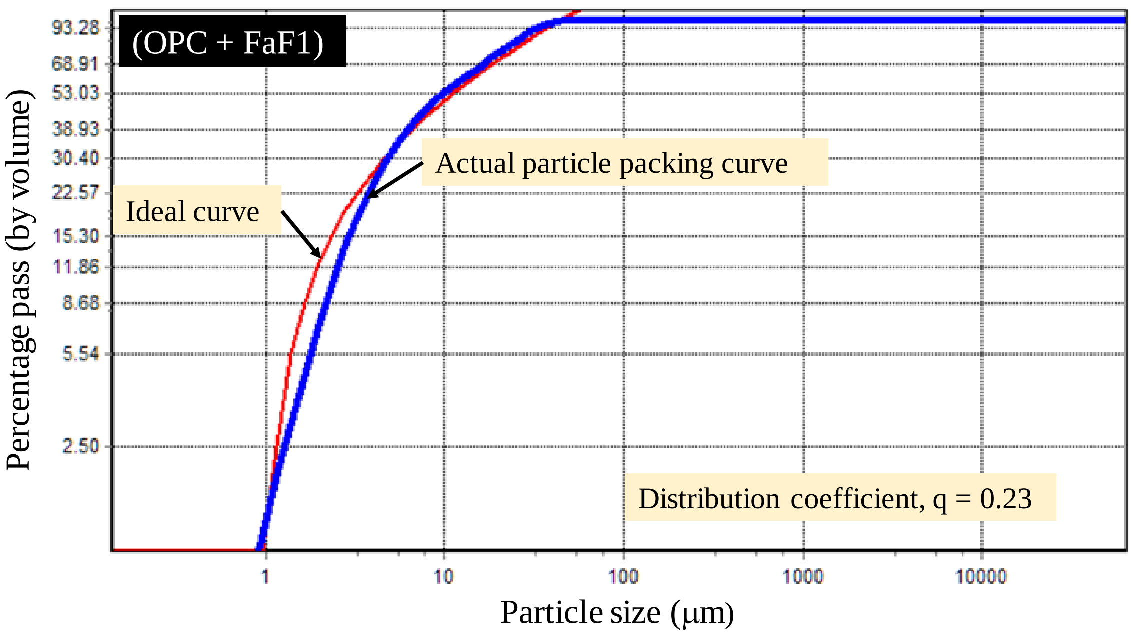


Figure 4-1. Ideal gradation curve and actual overall particle size distribution for OPC and FaF1 combination

From the selected range of proportions, the proportion with the highest packing density can be determined by the Puntke test, which is a simple and cheap method to determine the packing density of the binders (Nanthagopalan et al. 2008). The principle of the Puntke test is that the water added to the dry binders will fill all the voids and act like a lubricant to make the material compact efficiently. Beyond a particular dosage of water, all the voids will be filled completely, and the excess water will appear on the surface. This can be identified by visually inspecting the glossy appearance on the surface of the grout mix. The advantage of this test is that as the test is performed in the wet condition, it can closely simulate the condition of binders in the cement paste (Nanthagopalan 2008).

For Puntke test, about 20 cm^3 of the binder was taken in a clean vessel and water was added drop by drop using a pipette. Simultaneously, the system should be kept in constant agitation. Water was added until the glossy surface appeared on the surface of the mix. From the amount of the water added to the system, the packing density of that combination of binders can be determined. Figure 4-2 shows the different steps involved in the Puntke test.

a) Binders in the container with uniform mixing **b) Glossy appearance on the surface**

Figure 4-2. Steps involved in the Puntke test

From the volumes of the powder and water, the packing density was determined by Equation 4.2.

Packing density, $\phi_p = 1 - \frac{V_w}{V_w + V_p}$ Eq. 4.2

where is the ϕ_p packing density, V_p is the volume of powder, and V_w is the volume of water. OPC was replaced with different SCMs on volume basis until the mix with the highest packing density was obtained. Initially, the Puntke tests was conducted with pure water. As the formulated grouts have HRWR, the Puntke tests were carried out by adding an arbitrary amount (0.1% bwob) HRWR. The addition of HRWR makes the binders to disperse more effectively and breaks the agglomerated particles, and results in the enhanced compaction of the binders (Nanthagopalan, 2008). For dispersing the densified silica fume particles more effectively, along with the HRWR, a high-shear hand blender with an angular velocity of 3000 rpm. Irrespective of the binder proportions, the HRWR dosage was kept constant. Figure 4-3 shows the Puntke test results of the mix with OPC and FaF1. Figure 4-3 shows the variation of the packing density for OPC and FaF1 combination. The maximum packing density occurred at a replacement of 42% FaF1 with OPC. The addition of HRWR did not change the binder proportion for the maximum packing density. However, the absolute value of packing density was increased when the HRWR was added, which can be due to the increased dispersion of binders - resulted in a more compacted state (Nanthagopalan and Santhanam 2009). Similarly, the packing densities of the combinations of OPC, FaF1, and FaF2 are given in Table 4-1. The packing density was maximum when the OPC, FaF1, and FaF2 was in the proportion of 60:20:20. The same process repeated for different binder combinations, for obtaining the volume proportions of the highest packing density. The combinations and proportions of binders exhibiting high packing density, good flow, and stability was chosen for further study. Also, no inert filler (say, limestone powder, quartz powder material, etc.) was used in the mixture proportion to completely avoid the softgrout formation.

Generally, there is a tendency to use w/b ratio of more than 0.40 to achieve high fluidity and reduce the paste volume per cubic meter. This can help the contractors to reduce the cost of the grout per cubic meter volume. However, that practice is not advisable since it can result in the high amount of bleeding especially for vertical post-tensioning applications. Therefore, the w/b ratios of PBGs were chosen based on the water demand for normal consistency. Also, the target w/b ratio was fixed in a range of 0.25 to 0.30 for all the combinations of binders, which helped in increasing the bleed resistance.

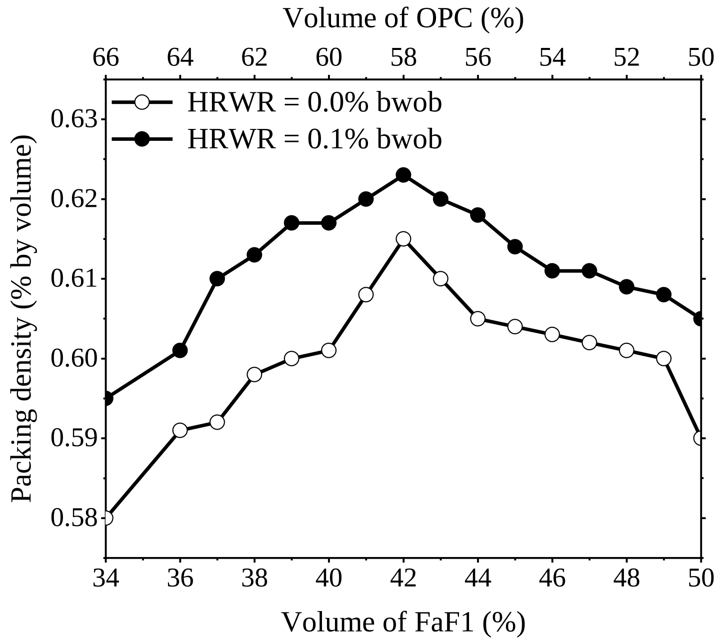


Figure 4-3. Packing density of different blends of OPC and FaF1

Table 4-1. Packing density of the ternary blends.

Blend ID	Quantity (% bvob)			Packing density
	OPC	FaF1	FaF2	
B1	50	30	20	0.668
B2	55	30	15	0.660
B3	60	20	20	0.673
B4	65	25	30	0.659
B5	70	20	10	0.648
B6	50	20	30	0.663
B7	55	15	30	0.654
B8	60	10	30	0.651
B9	65	30	25	0.645
B10	70	10	20	0.634

Optimizing the dosages of HRWR, VMA, and SRA are very crucial to achieve a bleed-resistant grout without compromising the fluidity. Several flow and bleed tests were carried out to optimize the dosage of these chemical admixtures. The dosage of HRWR was optimized by measuring the efflux time using a Marsh cone as per EN445 (2007). Initially, the saturation dosage of superplasticizer was measured. The saturation dosage is the dosage of HRWR would be the dosage beyond which there is no significant decrease in the efflux time but produces segregated grout (Aguillo et al. 1999). Similarly, another way of measuring the saturation dosage of HRWR is shown in Figure 4-4. The internal angle corresponding to each data point from the Marsh cone test can be calculated. Then, the HRWR dosage corresponding to an internal angle of 140 ± 10° would be the saturation dosage at that w/b ratio (Gomes et al. 2001). However, the saturation dosage of superplasticizer will change if the viscosity modifying agent (VMA) is added to the system. As the developed grouts have VMA in it, it is important to determine the changes in efflux time. In order to determine the dosage of the VMA, the wick-induced bleed test was used. The wick-induced bleed test closely simulates the bleed behaviour of the grout inside the duct. Using flow cone and the wick-induced bleed test, the balance dosages of the superplasticizer and VMA were determined.

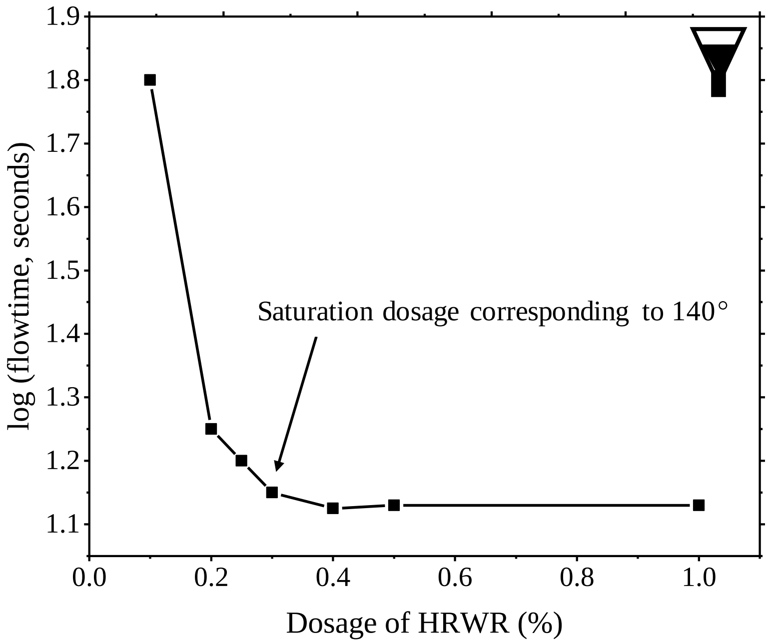


Figure 4-4. Method for the determination of saturation dosage of superplasticizer

Similarly, the dosage of viscosity modifier was optimized by measuring the volume of accumulated bleed water in a wick-induced bleed test (EN:445 2007). Since both HRWR and VMAs affect the fluidity and bleed resistance, these two tests were carried out parallelly. Generally, the fluidity of the grout increases as the HRWR dosage increase (Agullo et al. 1999). Similarly, viscosity modifying agents will increase the viscosity of the water in the suspension, which results in the high bleed resistance. Therefore, a balance between the dosages of HRWR and VMAs are necessary to achieve the grout with good fluidity and bleed resistance (Khayat et al. 1999, 2008). Figure 4-5 shows the variation of the flow time (which is an indication of fluidity) with different dosages of HRWR and VMA. From Figure 4-5, it is apparent that the flow time decreases as the dosage of HRWR increases and vice versa. Similarly, as the dosage of VMA increase, the flow time increase – indicating reduction in the fluidity. Table 4-2 shows the variation of bleed water volume with different dosages of HRWR and VMA. As the dosage of VMA increase, the volume of bleed water decreases and vice versa. On the other hand, as the dosage HRWR keeping the dosage of VMA constant, the volume of volume water increase. The experimental results indicate that the dosages of HRWR and VMA need to be balanced to achieve a grout mix with desired levels of fluidity and bleed resistance. Same experiments were repeated for all grouts to optimize the HRWR and VMA dosages.

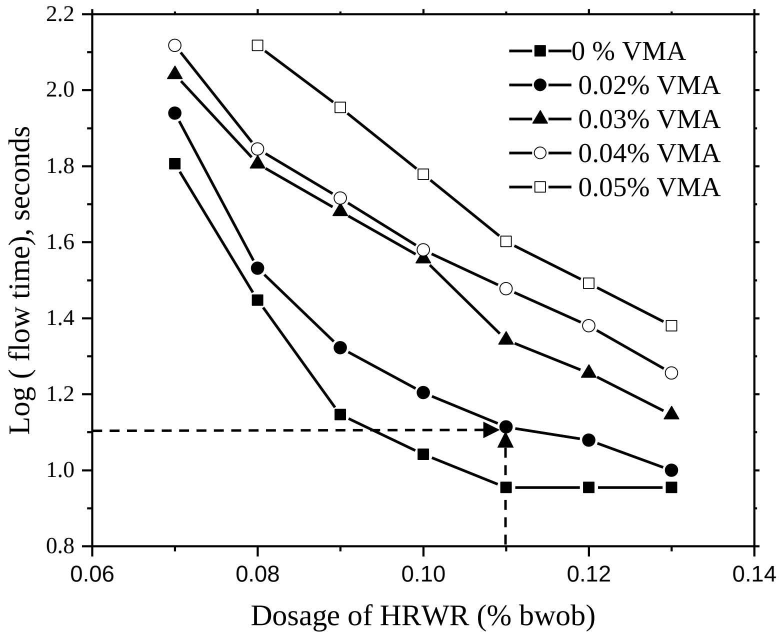


Figure 4-5. Flow time curve with different dosages of VMA

Table 4-2. Volume of bleed water with different dosages of HRWR and VMA

VMA (% bwob) / HRWR (% bwob)	0	0.02	0.03	0.04	0.05
0.07	1.9 ml	0	0	0	0
0.08	2.0 ml	0	0	0	0
0.09	2.1 ml	0	0	0	0
0.10	2.2 ml	0	0	0	0
0.11	2.5 ml	0	0	0	0
0.12	3.8 ml	0	0	0	0
0.13	4.9 ml	1 ml	0.5 ml	0	0

As discussed in Section 2.5.2.7, the PT grouts should be dimensionally stable inside the PT duct. Otherwise, the shrinkage cracks can form, and the strands can get de-bonded from the hardened grout. The developed PBGs at this stage is non-expansive but can shrink as they do not any system to help in reducing the shrinkage deformations. Therefore, it is important to reduce the shrinkage as low as possible by necessary means. As the objective of the study is to develop a PBG with desired fresh properties and dimensional stability, it is sufficient to introduce the shrinkage reducing mechanism in the best performing grout. The best performing grout (the grout which exhibits desired levels of fluidity and bleed resistance as per EN 447: 2007). Therefore, the shrinkage reducing agent (SRA) was added in the best performing grout.

The dosage of SRA was optimized by measuring the surface tension and critical micelle concentration (CMC) of the liquid phase of the grout using a Sigma 700 tensiometer according to ASTM D 1331 (2012). Grouts were prepared with different dosages of SRA by weight of the binder (bwob), and about 20 ml of the liquid phase of the grout was extracted a Gelman Pressure cell, and the change in surface tension was measured. Figure 4-6 shows the variation of the surface tension of the liquid phase with respect to changes in SRA dosage. The reduction in surface tension was very steep at lower dosages and gradually becomes asymptotic as the SRA dosage increases. This reduction of surface tension is approximately proportional to the reduction of shrinkage (Tazawa and Miyazawa 1995). Also, the dosage of the SRA should not be more than the CMC as it creates micelles beyond CMC. Therefore, the dosage of SRA beyond CMC will not be effective in reducing the surface tension of the liquid phase (Rajabipour et al. 2008). As shown in Figure 4-6, the SRA dosage was chosen when the further addition of SRA does not decrease the surface tension and below the CMC. After determining the dosage of SRA from the tensiometer studies, the shrinkage deformations of the PBGs containing the optimum dosage of SRA was determined. The shrinkage studies were carried out on 25 mm × 25 mm × 285 mm prism specimens as per ASTM C157 (2016). Immediately after casting, the specimens were covered with a polyethylene sheet to prevent moisture loss from the specimen. The specimens were demoulded after 24 hours and length was measured. The specimens were stored at 25°C and 65% relative humidity for the entire test duration. For determining the autogenous shrinkage, the specimens were wrapped with two layers of aluminium foil tape. The autogenous and total shrinkage deformations were measured using an extensometer with an accuracy of 0.001 mm, for 70 days.

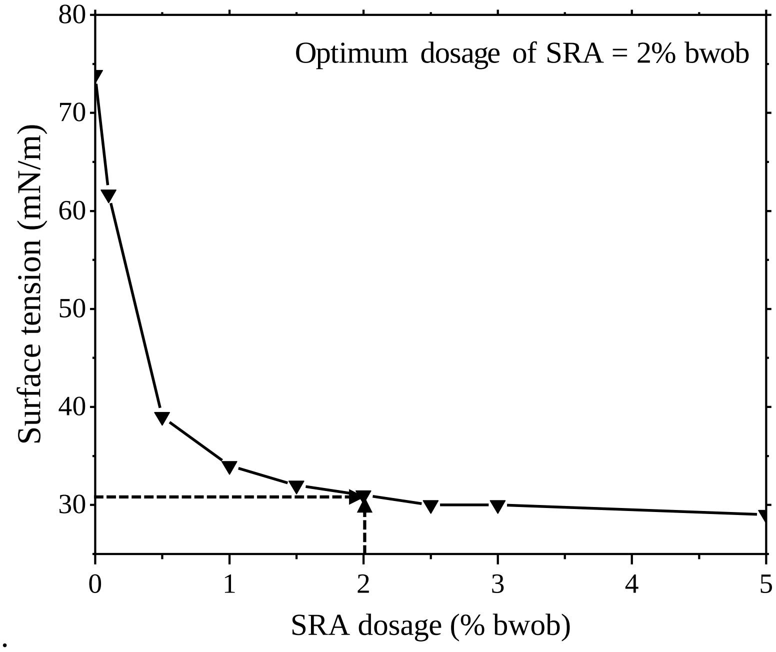


Figure 4-6. Variation of the surface tension of pore solution with SRA dosage

As discussed above, six different grouts were developed with different combinations and proportions of binders and chemical admixtures. One grout which exhibits te desired fresh and hardened properties were identified as best performing grout. Then, the best performing grout from the six different grouts was produced by blending at an industrial blending facility. The mixture proportion of all nine grouts per cubic meter is listed in Table 4-3.

Table 4-3. Composition of the pre-blended grouts (PBGs)

Material	Quantity (kg/m^3)								
	PBG1	PBG2	PBG3	PBG4	PBG5	PBG6	PBG7	PBG8	PBG9
OPC	1473	1120	1088	1119	951	951	951	951	935
FaF1	0	320	512	0	317	317	317	317	311
FaF2	0	0	0	480	317	317	317	317	311
SF	164	160	0	0	0	0	0	0	0
Water	458	432	432	432	428	428	428	428	420
HRWR	1.80	1.44	1.44	1.43	1.43	1.43	1.43	1.43	1.43
VMA	0	0	0.80	0.79	0.50	0	0.80	0.63	0.63
NC	0	0	0	0	0	1.58	0	0	
SRA	0	0	0	0	0	0	0	0	31.7
w/b	0.28	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27

HRWR: High Range Water Reducer; VMA: Viscosity Modifying Agent; NC: NanoClay; SRA: Shrinkage Reducing Agent.

4.2 PHASE-2: PERFORMANCE EVALUATION OF PBGS ON LAB SCALE

The performance of the formulated grouts was experimentally assessed based on the fluidity, bleed resistance, and dimensional stability. The experiments were repeated with five replicas of each grout mix to obtain statistically consistent and reproducible results.

4.2.1 Fluidity and fluidity retention

The fluidity of the PBGs was assessed by a Marsh cone as per EN445 (2007) and expressed in terms of efflux time. Figure 4-7 and Figure 4-9 shows the results of the efflux time measurements and spread diameter measurements of all the PBGs immediately after mixing. The PBGs 1 & 2 has the highest efflux time and lowest spread. The high efflux indicates the low fluidity of PBGs 1 & 2 compared to other PBGs, although they have the highest HRWR and water content (see Table 4-4). This can be due to the presence of very fine silica fume particles present in PBG1 and combination of SF and FaF1 particles in PBG2. Since the fine SF and FaF1 particles increased the surface area and resulted in more water demand, the fluidity decreased. PBG3 has the lowest efflux time, and the largest spread diameter, which indicates the highest fluidity. PBG 4-6 has reasonably good fluidity because of the ball bearing action provided by the spherical fly ash particles. In the factory blended grouts, PBG8 has the highest fluidity due to the presence of SRA particles, which decreased the surface tension of the liquid phase of the grout. According to EN 447 (2007) specifications, the efflux time and spread diameter immediately after mixing should not be more than 25 seconds and 140 mm respectively (EN:447 2007). All the PBGs except PBG1 and PBG2 satisfied this acceptance criterion.

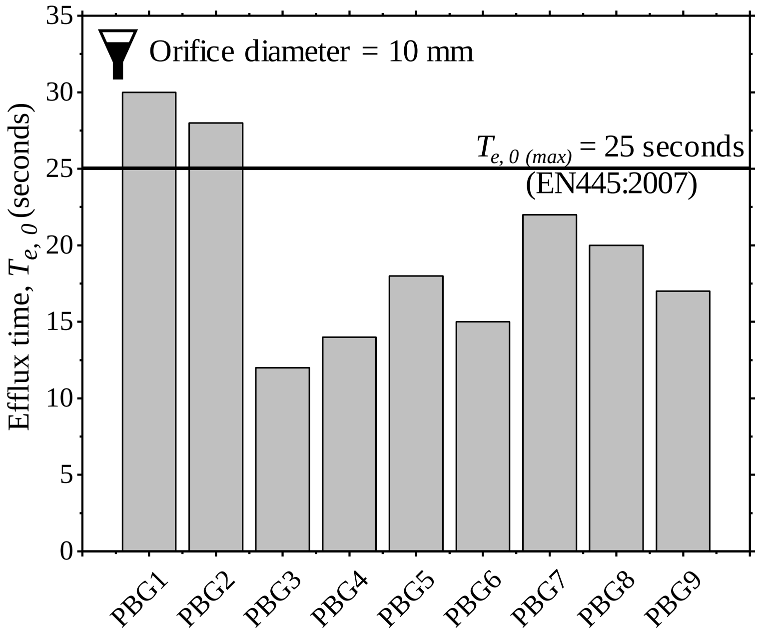


Figure 4-7. Efflux time immediately after mixing

Figure 4-8 shows the change in efflux time measured up to three hours after mixing. Similarly, Figure 4-10 shows the percentage change in spread diameter measured up to three hours after mixing. PBGs exhibited good fluidity retention during the period of testing, even though there was a general trend of decrease in fluidity due to the hydration and thixotropy. It was observed that the percentage change in efflux time was more than the percentage change in spread for all the PBGs. This indicates that the Marsh cone test is more sensitive to check the fluidity retention than grout spread test. The PBG1 and PBG2 have shown the highest percentage reduction in spread diameter. This can be due to the higher rate of time-dependent build-up of yield stress in PBG1 & 2 than the other PBGs. The rheological tests were not conducted to confirm the time-dependent evolution of yield stress since the constituent particles in the grout started to settle as the time progresses. However, the grout spread tests and Marsh cone tests gave a good indication of change on fluidity. PBGs 3,4, and 5 showed good fluidity retention and PBG5 has the lowest change in fluidity among all the PBGs.

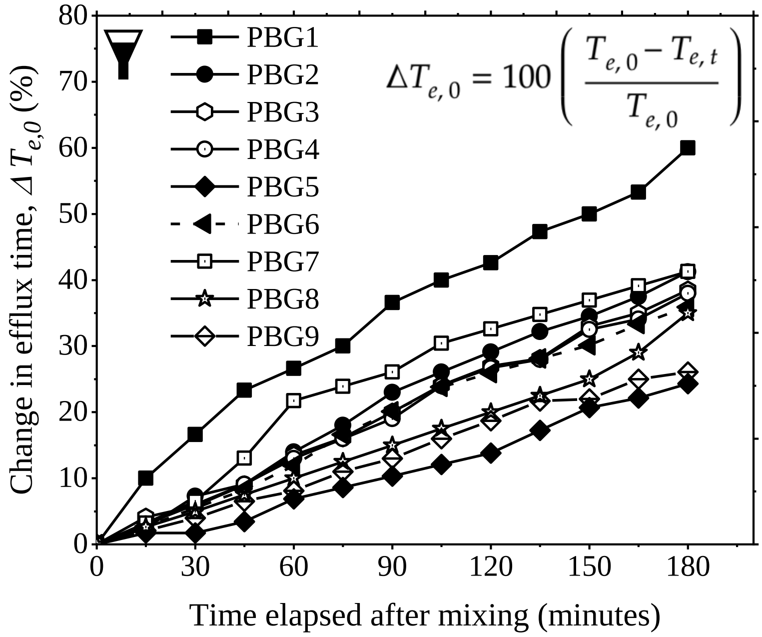


Figure 4-8. Retention of efflux time up to 3 hours

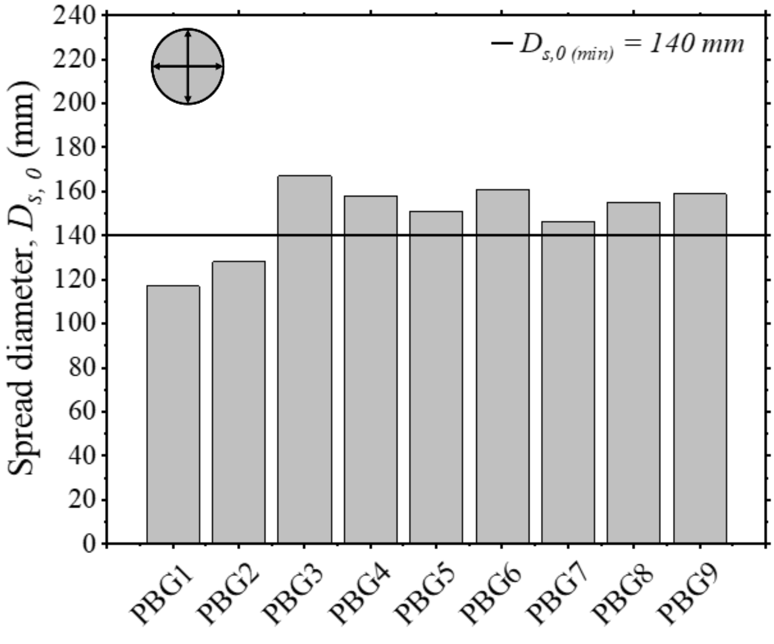


Figure 4-9. Spread diameter immediately after mixing

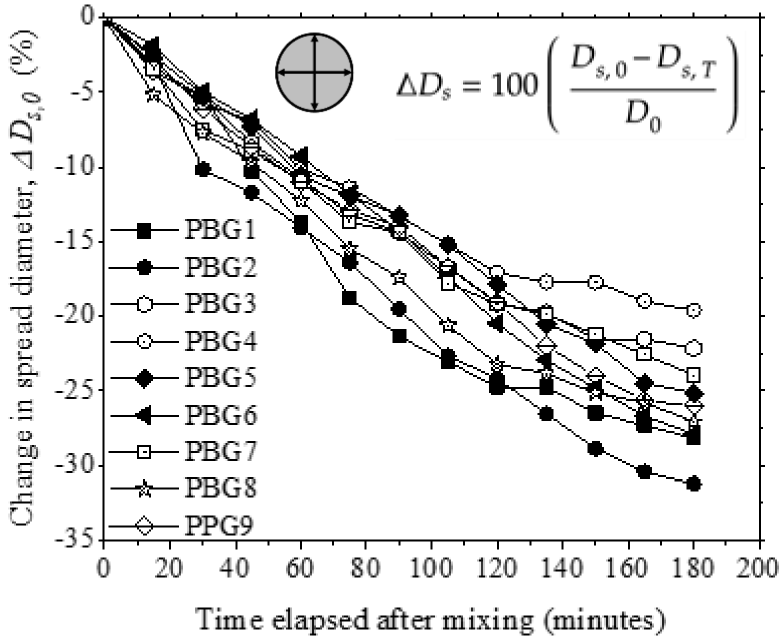


Figure 4-10. Retention of spread diameter up to 3 hours

As per EN 447:2007, the percentage change in fluidity 30 minutes after the mixing should not be more than 20%. Except for PBG1, all other grouts satisfied this criterion. It is important to measure the fluidity retention for up to three hours since the grouting operations in the field can go beyond 2 hours. Therefore, the fluidity retention was measured up to three hours after the mixing. Also, based on the observations, it is recommended that the change in fluidity should not be more than 40%, three hours after the mixing.

4.2.2 Bleed resistance

Figure 4-11 shows the standard and wick-induced bleed results. PBGs 1 & 2 has negligible bleed, but PBGs 3 & 4 has the highest bleed. This can be attributed to fine SF particles in PBGs 1 & 2, which increased the overall packing of the system. Similarly, good bleed resistance was observed in PBG5 with high fluidity. The balanced combinations of chemical admixtures and the presence of two different fly ash particles increased the fluidity with a good bleed resistance. All PBGs except PBG3 & 4 passed the allowable bleed (0.3%) limit as per EN 445 (2007).

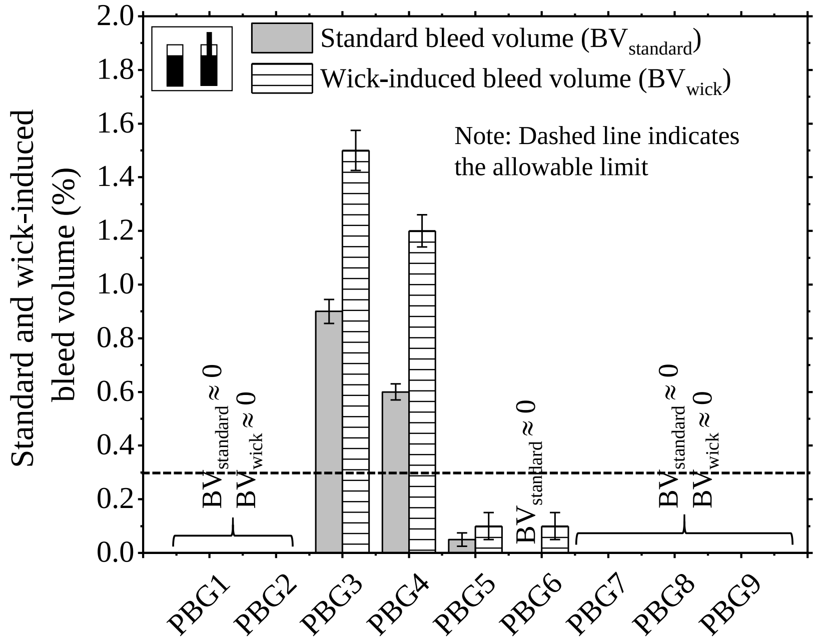


Figure 4-11. Standard and wick-induced bleed volume of PBGs

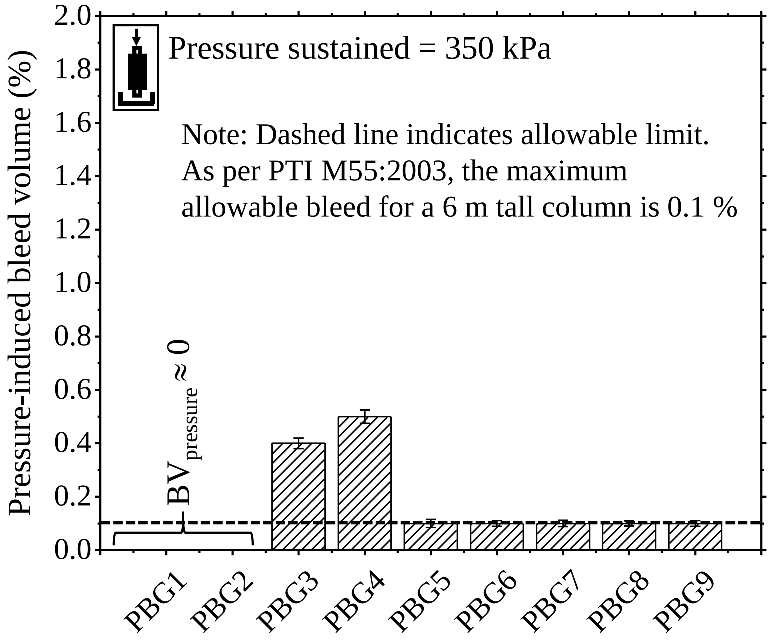


Figure 4-12. Pressure-induced bleed volume of PBGs

Figure 4-12 shows the pressure-induced bleed test results at a maximum pressure of 350 kPa. As expected, PBG1 & 2 has the lowest observed bleed water volume. PBG3 had the maximum bleed. The results of the inclined tube bleed test are given in Table 4-4. The test was conducted only for best performing grout, and the factory produced grouts (i.e., PBG5 and

PBGs 7 - 9). Only the PBGs 5 & 8 had observable bleed after 3 hours. Although PBGs 5 & 8 had a measurable volume of bleed water, it was well below the acceptable upper limit as per EN 447:2007. The reason for no bleed in PBGs 6, 7, and 9 can be due to the higher dosage of VMA compared to PBG8. Consequently, the fluidity was low for PBGs 6 & 7 compared to PBG9.

During the pumping and flow through the duct, the grout mix undergoes a wide range of shear stress. In PT duct with congested strands, the path needs to be followed by the grout to fill the interstitial space between the strands and duct will be highly tortuous. Such a path induces rolling and sliding motion in the fresh grout mix. The grout should not experience phase separation even when flows through such a pathway. Even though PBG5 and PBG6 exhibited similar bleeding at the same applied pressure the rate at which bleeding occurred was different. The change in the rate of bleeding was measured with the pressure-induced bleed apparatus. Figure 4-13 indicates the change in the rate of the bleed water comes out of the Gelman pressure cell with respect to the cumulative time taken to bleed. From Figure 4-13, it is apparent that as time progresses, the rate of bleeding exhibited by PBG6 grout reduces as compared to the PBG5 although the cumulative amount of bleeding was similar. When the pressure is applied to the grout, internal structure undergoes large deformations by breaking of the temporary bonds (shear rejuvenation). This shear rejuvenation may or may not get stabilized with time as the internal structure undergoes aging (rebuilding of bonds) simultaneously. The stabilization depends on the competition between the shear rejuvenation and the aging process. However, in PBG6, the aging/rebuilding of bonds occurs quickly and overtakes the shear rejuvenation process (Kawashima et al. 2013). Due to the presence of highly thixotropic nanoclay particles, the process of rebuilding of bonds (formation of flocs) increases with time in PBG6 grout mix as compared to PBG5 grout. On the other hand, PBG-Control grout mix exhibited an almost constant rate of bleeding for the entire test duration

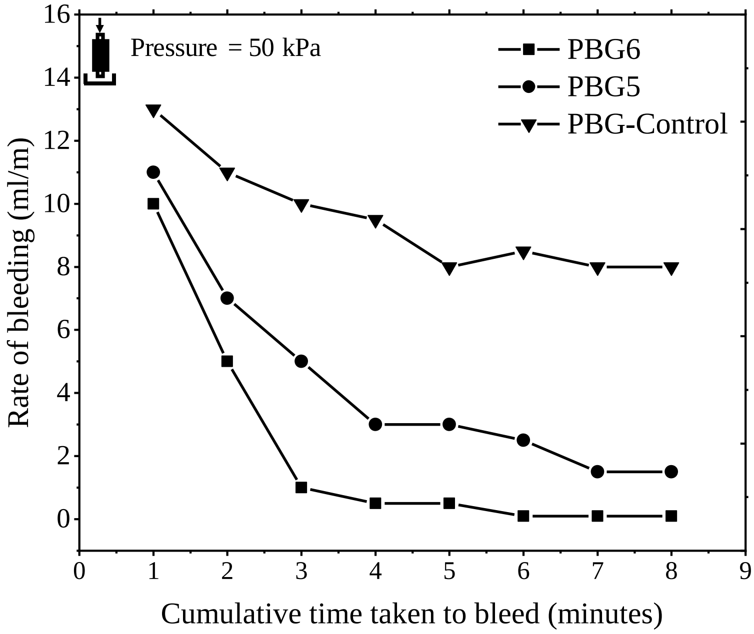


Figure 4-13. Time-dependent change in the rate of bleeding in pressure-induced bleed test

4.2.3 Rheological behaviour

The yield stress and viscosity of the best-performing grouts (i.e., PBGs 5 - 9) were measured using the co-axial cylinder viscometer. The flow curve was fitted to the Herschel-Bulkley model, parameterized by the yield stress (τ_0), shear rate ($\dot{\gamma}$), consistency (*K*) and an exponent (*n*). In the case of simple shear motion, the shear stress (τ) can be related to the shear rate ($\dot{\gamma}$) by Equation (5.2)

$$\dot{\gamma} = 0, \quad \text{if} \quad \tau = \tau_0$$
$$\tau = \tau_0 + K\dot{\gamma}^n \quad \text{if} \quad \tau \geq \tau_0 \qquad \text{Eq. 4.2}$$

when n = 1, the Herschel–Bulkley model is reduced to the Bingham model (de Larrard et al. 1998, Jayasree 2008, Nguyen et al. 2011), which can be used to simulate the rheological behaviour of Newtonian and near -Newtonian fluids with yield stress. Several researchers have used the Bingham model to simulate the rheological behaviour of cement grouts with high w/b ratio when grout behaves like a near-Newtonian fluid (Jayasree et al. 2011). However, the non-linear behaviour of the pre-blended grouts with low w/b ratio can be better captured by fitting to the Herschel-Bulkley model. Then, the yield stress was determined by extrapolating the flow curve to the shear stress axis and measuring the shear stress corresponding to zero shear rate. Figure 4-14 shows the flow curve of PBG9. The curve represents the experimental data as well as the Herschel-Bulkley model fit. Ss discussed above, the yield stress was determined by extrapolating the fitting curve to the shear stress axis; and then measuring the shear stress corresponding to the zero-shear rate. Appendix A contains the flow curves of PBG 5 to PBG8. For all PBGs, the yield stress was determined by the same method. From the fit data, it is apparent that the Herschel-Bulkely model can simulate the flow behaviour of the PBGs with a reasonable accuracy. It was observed that, the PBG7 has the highest yield stress and lowest measure bleed. It indicates that the bleed resistance generally increases with the increase in yield stress. The similar indirect relationship between the amount of bleed water and the yield stress was observed previously (Perrot et al. 2012). However, unlike other grouts, PBG9 has high bleed resistance even though the measured yield stress was the lowest. The reason for low yield stress for PBG9 can be due to the reduced surface tension of the mixing water by the reaction of SRA. However, as time progresses, the SRA concentration in pore solution increases due to the difference in the rate at which water is consumed for the hydration and the SRA have been taken up by the hydration products (Rajabipour et al. 2008). Since the bleed water was measured after three hours, the SRA concentration in pore fluid could have crossed the CMC and triggered the micelle formation. This might have reduced further settlement of particles and thus reduced the bleeding. The slope of the consistency (apparent viscosity) vs shear rate curve decreases with respect to time (see Figure 4-15) indicating the shear thinning behaviour of the PBGs. The PBG9 has the highest shear thinning behaviour compared to other PBGs. This can be due to the decrease in the surface tension of the liquid phase by the presence SRA, resulting in the grout to shear more easily with an increase in the shear rate. The correlation between the efflux time and the rheological parameters are not studied. However, the measured rheological parameters can be used for simulating the flow of grout through the duct using computational fluid dynamics simulations and thus, the locations of voids can be determined.

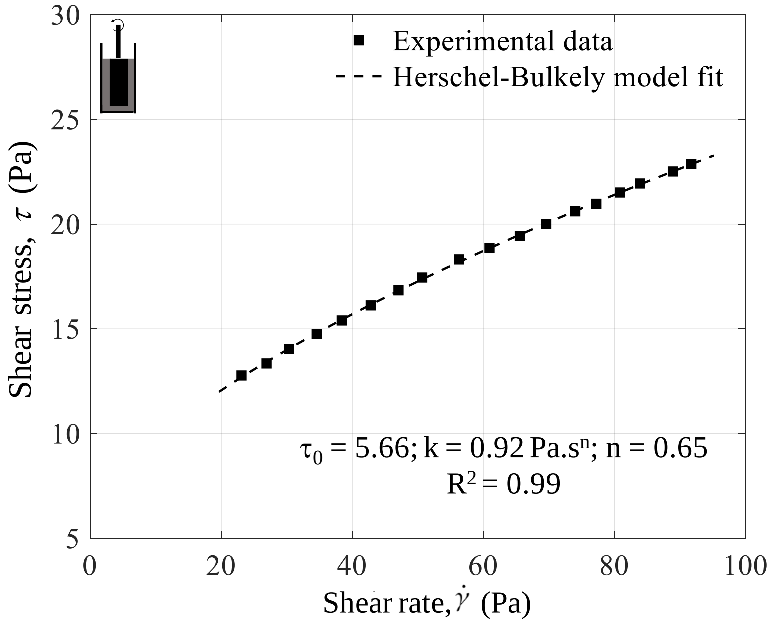


Figure 4-14. Flow curve (shear rate vs. shear stress plot) of the PBG9

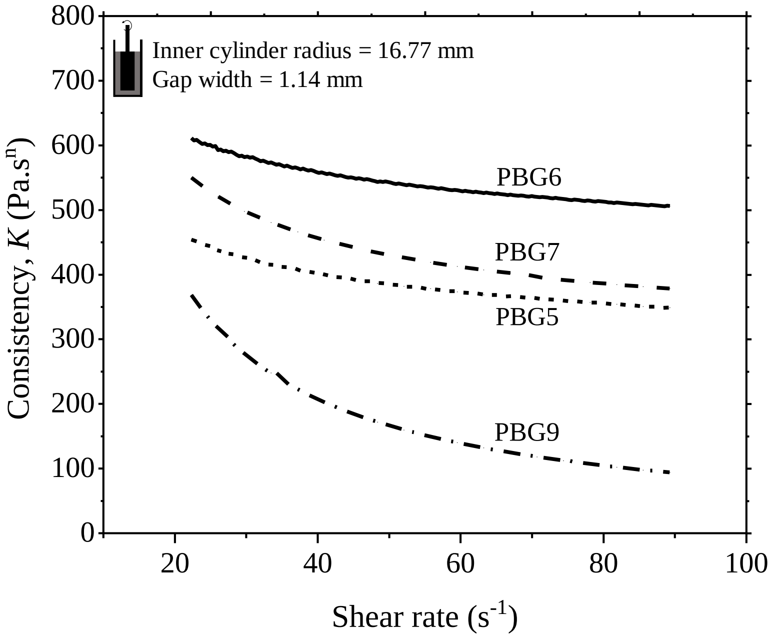


Figure 4-15. Shear thinning behaviour of PBGs

4.2.4 Dimensional stability

Dimensional stability is also one of the design parameters in the development of PBG. As discussed in Section 2.5.2.7, grout will be dimensionally stable if the shrinkage and expansion deformations are within the limits and not causing the cracks. As per PTI M55 1-12 (2013) standard, the shrinkage of the PT grout after 28 days should not be more than 0.2% of the reference length (PTI M55 1-12: 2013). There will not be any expansion because no expansive agents are added to the grout mix. However, as the developed PBGs contain high cement content and low water content, the autogenous shrinkage will be high. Thus, appropriate chemical admixtures need to be added in the PBGs to achieve desired levels of dimensional stability. A glycol-based shrinkage reducing agent was added to the grout, which reduces the surface tension of the liquid phase of the grout. A detailed description of the optimization of the dosage of SRA is given in Section 4.1.1

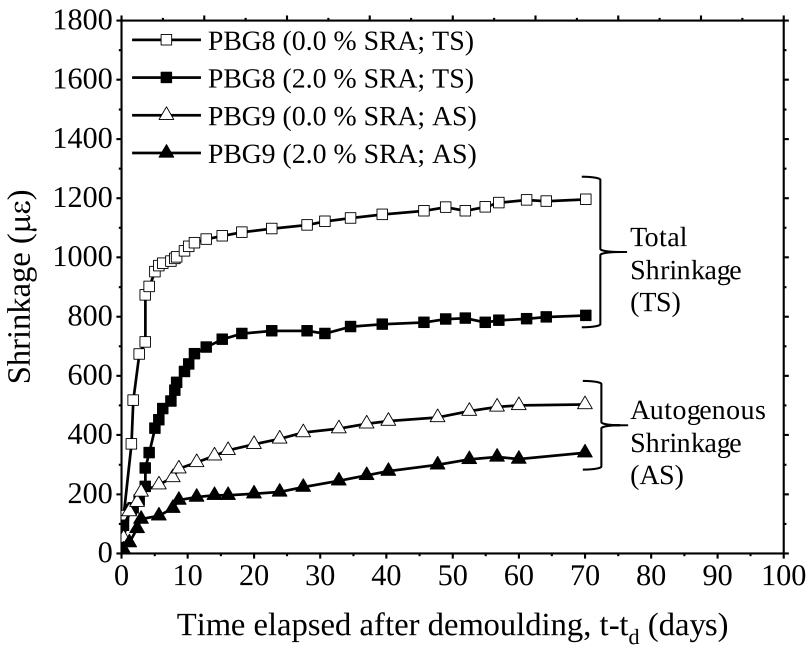


Figure 4-16. Observed shrinkage strains for PBG8 and PBG9 (t_d = 1 day)

For cement pastes without any aggregates, the autogenous deformations will happen mostly in the first 24 hours. However, the deformations occurring during the initial 24 hours (settlement, thermal contraction, plastic shrinkage, etc.) were considered as fresh or setting of grout and not included in the shrinkage strain measurement. The evolution of shrinkage strains (autogenous and total) in the prismatic grout specimens are given in Figure 4-16. After 70 days, the autogenous shrinkage and total shrinkage were reduced by 31% and 34% respectively with the addition of 2.0% SRA. The shrinkage behaviour inside the PT ducts may not be similar due to the presence of strands. For accurately measuring the shrinkage strains inside the ducts with congested strand system, a more realistic large-scale tendon-duct studies are required (Yoo et al. 2010, 2017). However, this reduction in shrinkage strains due to the addition of SRA will be similar in that case also.

The shrinkage of the PT grouts should not be more than 0.2% of the initial length as per PTI M55.1-22 (2013). From Figure 4-16 and Table 4-4, it is clear that the observed shrinkage of PBG9 was about 0.16% at 28 days of age. Thus, the shrinkage deformations are within the range recommended by PTI M55.1-22 (2013); and meets the acceptance criterion.

Similarly, EN 447 (2007) and PTI M55.1-22 (2013) has recommended specifications on the expansion of the PT grout (applicable for grouts with expansive in nature) also; and specifies to measure the expansion by ASTM C1090 (2015). However, the grouts developed in this study are not expansive or shrinkage compensating. Thus, the expansion of the developed grouts was not studied.

4.2.5 Set/hardened properties

The setting times and cube compressive strengths of the PBGs are given in Table 4-4. The setting time was determined by the time corresponds to a depth of penetration of 35 mm as per ASTM C 953 (2010). The setting time of the PBG9 was highest among all PBGs. The reason can be a delay in hydration reaction by reduced dissolution of alkali ions, admixture adsorption on cement particles, and the bond formation of among the hydration products by the addition of SRA (Mehta and Monteiro 2006; Rajabipour et al. 2008). The cube compressive strength of the PBG1 was the highest and PBG8 was the lowest for 3, 7, and 28-day cured specimens.

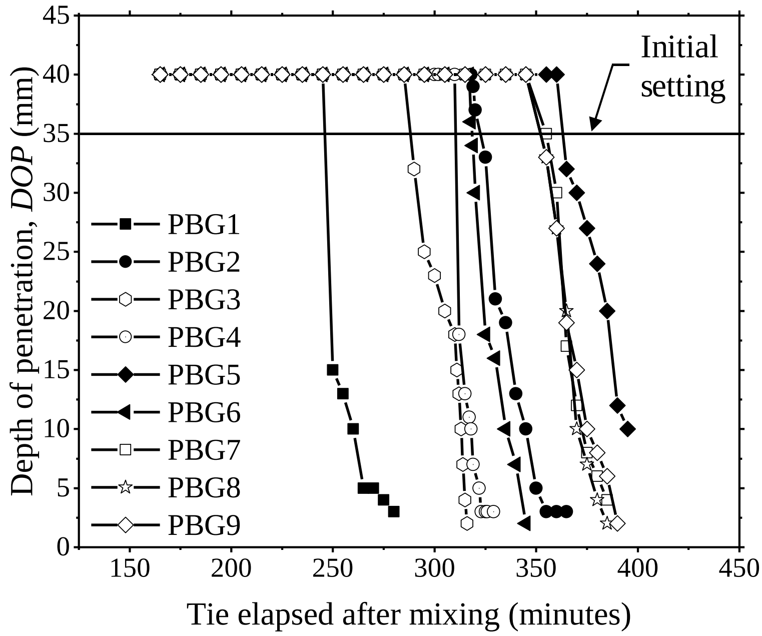


Figure 4-17. Setting time of PBGs

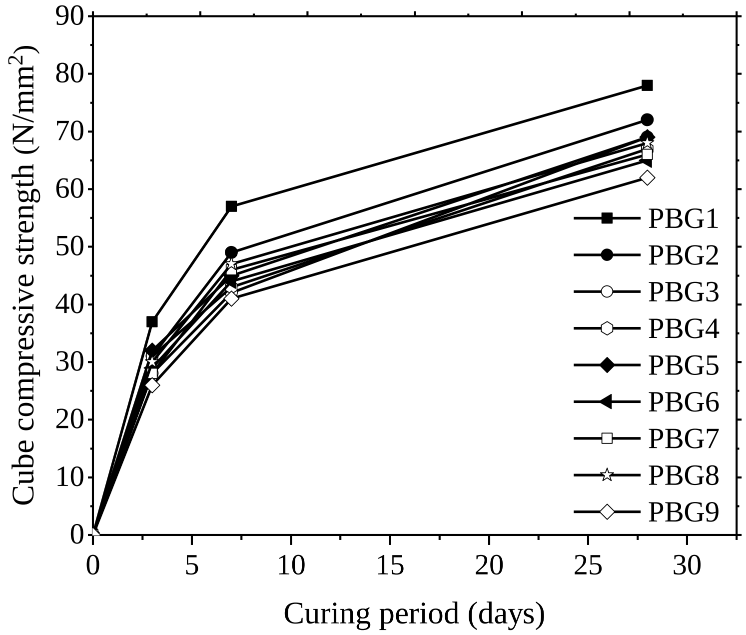


Figure 4-18. Cube compressive strength of PBGs

Table 4-4. Fresh and hardened properties of the PBGs

Parameter	Results of PBGs								
	PBG1	**PBG2**	**PBG3**	**PBG4**	**PBG5**	**PBG6**	**PBG7**	**PBG8**	**PBG9**
$T_{e,\,0}$ (s)	30	28	12	14	18	15	22	20	17
$T_{e\ 30}$ (s)	33	31	13	15	19	18	23	21	22
$T_{e,\,180}$* (s)	37.5	35	18.5	23.5	25	28.5	32.5	31	28
$D_{e,\,0}$ (mm)	117	128	167	158	151	161	146	155	159
$D_{e,\,30}$ (mm)	114	124	161	153	146	154	141	147	148
$D_{e,\,180}$* (mm)	84	88	130	127	113	116	121	123	134
τ (Pa)	-	-	-	-	8.4	12.7	17.5	11.8	5.9
$BV_{Standard}$ (mm)	0	0	0.9	0.6	0.05	0	0	0	0
$BV_{Wick\text{-}induced}$ (%)	0	0	1.5	1.2	0.1	0.1	0	0	0
$BV_{Pressure,\,350}$ (%)	0	0.1	0.4	0.5	0.1	0.2	0.1	0.1	0.1
$BV_{Inclined}$ (%)	-	-	-	-	0.1	-	0.0	0.0	0.0
$ST_{Initial}$ (hours)	4.1	6.2	4.8	5.1	5.3	6.5	6.5	6.4	7.8
ST_{Final} (hours)	12.0	14.1	13.5	13.8	14.1	14.5	14.1	14.0	16.4
$AS_{70\ days}$ ($\mu\varepsilon$)	-	-	-	-	-	-	-	503	339
$TS_{70\ days}$ ($\mu\varepsilon$)	-	-	-	-	-	-	-	1216	803
$AS_{28\ days}$ ($\mu\varepsilon$)								367	161
$TS_{28\ days}$ ($\mu\varepsilon$)								1014	711
$f_{c,\ 3\text{-day}}$ (MPa)	37	31	28	31	32	29	28	30	26
$f_{c,\ 7\text{-day}}$ (MPa)	57	49	42	43	45	44	46	47	41
$f_{c,\ 28\text{-day}}$ (MPa)	78	72	69	67	69	65	66	68	62

Table 4-4 shows the fresh and hardened properties of all the nine different PBGs

4.2.6 Selection of best performing grout

From Phase-2, a grout has been identified as best performing one based on the performance in fresh and hardened properties. The specifications from EN 447 (2007) standard was taken as the benchmark for the selection process. This selected grout has been named as 'TendonFill'. The characteristics of the TendonFill (grout material) and TendonFill grout is listed in Table 4-5.

Table 4-5. Properties of the TendonFill grout material/grout

Properties of PBG9	Result/Value
Colour	Grey
Bulk density	2200 kg/m^3
Yield per bag*	16 L
Material cost per bag**	₹ 210
Material cost per cubic meter of grout**	₹ 13,500

*when mixed with 6.75 litre of water
**Considering water is free of cost

4.2.7 Robustness assessment

Depending on the climatic conditions and the quality control measures at the site, the ambient temperature of mixing and the amount of water added, respectively, could vary. The conditions at the construction field are very difficult to control. Thus, it is anticipated that a good quality grout should also be robust against such possible variations in occur at the field. Therefore, the robustness of the best performing grout (PBG9) selected from the Phase-2 was assessed with respect to the variations in the ambient temperature of mixing and the water content. For that, the sensitivity of the fresh properties (fluidity and bleed resistance) of the grout with respect to variations in the ambient temperature and the water content was determined. The tests were conducted at two different temperatures (15° and 35° C) other than the standard temperature (25° C); at constant relative humidity. Similarly, water content was varied between ± 15 kg/m^3 of the reference water content of 420 kg/m^3.

4.2.7.1 Variations in ambient mixing temperature

As discussed in Section 2.5.2.1 and Section 3.3.1, the fluidity of the fresh grout can be assessed by the Marsh cone test and grout spread test. Therefore, the changes in efflux time and spread diameter with respect to variations in ambient temperature of mixing was assessed by a Marsh cone and spread test conforming to EN 445 (2007) respectively.

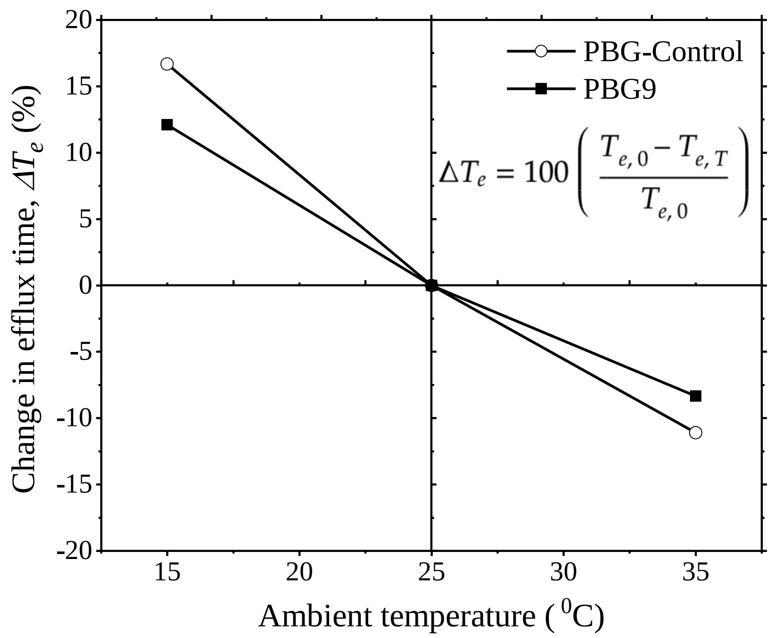


Figure 4-19. Variation of efflux time of PBGs with respect to changes in ambient temperature of mixing

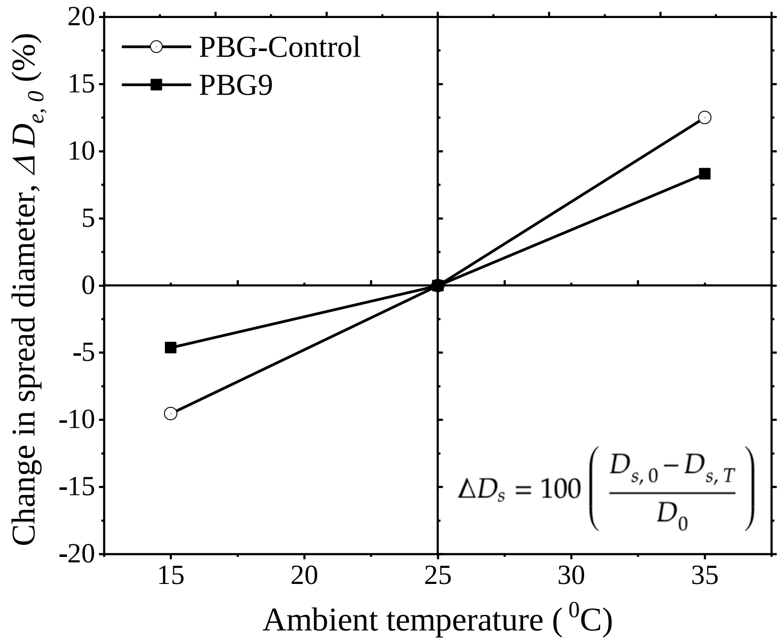


Figure 4-20. Variation of spread diameter of PBGs with respect to changes in ambient temperature of mixing

Figure 4-21 and Figure 4-22 represents the change of efflux time and spread diameter with respect to the variations in the ambient temperature respectively. As the ambient temperature increases, the efflux time decreases – indicating enhanced fluidity. A similar trend was observed with the spread diameter also. At constant relative humidity, when the ambient temperature increased, the variation of fluidity was determined by two compensating mechanisms; i.e., the increase in the water demand with the increase in temperature and the increase in the efficiency (rate of adsorption) of the HRWR. The latter mechanism will be predominant if the dosage of HRWR is higher and the constituent particles of grout are in a highly dispersed state (John and Gettu 2014). Here, the fluidity was enhanced due to the latter mechanism. There was no significant change in the bleed resistance when the ambient temperature varied.

4.2.7.2 Variations in water content

Similarly, Figure 4-21 and Figure 4-22 shows the changes in efflux time and spread diameter with the variations in the water content. As expected, with the increase in water content, the efflux time and spread diameter increases; indicating the enhanced fluidity. However, the variation of fluidity was more in PBG-Control than PBG6 and PBG9. This indicates the PBG9 and PBG6 grout mixes have more robustness than PBG-Control. Therefore, these two grouts can be used in site conditions without much changes in the fresh properties.

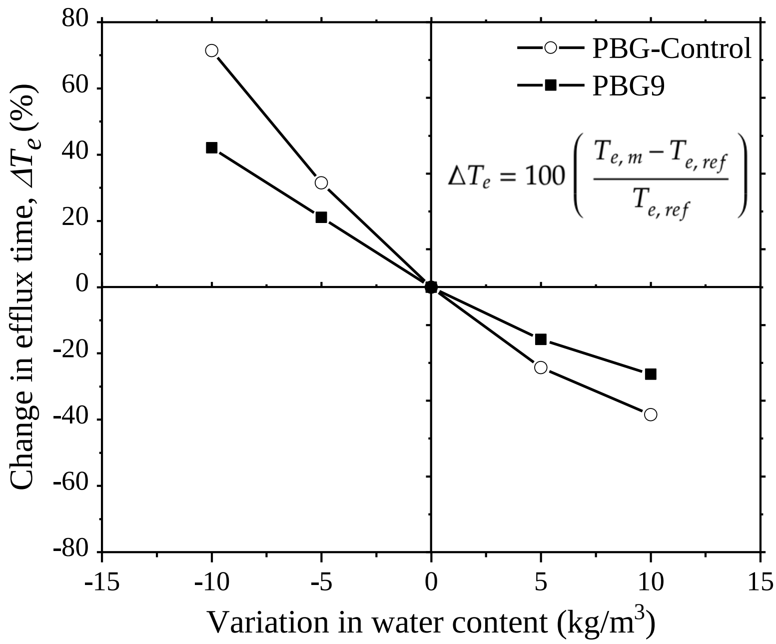


Figure 4-21. Variation of the efflux time of PBGs with changes in w/b

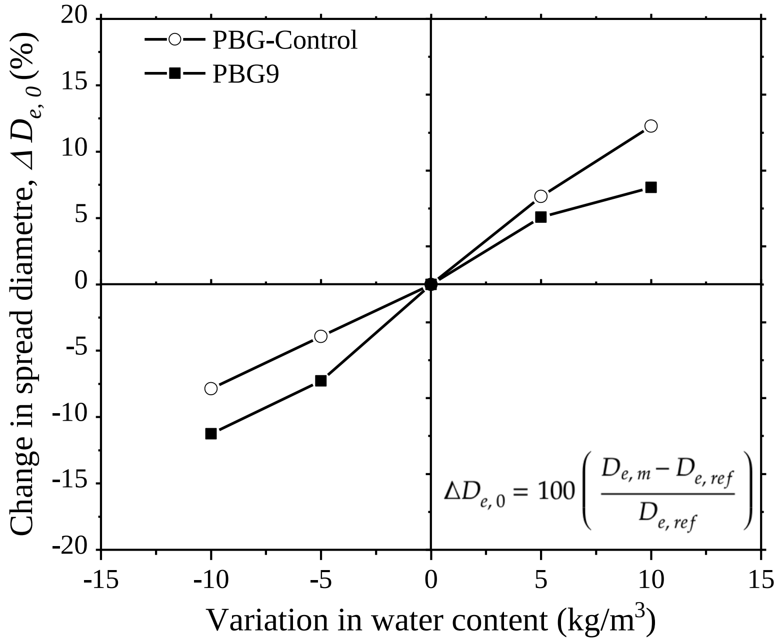


Figure 4-22. Variation of the spread diameter of PBGs with changes in w/b

4.3 PHASE-3: PROTOTYPE TENDON GROUTING TESTS

TendonFill has been blended in an industrial blending facility, packed into 25 kg bags and transported to IIT Madras. Figure 4-23 shows the 120 bags of TendonFill stored at IIT Madras. Then, the prototype tendon grouting tests are carried out to assess the bleed resistance of the TendonFill grout on a real scale with congested strand system. Similarly, a widely used grout composition (Site-batched-grout; SBG) was also tested in prototype tendon grouting tests to compare the performance of the TendonFill with the SBG. The details of the mixture proportion of SBG is given in Table 4-6.

Table 4-6. Composition of the TendonFill and SBG

Material	Quantity (kg/m3)	
	TendonFill	SBG
OPC	935	1300
FaF1	311	0
FaF2	311	0
SF	0	0
Water	420	585
HRWR	1.43	0
VMA	0.63	0
PEA*	0	5.85
SRA	31.7	0
w/b	0.27	0.45

*PEA: Plasticized Expansive Admixture

a) Pre-blended grout material in 25 kg bags

b) 3 metric ton grout material (120 bags) stored at IIT Madras

Figure 4-23. Grout material being stored at IIT Madras for further testing

As discussed in Section 3.4.2, the performance of the TendonFill and SBG was assessed based on the fluidity (using Marsh cone test), the volume of accumulated bleed water in wick-induced bleed test and prototype tendon grouting tests and volume of softgrout formed.

a) Pumping grout to the vertical duct

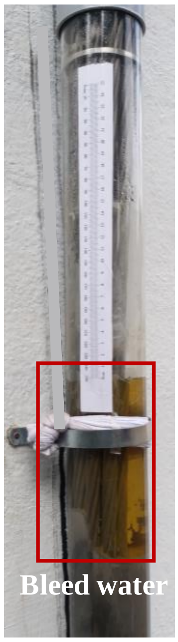
b) Injecting grout to inclined duct

Figure 4-24. Grouting of tendons inclined at different inclinations

The grouting operation was carried out as per PTI M55.1-12 (2013) standard. The grouting of tendons was carried out at an ambient temperature of 32 ± 5° C. In order to keep the grout temperature below 30° C, the mixing water used had a temperature of 22 ± 5° C. Therefore, the temperature of the grout was 25 ± 5° C. A high-shear mixer and a positive displacement pump was used for mixing and pumping. A detailed description of the mixing process was given in Section 3.4.2. PTI M 55.1-12 (2013) specifies that the grouting pressure should not be more than 10 MPa. Therefore, the pumping pressure of the grout was fixed as 5 MPa. Figure 4-24 shows the grouting operation to the tendon-duct system. As shown in Figure 4-24, the freshly prepared grout was pumped into the ducts from the lowest point. When the fresh grout mix is pumped into the duct, there is a chance of separation of the liquid layer from the grout due to the pumping pressure. This would be manifolded in the case of SBG as it contains more water in it. Therefore, about 1 liter of the pumped grout was allowed to overflow through the top end; in order to make sure that the pumped grout is consistent enough. Please see Figure 3-15 in Section 3.4.2 for the schematic diagram and the actual tendon-duct setup after grouting. After the grouting, the entire tendon-duct system was covered with cotton cloths to avoid moisture loss due to evaporation.

Figure 4-25 shows the comparison of the volume of the accumulated bleed water in TendonFill grout and the site-batched-grout. From Figure 4-25 (b), it is apparent that the SBG has a large volume of accumulated bleed water; while the TendonFill does not have any observable volume of bleed water. The SBG has exhibited about 10% bleed water volume relative to the volume of the grout in the duct. This indicates that one of the most widely used grout in India have very low bleed resistance. This bleed water will get evaporated or re-absorbed later, leaving voids. The presence of voids and exposed strands can later result in the premature corrosion of the strands. It is interesting to note that a similar grout mix has been used in the construction of PT beams and slabs in Mumbai port trust (Mumbai port trust 2017). The use of SBG in the grouting of the PT systems can result in the premature corrosion of the strands and thus reduce the corrosion free service life significantly; especially, as India is witnessing a boom in the use of PT concrete systems in large-scale infrastructure projects. Thus, it is very important to use bleed resistant cementitious grouts to achieve a durable PT concrete system.

a) PBG9 3 hours after grouting



b) SBG 3 hours after grouting

Figure 4-25. Excessive bleeding in SBG and zero bleeding in TendonFill; from the visual inspection

Three days after grouting, the tendon-duct system was disassembled and dissected at various locations throughout the duct. Figure 4-26 shows the dissected cross-sections of the tendons inclined 10° to the horizontal ground. The tendons were cut at 2 m intervals throughout the length. From Figure 4-26, it is apparent that the cross-sections of the SBG show cracks and voids at different cross-sections while the TendonFill grout does not have any voids or cracks. It can be noted that these voids are formed at the top side of the cross-section of the duct. That can be due to the evaporation/re-absorption of the accumulated bleed water. These voids can expose the strands to the deleterious ions from the atmosphere and thus, result in the corrosion. However, the TendonFill grout exhibit excellent bleed-resistance and thus, there was no voids at the top end and throughout the duct.

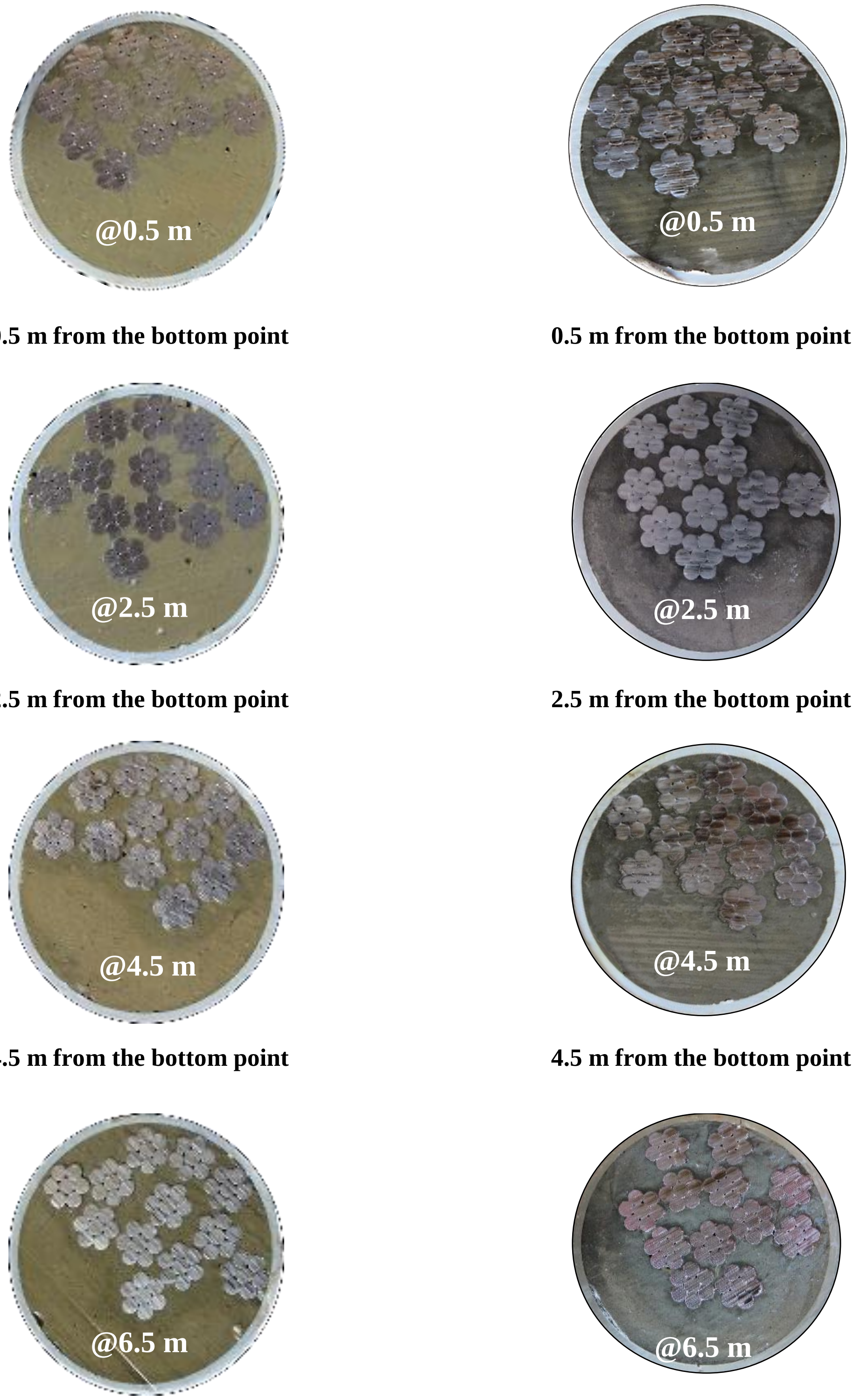
Figure 4-27 shows the cross-sections of the tendon system inclined 30° to the horizontal. TendonFill grout does not have any voids throughout the cross section as in this case of tendons inclined 10° to the horizontal. Similarly, Figure 4-28 shows the cross-sections of the tendon system inclined 90° to the horizontal. The grout present inside the vertical tendon system experiences complete self-weight of the grout column above one point. Thus, the tendons aligned vertical to the ground would represent the most critical state of bleeding scenario among all the tendon alignments tested. However, the tendons aligned angles other than 90°, the self-weight will get reduced by the factor of the sine of that angle. However, in such angles, the length of the duct can be increased and thus, more volume of the grout can be pumped into the duct.

Table 4-7 enlists the fresh properties of the TendonFill and SBG from the prototype tendon grouting test.

Table 4-7. Results of the prototype tendon-grouting tests

Parameter	TendonFill	SBG
Efflux time, $T_{e,0}$	18	13
Volume of bleed water, $BV_{\text{wick-induced}}$ (%)	0	6%
Volume of bleed water (%) • 10° • 30° • 90°	 0 0 0	 6 8 10
Visual inspection	No voids or cracks	voids at the top portion of the duct

TendonFill | **SBG**



0.5 m from the bottom point | 0.5 m from the bottom point

2.5 m from the bottom point | 2.5 m from the bottom point

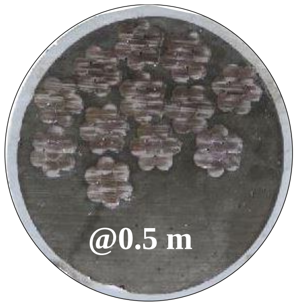
4.5 m from the bottom point | 4.5 m from the bottom point

6.5 m from the bottom point | 6.5 m from the bottom point

Figure 4-26. Cross-sections of the prototype tendon-duct system (at 10° inclination)

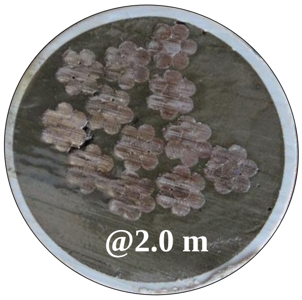
TendonFill | **SBG**

0.5 m from the bottom point



0.5 m from the bottom point

2.0 m from the bottom point



2.0 m from the bottom point

3.5 m from the bottom point

3.5 m from the bottom point

Figure 4-27. Cross-sections of the prototype tendon-duct system (at 30° inclination)

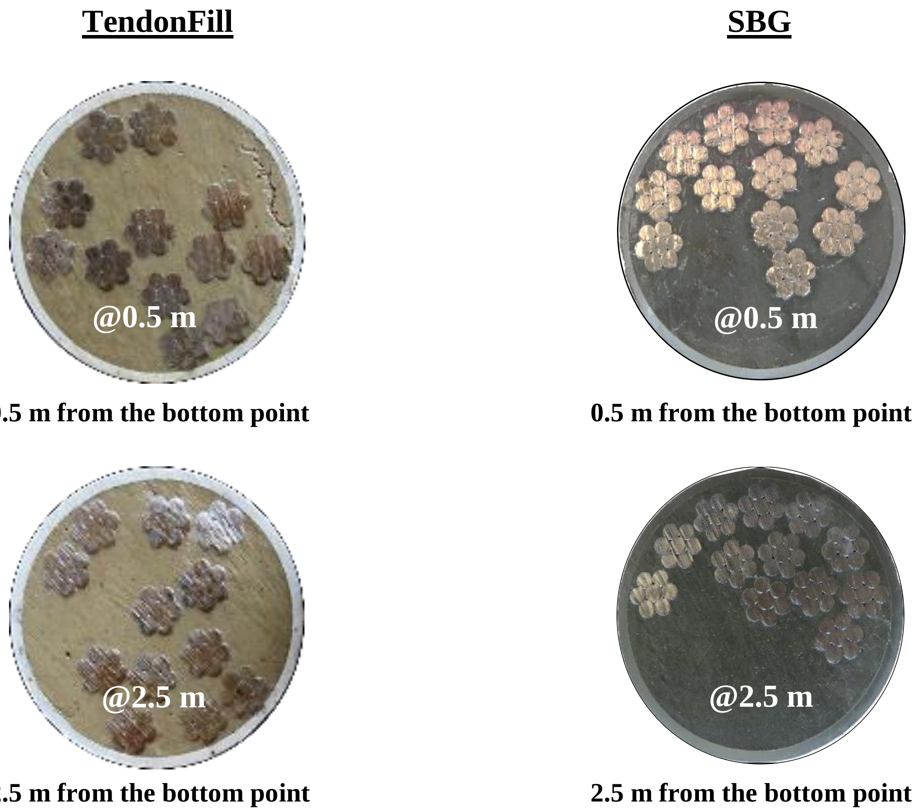


Figure 4-28. Cross-sections of the prototype tendon-duct system (at 90° inclination)

4.3.1 Performance specifications

Grouting is one of the most important operations for ensuring the durability of the PT concrete elements. Unfortunately, it is also one of the most neglected and carelessly carried out operation at the construction site. Though there are several standards have been published by different agencies around the world, the grouting materials and grouting practices are not foolproof; especially in the developing countries. The agencies are constantly trying to improve the standards and guidelines for the better and refined grouting operation. For instance, the post-tensioning institute recently made several modifications in their grouting standard, to improve the quality of grouting operations. One of such revision is, the flushing of the PT ducts with water is no longer permitted whether to clean the ducts prior to grouting or to remove grout in the event of a problem (Neff 2012).

Based on the present study, a set of stringent and comprehensive performance specifications were developed. These performance specifications are the combination of most stringent specifications from various national standards published around the globe and the recommendations from the present study. Table 4-8 tabulates the specifications on the properties of the PT grout. These specifications are divided into two sections namely quality assurance and quality control. The quality of the PT grout can be assessed by a number of tests such as flow cone tests, grout spread tests, wick-induced bleed tests, pressure-induced bleed tests, and inclined tube tests, etc. However, at the construction site all these tests cannot be done, and therefore some of the easy tests can be done to assess the PT grout quality.

Table 4-8. Recommended specifications for the PT grouts

Parameter	Acceptance criteria	Quality Assurance	Quality Control
$T_{e,\,0}$ (s)	$T_{e,\,0} \leq 25$		✓
$T_{e\,30}$ (s)	$1.2\ T_{e,\,0} \geq T_{e\,30} \geq 0.8\ T_{e,\,0}$ & $T_{e\,30} \leq 25$	✓	
$T_{e,\,180}$* (s)	$1.4\ T_{e,\,0} \geq T_{e,\,180} \geq 0.8\ T_{e,\,0}$ & $T_{e,\,180} \leq 25$	✓	
$D_{s,\,0}$ (mm)	$D_{s,\,0} \geq 140$		✓
$D_{s,\,30}$ (mm)	$1.2\ D_{s,\,0} \geq D_{s,\,30} \geq 0.8\ D_{s,\,0}$ & $D_{s,\,30} \geq 140$	✓	
$D_{s,\,180}$* (mm)	$1.4\ D_{s,\,0} \geq D_{s,\,180} \geq 0.6\ D_{s,\,0}$ & $D_{s,\,180} \geq 140$	✓	
$BV_{Standard}$ (%)	≤ 0.10		✓
BV_{Wick} (%)	≤ 0.30		✓
$BV_{Pressure,\,350}$ (%)	≤ 0.10	✓	
$BV_{Inclined}$ (%)	≤ 0.30	✓	
$BV_{Prototype\ grouting}$ (%)*	≤ 0.30	✓	
$ST_{Initial}$ (hr.)	≥ 3.0		✓
ST_{Final} (hr.)	≤ 24.0	✓	
Δ L (%)	$-0.2 \leq \Delta L\ (\%) \leq 0.2$ at 28 days	✓	
	$\Delta L\ (\%) \leq 0.1$ at 1 day	✓	
Volume of softgrout ($V_{softgrout}$)*	$V_{softgrout} = 0$	✓	✓

* The specifications developed based on the present study.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 SUMMARY OF THE RESEARCH

The study was conducted to develop a flowable, bleed resistant, and shrinkage resistant cementitious grout without the tendency to form softgrout. Also, a set of performance specifications on the grout materials and guidelines for the grouting practices are developed from this study. The study was conducted in three phases to achieve the objectives within the scope. In phase one, suitable materials were identified, and a flowable, bleed resistant cementitious grout was developed. The performance of the developed grouts was assessed in Phase-2 by measuring the fresh, and hardened properties of the developed grout and the best performing grout (i.e., the grout which meets all the stringent and comprehensive performance specifications) was chosen for the Phase-3. The chosen grout was blended on an industrial scale, and properties were evaluated, and the mixture design was fine-tuned further. Then, the bleed resistance of this grout was assessed and compared with the site-batched-grout (i.e., indigenous grout widely used in the developing world) with large-scale prototype tendon grouting tests.

5.2 GENERAL CONCLUSIONS

1) PT grouts should not be qualified based on only the efflux time criterion. The acceptance criteria should be based on the comprehensive performance specifications. The performance specifications must include criteria on bleed resistance, dimensional stability, and softgrout formation.

2) Even though commercially available, high-performance pre-packaged grouts exhibit excellent fluidity and bleed resistance, they tend to form softgrout at the crown points/elevated portions of the PT ducts.

3) Most of the standards/codes published by agencies around the world such as PTI, EN, MORTH, IRC, etc. are not comprehensive and stringent enough to differentiate good

quality grouts from poor quality grouts. In addition, these standards not widely available/used in India and several parts of the world.

5.3 SPECIFIC CONCLUSIONS

1) The binder proportioning by maximizing the packing density helped in achieving the desired flow and bleed characteristics. Replacement of OPC with 48% by volume of FaF 1 and FaF 2 and appropriate dosages of chemical admixtures can yield a grout with excellent fluidity and bleed resistance without the formation of softgrout.

2) In the large scale prototype tendon setups with congested strands, PBG9 can exhibit excellent bleed resistance and no tendency for softgrout formation. On the other hand, SBG which is widely used in the PT construction sites exhibits very low bleed resistance; even though it can exhibit excellent fluidity.

3) For PBG9, a reduction in temperature from 35 to 15°C can increase the efflux time by 20%. Similarly, a variation of w/b from 0.26 to 0.28 can result in a maximum of 30% change in efflux time from that of the 0.27 w/b.

4) The addition of 2% bwob SRA can decrease the autogenous shrinkage by about 30%, decrease the total shrinkage by about 35%, increase the fluidity by about 10%, and result in a negligible change in bleed water volume.

5) The addition of 0.1% bwob nanoclay can increase the viscosity to the desired level, decrease bleed resistance, reduce the efflux time decrease without decreasing the spread diameter.

5.4 RECOMMENDATIONS FROM THE PRESENT STUDY

5.4.1 Good grouting practices

1) Grouted PT tendon ends must be covered with fiber reinforced plastic with an anti-oxidant coating. The grout caps must have a service life of at least 75 years with an environmental stress endurance of 192 hours as per ASTM D 1693 (2015). The end caps must be attached to anchor plates with stainless steel bolts. The use of proper end caps will arrest the ingress of moisture to the tendons (FHWA 2004).

2) The grouting of draped or horizontal tendons should be carried out from the lowest points of the tendon profile. The inlet points can be initial anchorage zone or at the intermediate lower points. To ensure the grout has completely filled the duct, a fixed quantity of grout must be discharged through the outlet.

3) The grouting operation should be carried out by keeping the tendons and ducts in the dry state. Water should not be pumped inside the duct prior to pumping. The pumping of water prior to grout injection will facilitate the corrosion of the tendons.

5.5 SCOPE FOR THE FURTHER STUDY

1) The present study dealt with the qualitative aspects of the formation of the softgrout. However, quantitative evaluation of the softgrout will give more insight into the quality of PT grouts and can help in achieving durable PT concrete structures. The quantitative evaluation can be carried out by measuring the density, softness, permeability, etc. of the hardened grout mix at different locations.

2) The flow of the PT grout can be simulated using computational fluid dynamics software using the yield stress, viscosity, and thixotropy as the input parameters and choosing an appropriate non-newton model.

3) There exists an indirect relationship between the yield stress of the cementitious grout and the amount of bleed water. Generally, the grout mix with more yield stress exhibits more bleed resistance. However, to draw solid conclusions the more study on the forces acting on the grout molecules (Brownian motion, attractive colloidal forces, and gravity) need to be considered and the relationship of them with the temperature and hydration must be assessed.

4) The robustness of the developed grout mix can be further analyzed with respect to the variations in dosages of chemical admixtures (HRWR, VMA, Nanoclay, and SRA) and mix variables (mixing sequence, mixing time, and mixer type).

5) The shelf life of the developed pre-blended grout can be studied by assessing the particle size distribution and specific surface area, specific gravity of the grout materials and fresh, set/hardened properties of the grout mix for a fixed time (say six months); by keeping the grout bags at different ranges of relative humidity conditions.

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APPENDIX A – RESULTS OF THE RHEOLOGICAL TESTS

A.1 FLOW CURVES OF PBGS 5 - 8

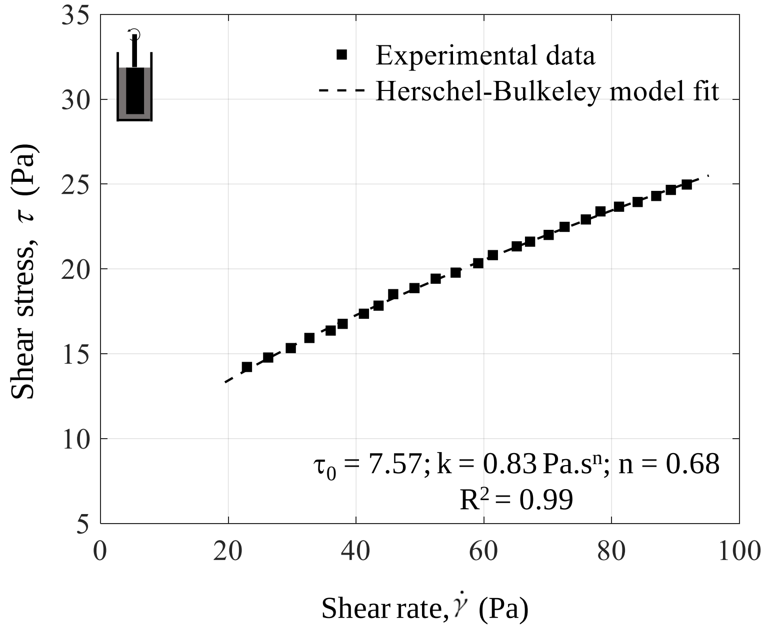

Figure A 1Flow curve of PBG5

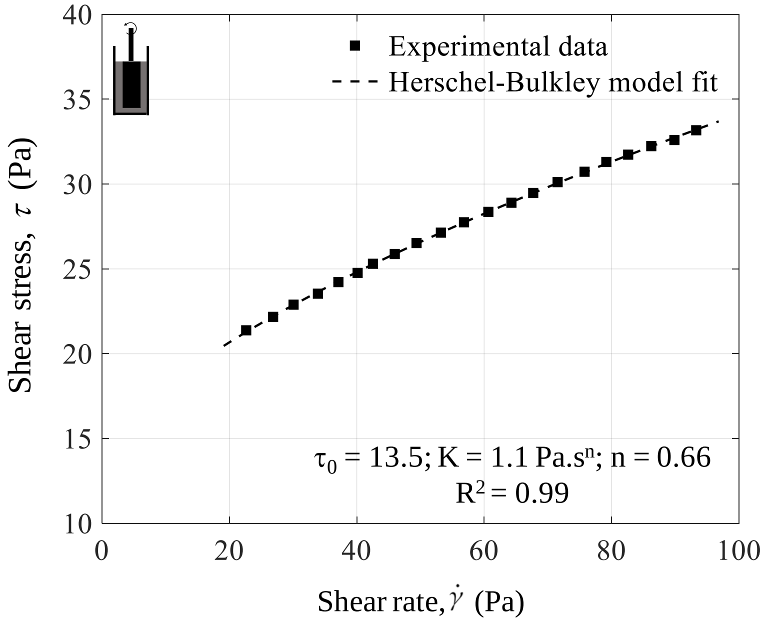

Figure A 2 Flow curve of PBG6

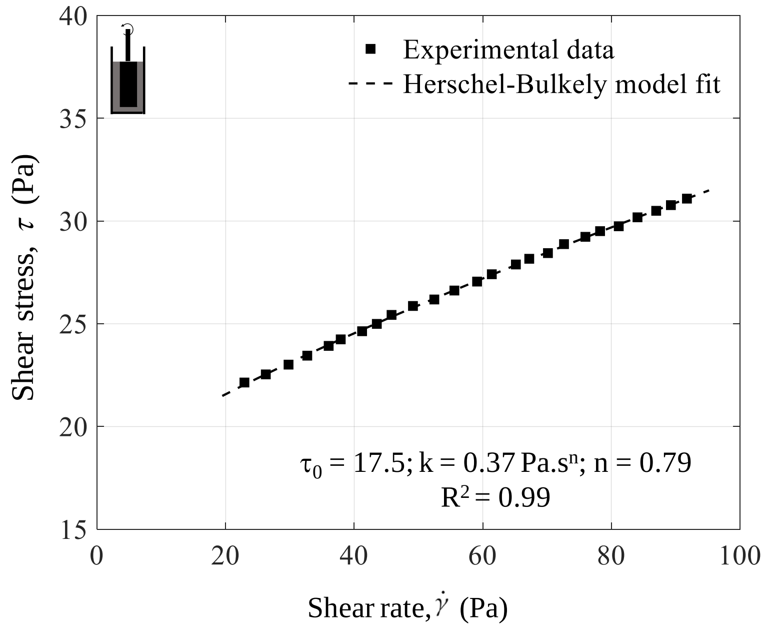

Figure A 3 Flow curve of PBG7

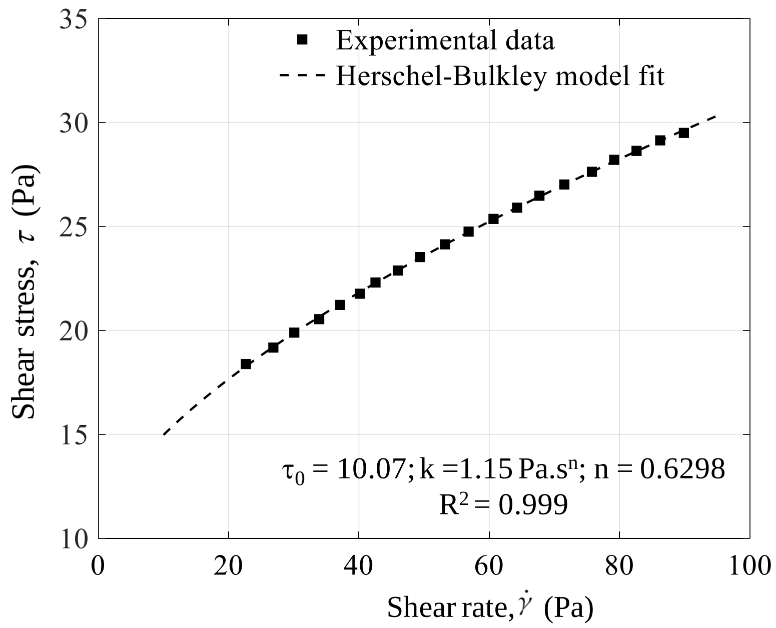

Figure A 4 Flow curve of PBG8

APPENDIX B - MODIFICATIONS FOR THE MORTH STANDARD

B.1 PROPOSED MODIFICATIONS FOR THE MORTH STANDARD

From the study, a set of comprehensive and stringent performance specifications have been developed. In India, the **'Specifications for road and bridge works'** (popularly known as the MORTH 5th revision) published by Ministry of Road Transport and Highways (MORTH) by the Government of India, is widely followed for the construction and grouting of the PT road bridges (MORTH 2013). Similarly, for the grouting of railway and metro PT bridges follows the Indian Railway Standard (IRS) '**Code of practice for plain, reinforced & prestressed concrete for general bridge construction'** (IRC 2003)

Table B 1. Specifications on the grout material

Specifications in MORTH 5th revision	Proposed modification
• **Water** Only clean potable water free from impurities shall be permitted. No sea or creek water to be used at all.	• **Water** No modification
• **Cement** Ordinary Portland cement should be used for the preparation of the grout. It should be fresh as possible and free from any lumps. Pozzolana cement shall not be used.	• **Cement** Ordinary Portland cement and supplementary cementitious materials conforming to ATM C 618 (2013) can be used in the preparation of the grout. The materials should be fresh as possible and free from any lumps.
• **Sand** Sand can be used if the internal diameter of the ducts exceeds 150 mm. Sand should conform to IS 383 and shall pass through IS sieve no. 150. The weight of the sand shall not be more than 10% of the weight of cement unless proper workability can be ensured by the addition of suitable plasticizers.	• **Sand** Sand should not be used in the grout mix as it will reduce the fluidity. Also, the sand can result in clogging of the pump.

• **Admixtures** Acceptable admixtures conforming to IS 9102 may be used. When the expanding agent is used, the total unrestrained expansion should not exceed 10%. The aluminum powder as an expanding agent is not recommended.	• **Admixtures** Acceptable admixtures conforming to IS 9103 (1999) or ASTM C 494 (2017) may be used. When the expanding agent is used, the total unrestrained expansion should not exceed 10%. The aluminum powder as an expanding agent is not recommended.

Table B 2. Specifications on the mixing procedure

Specifications in MORTH 5th revision	Proposed modification
Proportions of the materials should be based on field trials made on the grout before the commencement of grouting but subject to the limits specified above. The materials should be measured by weight.	No modification
Water should be added to the mixer first, followed by Portland cement and sand is used. Admixture if any, may be added as recommended by the manufacturer.	No modification
Mixing time depends upon the type of the mixer but will normally be between 2 and 3 minutes. However, mixing should be for such a duration as to obtain uniform and thoroughly blended grout, without excessive temperature increase or loss of expansive properties of the admixtures. The grout should be continuously agitated until it is injected.	Mixing time should be sufficient enough to disperse all the binders and chemical admixtures and to make a homogenous and consistent mix of grout without any lumps. For thixotropic, pre-packaged grouts are used, the mixing time should be 3 to 5 minutes at a rotational speed of 1500 rpm with a colloidal mixer.
Once mixed, no water shall be added to the grout to increase its fluidity	No modification

Table B 3. Specifications on the grouting equipment

Specifications in MORTH 5^{th} revision	Proposed modification
• **Grout mixer and agitator** It is essential that the grout is maintained in a homogeneous State and of uniform consistency so that there is no separation of cement. Use of grout mixers to obtain a colloidal grout is essential. The mixer should have an additional storage device with an agitator to keep the grout in the fresh state.	• **Grout mixer and agitator** Colloidal mixer with a rotational speed of 1500 – 2500 should be used for proper mixing of ingredients. Proper mixing is of utmost importance to achieve a homogenous mix of grout. The mixer should have an additional storage device with an agitator to keep the grout in the fresh state.
• **Grout pump** The pump should be a positive displacement type and should be capable of ejecting the grout in a continuous operation. The grout pump must be fitted with a pressure gauge to enable pressure of injection to be controlled. The minimum pressure at which grout should be pumped shall be 0.3 MPa, and the Grout Pump must have a relief arrangement for bypass of the grout in case of buried up of pressure beyond 1 MPA. The capacity of the grout pump should be such as to achieve a forward speed of grout of around 5 - 10 m/ min. The slower rates are preferable as they reduce the possibility of occurrence of voids. If the capacity of the pump is large, it is usual to grout two or more cables simultaneously through a common manifold. Use of hand pumps is not permitted for grouting.	• **Grout pump** No modification

Table B 4. Specifications on the properties of grout

Specifications in MORTH 5th revision	Proposed modification
• **w/c ratio** Water/cement ratio should be as low as possible, consistent with workability. The ratio should not normally exceed 0.45	• **w/c ratio** Water/cement ratio should be as low as possible, consistent with workability. The ratio should not exceed 0.35.
• **Grout temperature** The temperature of the grout shall not exceed 25° C	• **Grout temperature** The temperature of the grout shall not exceed 25° ± 10 C
• **Deleterious materials** Chlorides (Cl^-) ≤ 0.1 Sulphates (SO_3) ≤ 4.0 Sulphide (S^{2-}) ≤ 0.01	• **Deleterious materials** No modification
• **Compressive strength** The compressive strength of 100 mm cube of the grout shall not be less than 27 MPa at seven days or 30 MPa at 28 days.	• **Compressive strength** No modification
• **Setting Time** 3 ≤ Initial setting time ≤ 12 Final setting time > 24 hours	• **Setting Time** No modification

• **Bleeding** The bleeding shall not be more than 0.3 percent of the volume of after three hours kept at rest.	• **Bleeding** Bleed resistance is one of the most important property. Bleed resistance of the grout should be checked under four different conditions. The maximum allowable volume of bleed water should be 1. Standard bleed ≤ 0% (tested as per ASTM 940: 2010) 2. Wick-induced bleed) ≤ 0.3 % (tested as per EN 445: 2007) 3. Pressure-induced bleed ≤ 0 % (tested as per ASTM 1741: 2013) 4. Inclined tube bleed ≤ 0 (tested as per EN 445: 2007)
• **Field trials** No reference in the standard	• **Field trials** Field trial/mock tests should be done before choosing a new grout material. The prototype tendon-grouting tests with strand area to duct area ratio less than 0.5 can be used for field tests. The volume of bleed water in prototype tendon-grouting tests shousl be zero.
• **Softgrout** No reference in the standard	• **Softgrout** Volume of softgrout ≤ 0
• **Volume change** Volume change of grout kept at rest for 24 hours and tested as per ASTM C1090 shall be within the range of 1% and 5% of the original volume	• **Volume change** Volume change of grout kept at rest for 24 hours and tested as per ASTM C1090 (2015) shall be within the range of 1% and 4% of the original volume.

• **Fluidity** Fluidity is tested as per ASTM C939 standard using standard flow cone	• **Fluidity** Fluidity should be tested as per ASTM C939 (2010) or EN 445 (2007) 1. Efflux time immediately after mixing should not be more than 25 seconds 2. Change in efflux time, 30 minutes after mixing should not be more than 20 % of the initial value 3. Change in efflux time, 180 minutes after mixing should not be more than 40 % of the initial value 4. Spread diameter immediately after mixing should not be more than 140 mm 5. Change in spread diameter, 30 minutes after mixing should not be more than 20 % of the initial value 6. Change in spread diameter, 180 minutes after mixing should not be more than 40 % of the initial value

APPENDIX C- PROCEDURE FOR PROTOTYPE TENDON GROUTING TESTS

C.1 INTRODUCTION

The prototype tendon grouting tests can simulate the condition of grout inside the duct by using the representative geometric profile of a tendon system. The type and size of tendons and duct, anchorages and other attachments must be same that of the system used in the real structure.

C.2 SIGNIFICANCE AND USE

The prototype tendon grouting tests can give the realistic performance of the PT grouts. Most of the times, the proper quality control cannot be achieved in the construction sites due to the variations in mixing, environmental conditions and the expertise of the workforce. In addition, due to the prototype tendon grouting tests can give a realistic performance of the grout in a congested tendon duct system. Therefore, before using a new grout material in a PT structure, the performance should be checked by prototype grouting tests. By testing the bleed resistance of the PT grout under three different duct profiles, the test can give a comprehensive and realistic performance indication.

C.3 SUMMARY OF THE PROTOTYPE TENDON GROUTING TEST

Figure C.1 shows the schematic diagram of the experimental test set-up. Three different tendon profiles inclined 10°, 30°, and 90° with the horizontal need to be assembled. The strand area to the duct area should not be more than 0.5 as per EN 523 (2003). The duct diameter and strand diameter can be chosen accordingly. In this study, the test was conducted with transparent acrylic ducts with a diameter of 70 mm and a wall thickness of 3 mm. Twelve seven wire (ϕ12.7 mm) strands were inserted in each duct. The ratio between cross-sectional areas of strand and duct was 0.4. Figure C.2 shows the schematic representation of the 30° angle (to the horizontal) tendon duct system. Transparent acrylic tubes must be used as ducts for better visual observation. The performance of the PT grout can be assessed in two stages (before grouting by using lab test and the in-situ tests after grouting).

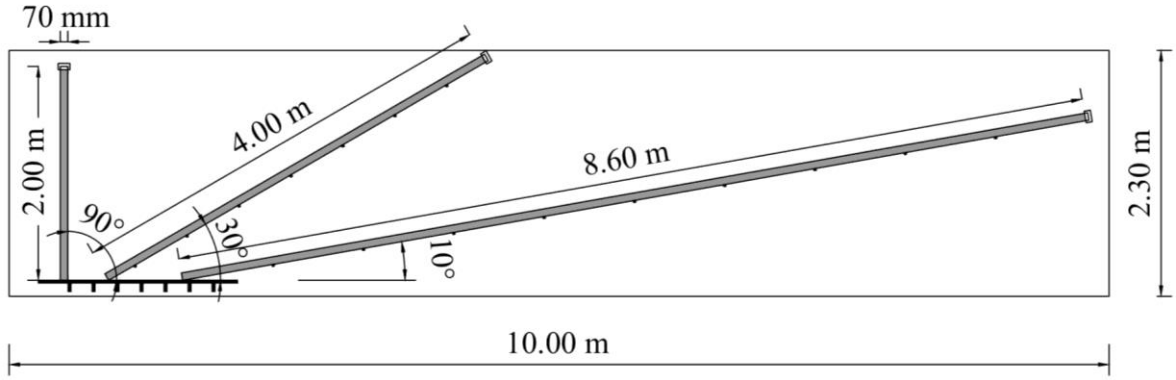

Figure C 5 Schematic representation of the prototype tendon grouting test setup

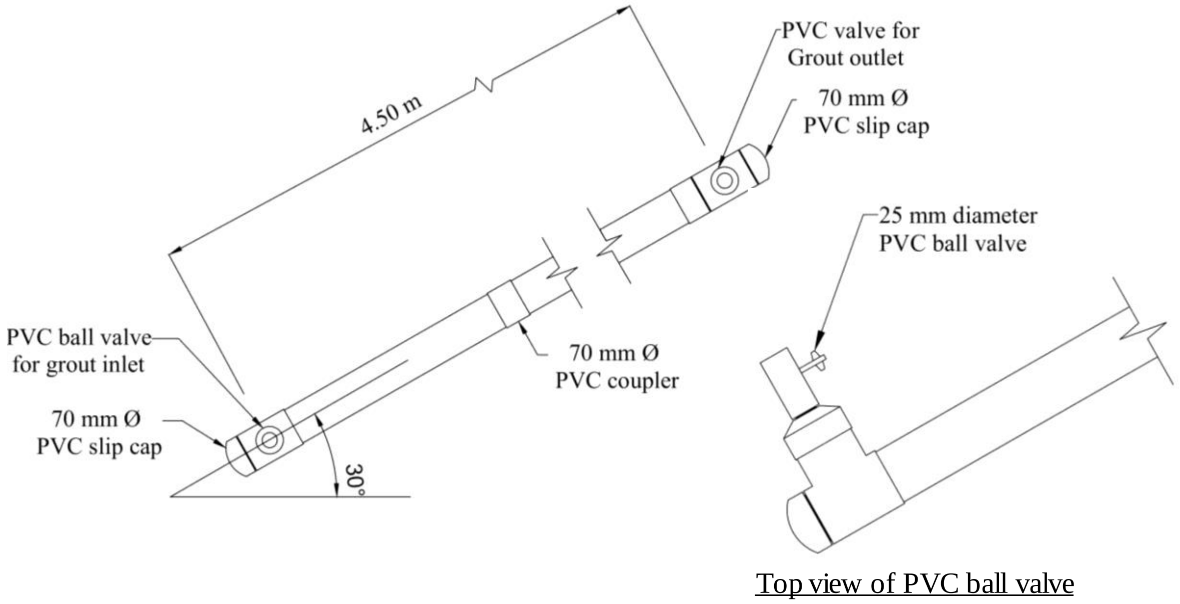

Figure C 6 Schematic illustration of the tendon-duct system (at 30° incination)

C.4 Mixing and grouting procedure

Initially, the volume of the grout needed to fill the duct should be determined. From the yield per bag of the pre-blended, pre-packaged grout bag, the number of bags needed to mix with water can be determined. Then, the mixing operation can be done as per the procedure is shown is given below.

Mixing procedure for PBG

1) Add potable water to the high-shear mixer

2) Transfer the bags of to the grout mixer slowly, while the mixer blades are rotating

3) Continue mixing speed to 1500 rpm and continue mixing for 300 seconds

For mixing the SBG, the procedure is given below. The mixing operation should be done with the utmost care. Otherwise, the ingredients will not get dispersed in the mix properly and will not yield a good quality grout.

Mixing procedure for SBG

1) Add potable water to the grout mixer

2) Transfer the bags of ordinary portland cement to the grout mixer slowly, while the mixer blades are rotating

3) Add the pre-defined amount of expansive admixture to the grout mix.

4) Continue mixing at an angular speed of 1500 rpm for 300 seconds

The procedure of grouting also very important for achieving the complete filling of the interstitial spaces between the strands and duct. After the mixing operation, the freshly mixed grout must be injected to the duct from the lowest point.

Grouting procedure

1) Prepare the grout mix

2) Conduct the quality control tests such as Marsh cone test and wick-induced bleed test

3) Attach the pump hose to the duct inlet valve (situated at the lowest point). Pump the fresh grout into the duct over a period of 1 minute. The upper end of the duct should be open to remove the air present inside the duct.

4) Stop the pumping of the grout until 2 litres of grout overflows though the outlet.

C.5 PERFORMANCE ASSESSMENT

The performance of the PT grout can be assessed in two stages. Table C-1 enlists the performance parameters, tests, and acceptance criteria. In the first stage, two quality control tests such as efflux time test and the wick-induced bleed test can be done on the freshly prepared grout mix before the grouting of the tendons. If the grout mix passes the quality control tests, the prototype tendon grouting can be done. In the second stage, the performance of the grout can be assessed by three different tests.

- by measuring the accumulated bleed water at the end of 3 hours.
- by measuring the volume of the softgrout, 24 hours and three days after the grouting
- by inspecting the dissected (3 days after grouting) tendon duct system. The duct-tendon system can be disassembled and dissected at regular intervals (say, 1m).

Table C-1. Parameters to assess the performance of grout

Parameter/assessment tool	Test method	Acceptance criteria
Efflux time, $T_{e,0}$	Flow cone test as per EN 445 (2007)	$T_{e,0} \leq 25$ seconds
Volume of bleed water, $BV_{wick\text{-}induced}$ (%)	Wick-induced bleed test as per EN 445 (2007)	$BV_{wick\text{-}induced}$ (%) ≤ 0.3
Volume of softgrout $V_{softgrout}$ (%)	Measure the volume of the softgrout layer 24 hours after grouting	$V_{softgrout}$ (%) = 0
Volume of bleed water, $BV_{Prototype\text{-}grouting}$ (%)	Measure the volume of accumulated bleed water 3 hours after grouting	$BV_{Prototype\text{-}grouting}$ (%) = 0
Visual inspection	Visual inspection on the cross-sections of the dissected tendon-duct system	There should not be any voids throughout the cross section

PAPERS PUBLISHED BASED ON THIS THESIS

PEER-REVIEWED JOURNAL PAPERS

JP1. Mohan, M. K., Pillai, R. G., Santhanam M., and Gettu R., "Performance of pre-blended grouts with high-volume fly ash for the use in post-tensioned concrete," To be communicated to *Cement and Concrete Composites*, in April 2019.

JP2. Mohan, M. K., Pillai, R. G., and Shah S. P., "Effect of nanoclay on the fresh and hardened properties of pre-blended cementitious grouts," To be communicated to *Cement and Concrete Composites,* by April 2019.

JP3. Mohan, M. K., Pillai, R. G., Santhanam M., and Gettu R., "Large-scale prototype tendon studies and performance specifications for the pre-blended cementitious grouts for post-tensioned concrete applications," To be communicated to *Construction and Building Materials*, by April 2019.

PATENT

P1: 'TendonFill -a flowable, bleed resistant, pre-blended cementitious grout without softgrout formation for post-tensioned concrete structures,' *Prior arts search is completed and the Indian patent Filing is in progress.* March 2019.

INTERNATIONAL CONFERENCE PAPERS

* Indicates presenter

CP1. Mohan, M. K.*, Pillai, R. G., Santhanam M., and Gettu R., "Fresh properties of the cementitious grouts for post-tensioning applications," Proceedings of the International RILEM workshop on Rheological Measurements of Cement-Based Materials (IRWRMC), University of Artois, Arras, France, May 30-31, 2018.

CP2. Mohan, M. K., Pillai, R. G.***,** Santhanam M., and Gettu R., "Performance specifications for the cementitious grouts used for post-tensioning applications," Proceedings of the 4th International Conference on Service Life Design for Infrastructures (SLD4), RILEM Week 2018, TU Delft, The Netherlands, August 26-29, 2018.

CP3. Mohan M. K.*, Pillai, R. G., Santhanam M., and Gettu R., " Performance specifications for the pre-blended cementitious grouts for use in post-tensioned concrete systems," Proceedings of the 3rd R.N. Raikar Memorial International Conference and Gettu-Kodur International Symposium, Mumbai, India, December 14-15, 2018.

NATIONAL CONFERENCE PAPER

CP4. Mohan, M. K., **Pillai, R. G.***, Santhanam M., and Gettu R., "Performance Specifications for cementitious grouts used in post-tensioned concrete systems," Conference on innovations in concrete infrastructures, ICI-IWC 2018, Bengaluru, India, September 19-22, 2018.

POSTER

PO1. Mohan, M. K.*, Pillai, R. G., and Santhanam M., "Fresh properties of High-Performance Grouts (HPGs) for Post-Tensioned Systems- A review of past work at IIT Madras," Poster presentation, RILEM Week 2017, Chennai, India, September 4-7, 2017.

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