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High-performance cementitious grouts for post-tensioned concrete systems – Performance specifications and prototype testing

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ABSTRACT

Grouted, post-tensioned (PT) concrete structures are protected from tendon corrosion by filling the interstitial spaces with cementitious grouts. To achieve complete grouting, the cementitious grout must be sufficiently flowable and bleed resistant. Nowadays, many commercial pre-packaged grouts are available. However, simulated bleed measurements with prototype-scale tendon grouting tests have shown that pre-packaged grouts tend to form a highly porous layer of grout, which poses a severe threat to corrosion protection. This study focuses on evaluating the performance of a novel pre-blended grout produced on an industrial scale using the fluidity and fluidity retention tests, standard, wick-induced, pressure-induced, and inclined tube bleed tests. Also, the ability of the fresh grout to retain its properties against slight variations in the ambient temperature and water content was studied. The performance of the pre-blended grout on a real scale was evaluated and compared with a widely used site-batched grout composition using prototype tendon grouting tests. In addition, a set of stringent and comprehensive specifications were developed for applications in PT systems. It was also observed that the pre-blended grout considered in this study met all the proposed specifications, therefore, can be used for the corrosion protection of tendons in PT structures.

1. Introduction

Grouted post-tensioned (PT) concrete structures are of high interest in large scale infrastructure projects in the construction industry because of their general durable nature with the advantages such as the enhanced constructability, cost-effectiveness, increased construction speed, and reduction in beam depth. The post-tensioned concrete structures are generally designed for a corrosion-free service life of 100+ years, and the seven-wire PT strands inside the concrete act as a backbone to the PT structures for such a prolonged duration. Therefore, it is essential to protect the PT strands from premature corrosion to achieve long service life [35]. Among various protective strategies for corrosion prevention of the PT strands, the application of cementitious grout is the most important method of protection. However, it is a challenging job to completely fill all the interstitial spaces between the strands and the duct with grouts due to the presence of congested strands, especially at locations of changing profile. In order to achieve complete filling of all the interstitial spaces between the strands in the tendon and the duct, the cementitious grout must be highly flowable. At the same time, the grout must be resistant to bleeding/segregation. If not, the liquid phase from the cementitious grout will separate during the grouting, pumping, and when the grout flows through the small interstitial spaces [45]. Therefore, developing high-quality grout, improving the existing grouting practices, and modifying current standard specifications for grout material is of utmost need in this area and are being discussed in this paper.

1.1. Properties defining performance of grouts

The desired properties/parameters of good-quality PT grouts are fluidity, fluidity retention, yield stress, apparent viscosity, bleed resistance, setting time, dimensional stability and compressive strength.

The grout must be fluid enough to fill even the smallest interstitial space between the tendons and duct, and the fluidity must be retained until the completion of the grouting process. Also, as the fluidity decreases, the pressure needed for pumping will increase [46]. Common tests to assess the fluidity of grouts and their retention are the Marsh cone test (determining efflux time) and Spread test (determining spread diameter) conducted at different time periods from the grout mixing.

Resistance to bleeding is an important quality defining parameter of the PT grouts [1–3], which prevents the separation of the aqueous phase

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List of abbreviations and symbols

ΔL_t	Change in length at ‘t’ days
A_{void}	Cross-sectional area of voids on a plane ⊥ to the tendon
$BV_{Inclined}$	Bleed volume in inclined–tube test
$BV_{Pressure,\ P}$	Bleed volume in pressure-induced bleed test (at pressure ‘P’)
$BV_{P,\ n}$	Bleed volume in tendon at an inclination of ‘n’
$BV_{Standard}$	Bleed volume in standard bleed test
BV_{Wick}	Bleed volume in wick-induced bleed test
$D_{s,\ t}$	Spread diameter ‘t’ minutes after mixing
FaF1	Class F fly ash 1
FaF2	Class F fly ash 2
$f_{c,\ t}$	Cube compressive strength at ‘t’ days (t = 3,7, and 28 days)
OPC	Ordinary portland cement
PBG	Pre-blended grout
PCG	Plain cement grout
PEA	Plasticised expansive admixture
PPG	Pre-packaged grout
PT	Post-tensioned
PTI	Post-tensioning institute
SBG	Site-batched grout
ST_{final}	Final setting time
$ST_{initial}$	Initial setting time
$T_{e,\ t}$	Efflux time, ‘t’ minutes after mixing
TFG	TendonFill grout
$V_{softgrout}$	Volume of softgrout formed on top of the wick-induced specimen

from the grout (segregation). Bleed resistance of PT grouts can be assessed by various test methods that can closely simulate the field conditions. These include the standard bleed test, wick-induced bleed test, inclined-tube bleed test [4], and pressure-induced bleed test [5]. The formation of softgrout is another concern resulting from segregation [6,7]. Excessive bleeding can also lead to segregation of solids, which may result in the formation of soft grout. While bleed water can be reabsorbed by the grout during hydration, soft grout has a lower pH, retains moisture, and can be extremely corrosive to the tendon. Soft grout has been found near corroded tendons has been attributed to segregetion of grout [6,8]. Fig. 1 shows some of the examples of soft grout formation due to segregation.

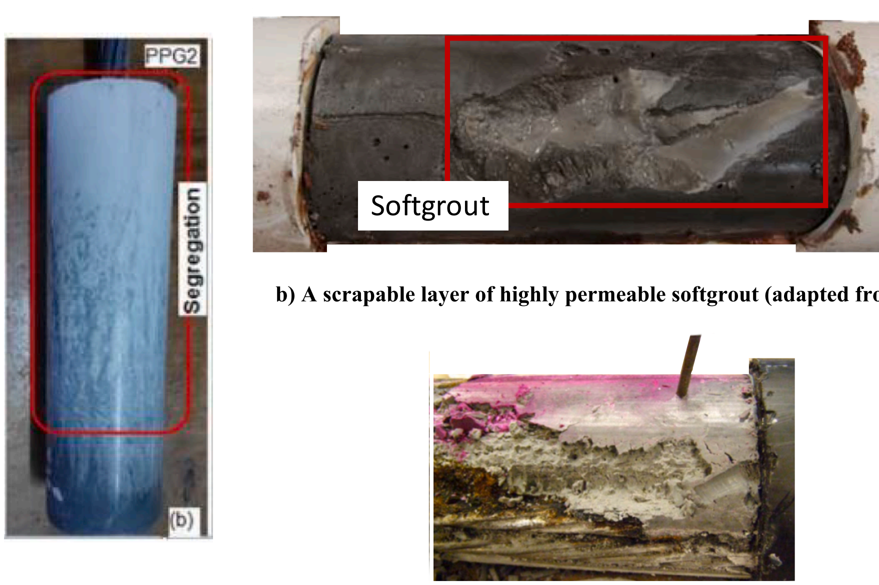
The dimensional stability of the hardened grout represents its resistance to shrinkage, expansion and cracking. The inclusion of shrinkage reducing admixtures (SRA) in the mix is commonly adapted to prevent shrinkage of the grouts [10]. Shrinkage can be measured by evaluating the change in length of PT grout specimens under closed conditions at different time periods.

1.2. Factors influencing grout behaviour

This section discusses the essential factors which influence the desired grout properties explained in the previous section. They include cement, water-binder ratio, mineral admixtures and inert fillers, chemical admixtures, cement-admixture interactions and the mixing procedure.

Ordinary portland cement is the most widely used binder in the design of PT grouts and generally occupies more than 50 % of the volume of the total binder. The surface area and particle size distribution of cement are important as they can influence the fluidity of the freshly prepared grout. Cement with a higher surface area can result in higher packing density when combined with fly ash and will exhibit enhanced bleed resistance [11]. Mizra et al. [12] observed that the viscosity of the grout mix increases as the surface area of the cement increases (i.e., mean diameter reduces) at low water-to-binder ratios (w/b). The authors deduced that the grout viscosity is directly proportional to the fineness of the cement based on the study conducted on 16 different types of cement [12]. 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 in cement 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 [12].

The water-to-binder (w/b) ratio is important as it is directly



b) A scrapable layer of highly permeable softgrout (adapted from [6])

a) Softgrout/segregation   c) A layer of softgrout with a pin pierced into it (adapted from [9])

Fig. 1. Softgrout/segregation exhibited by a commercially available PPG.

proportional to the fluidity and inversely proportional to the bleed resistance. Thus, PT grouts should have very low w/b to achieve excellent bleed resistance; however, a very low w/b ratio will result in enhanced autogenous shrinkage. The autogenous shrinkage will be significant if the w/c is less than 0.42 and grout with a very low w/c of 0.17, the autogenous shrinkage strain was reported as 700×10^{-6} at 28 days of age [13,14]. Therefore, a balanced w/b is desired to achieve a highly flowable grout with better bleed resistance.

Finally, the type of mixing, mixing speed, mixing time, and the sequence of addition of ingredients in the mixing significantly influence the fresh properties of the resulting grout. Also, the variations in these factors can affect the fresh properties of the PT grout [15]. 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 the high mixing energy. A low-speed paddle mixers may not disperse the ingredients completely. Therefore, a high-shear mixing method for the mixing of cement grout, according to ASTM C1738 [16] is generally used.

1.3. Existing global scenario for grout materials

PPGs with excellent fluidity and resistance to bleeding/segregation are used in the USA from the early 2000s onwards [17]. As these PPGs are properly engineered and made in factories with controlled conditions, they are expected to have desired flow properties and resistance to bleeding/segregation. However, there are reported incidents of the higher levels of chloride content in PPGs and the formation of softgrout. The improper mixture design method and the selection of ingredients without proper technical know-how are the main reasons for these problems [6,7,18–20]. On the other hand, plain cement grouts (PCGs) and SBGs with very low bleed resistance are being used in India for PT applications [3]. Fig. 2 shows the efflux times of such grouts (PCG, SBGs, and PPGs). These grouts are prepared and tested as per the water content prescribed by the manufacturer or the water content used at the construction site. From Fig. 2, it is apparent that PPGs have higher efflux time compared to SBGs and PCG indicating low fluidity. On the other hand, PCG and SBGs show very low efflux time compared to PPGs indicating good fluidity. The higher fluidity exhibited by PCG and SBGs can be due to the very high water content compared to PPGs.

Fig. 3 shows the bleed resistance of the same set of grouts. From Fig. 3, it is evident that commercially available PPGs have excellent bleed resistance compared to PCG and SBGs, even though their fluidity is relatively low. The reason for low fluidity and high bleed resistance for

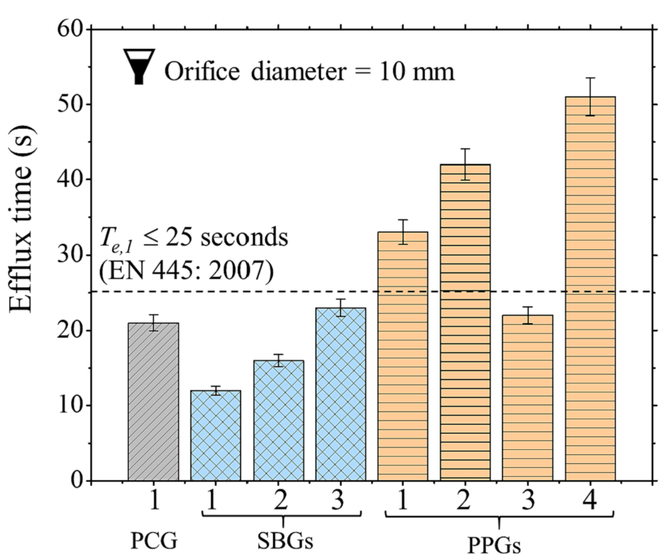


Fig. 2. Efflux time of the PCG, SBGs, and PPGs.

PPGs can be due to the presence of chemical admixtures in the PPGs and the low water content, respectively. Generally, there is apractice of using the 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, the 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 [3].

1.4. Current specifications for grouts

Grouting is a complex process involving various tasks. Those tasks range from proper material selection to the pumping of the fresh grout. To achieve complete grouting, the different tasks involved in the process must be systematic. Various standards have been published by different agencies [21–25]. Table 1 lists the different performance parameters on the grout and duct materials and grouting operations to achieve a void-free grout system mentioned in various standards. The dashed line in each column indicates the absence of the specification on that parameter/property. From Table 1, it is apparent that most of the standards are not complete/comprehensive and stringent enough to differentiate good and poor-quality PT grouts. EN 447 [22], ISO 14824–1 [26], and PTI M55.1 12 [21] give more comprehensive and stringent specifications for grout materials. EN 447 [22], *fib* Bulletin 20 [23], PTI M55.1–12 [21], and MORTH [27] give more stringent specifications. In addition, there exist technical documents and detailed manuals/guidelines on PT tendon installation, selection of grout materials, test methods to assess the grout properties, grouting operations, etc., published by several agencies [28–31]., it is apparent that most of the standards are not complete/comprehensive and stringent enough to differentiate good and poor-quality PT grouts. EN 447 [22], ISO 14824–1 [26], and PTI M55.1 12 [21] give more comprehensive and stringent specifications for grout materials. EN 447 [22], *fib* Bulletin 20 [23], PTI M55.1–12 [21], and MORTH [27] give more stringent specifications. In addition, there exist technical documents and detailed manuals/guidelines on PT tendon installation, selection of grout materials, test methods to assess the grout properties, grouting operations, etc., published by several agencies [28–31].

1.5. Good and poor 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 the least care, and thus, voids are formed throughout the duct – leading to the exposed strands and eventually corrosion of strands. Different agencies have published guidelines for good grouting practices. Some of the good grouting practices include: 1) The grouting of draped or horizontal tendons should be carried out from the lowest points of the tendon profile. The inlet points can be the initial anchorage zone or at the intermediate lower points. To ensure the complete filling/grouting of the PT duct, a fixed quantity of grout must be discharged through the outlet until a consistent mix of grout come out through the outlet point [28]. 2) The grouting operation should be carried out by keeping the tendons and ducts in a dry state. However, there exists a common practice of flushing the PT ducts with water or oil to remove the impurities (say sand, dust, etc.) on the surface of PT tendons. 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 [28,32]. 3) Grouted PT tendon ends must be covered with fiber-reinforced plastic with an antioxidant coating. The end caps must have a service life of at least 75 years with an environmental stress endurance of 192 h. 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 [28]. Fig. 4 (a) and (b) shows examples of some

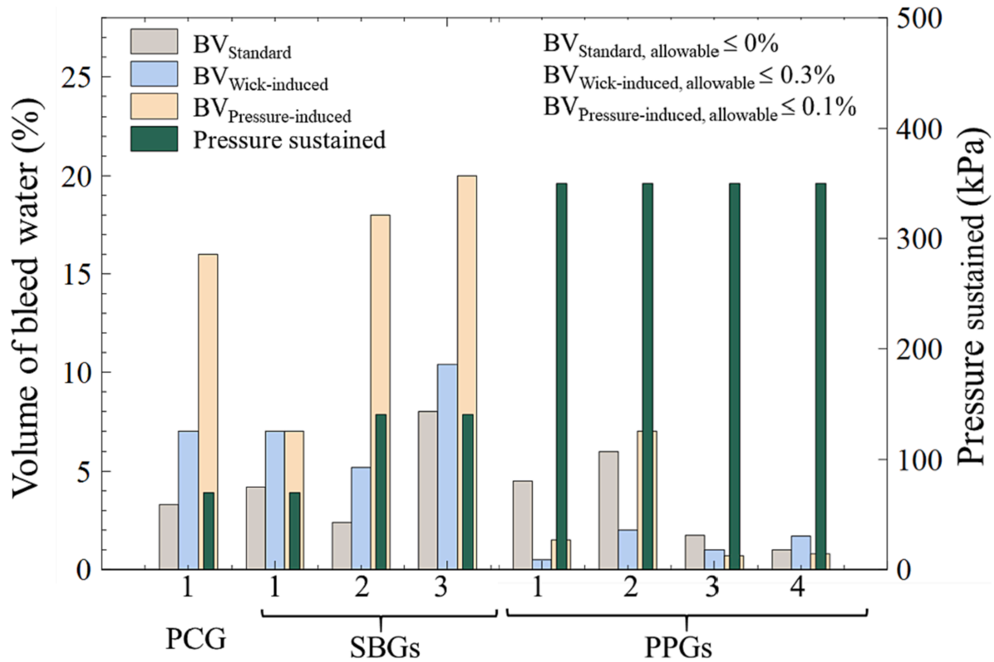


Fig. 3. Bleed volume of PCG, SBGs, and PPGs under three different simulated real bleed test conditions.

Table 1
Specifications for PT grouts and duct materials mentioned in various standards.

	Parameter	Reference standard					
		EN 447 & ISO 14824 1 [22] & [26]	PTI M55.1–12 [21]	fib bulletin 20 [23]	MORTH [27]	IRC [25]	JSCE [24]
Specifications	$T_{e,\,1}$ (s)	≤ 25	$5 \le T_{e,\,0} \le 30$	≤ 25	–	–	–
	$T_{e,\,30}$ (s)	$1.2\,T_{e,\,0} \ge T_{e,\,30} \ge 0.8\,T_{e,\,0}$ & $T_{e,\,30} \le 25$	–	–	–	–	–
	$D_{s,\,1}$ (mm)	≥ 140	–	–	–	–	–
	$D_{s,\,30}$ (mm)	$1.2\,D_{s,\,0} \ge D_{s,\,30} \ge 0.8\,D_{s,\,0}$ & $D_{s,\,30} \ge 140$	–	–	–	–	–
	$BV_{Standard}$ (%)		–	–	–	–	–
	BV_{Wick} (%)	≤ 0.3	≤ 0	≤ 0.3	≤ 0.3	–	$\le 2.$
	$BV_{Pressure,\ 350kPa}$ (%)	–	≤ 0	–	–	–	–
	$BV_{Inclined}$ (%)	≤ 0.3	≤ 0.3	≤ 0.3	–	–	–
	ST_i (hour)	≥ 3	$3 \le ST_i \le 12$	greater than 3	$3 \le ST_i \le 12$	–	–
	ST_f (hour)	≤ 24	–	less than 24	≤ 24	–	–
	$f_{c,\ 7\text{-day}}$	≥ 27	≥ 21	≥ 27	≥ 27	≥ 17	≥ 20
	$f_{c,\ 28\text{-day}}$	≥ 30	≥ 35	–	≥ 30	–	
	$\Delta L_{1\ day}$. (%)	–	$\le +0.1$	-0.5 to $+5.0$	–	–	-0.5 to $+0.5$
	$\Delta L_{28\ day}$ (%)	-1 to 5	$\ge +0.2$	–	1–5	–	
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 steel or smooth/corrugated HDPE pipes	–	–
	Cross-sectional area of the duct	≥ 2 to 3 times the cross-sectional area of the strands	≥ 2 to 3 times the cross-sectional area of the strands	≥ 2 to 3 times the cross-sectional area of the strands	≥ 2 times the cross-sectional area of the strands		–

good capping practices, as well as bad ones.

Some of the poor grouting practices include:1) Filling 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) Flushing the PT ducts with water before pumping 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 result in bleeding. The corrosion incidents were reported in PT tendons, which were flushed with water before grouting [20]. 3) Covering the anchorage ends with quick setting mortar (dry packing) or by concreting the anchorage recess before grouting [33]. The end caps made of cementitious materials are highly hygroscopic and thus facilitate the entry of moisture to the tendons and triggers corrosion. Fig. 4 (c) shows a case where cementitious end caps are coated with a water-proof coating, which is again not an ideal practice, especially in India where UV radiation is very high which damages the coating [34].

2. Research significance

This research focuses on assessing the performance of a novel pre-blended cementitious grout at different simulated real conditions. The

a) Good quality polymer-based end cap at blister of a PT bridge (adapted from [33])

b) Cementitious end-caps used in a girder

c) Cementitious end-caps used in a metro bridge

Fig. 4. Examples of good (a) and bad end-capping practices (b and c).

performance assessment of the novel grout is also complemented with the evaluation of properties of two pilot manufactured batches of the product and a shelf-life assessment of up to 6 months. Also, a set of comprehensive and stringent performance specifications are developed that could help in screening out the bad quality grouts and thus prolonging the corrosion-free service life of PT concrete structures.

3. Methodology

3.1. Materials and methods

The mixtures investigated in this study are a novel pre-blended grout material (designated as TFG) developed at IIT Madras and a typical grout composition (designated as SBG) used for PT applications. The detailed procedure for the development of TFG can be found in [35]. Two large-scale pilot productions of TFG (3 metric tons each) were carried at an industrial blending facility and are designated as TFG1 and TFG2. Fig. 5 shows the details of the industrial blending facility used for the pilot productions. The compositions of TFG (both TFG1 and TFG2 have the same composition) and SBG are given in Table 2. TFG contains 53 Grade OPC conforming to the IS 12269 [36] and two Class F fly ashes (denoted as FaF1 and FaF2) as binders. A polycarboxylic ether based high range water reducer and hydroxyethyl methylcellulose, glycol-based shrinkage reducing agent, was used as the chemical admixtures. TFG has a water-to-binder ratio (w/b) of 0.27. The only binder in SBG is 53 Grade OPC and a plasticised expansive admixture as the chemical admixture. SBG has a w/b of 0.45. Potable water was used for preparing the grouts.

For laboratory-scale experiments, the grouts were prepared using a custom-made high-shear mixer fabricated at IIT Madras. Such a high-

a) Dosing of ingredients

b) Blending of ingredients of PBG

Fig. 5. Industrial blender used for pre-blending the dry ingredients of the grout (Courtesy: Ultratech Cement ltd.).

Table 2
Composition of TFG and SBG.

Material	Quantity (kg/m^3)	
	TFG1 and TFG2	SBG
Ordinary portland cement	935	1300
Class F Fly ash 1	311	0
Class F Fly ash 2	311	0
Water	420	585
High range water reducer	1.43	0
Viscosity modifying admixture	0.63	0
Plasticised expansive admixture	0	5.85
Shrinkage reducing admixture	31.7	0

shear mixer was used to ensure the proper mixing of the grout materials. The detailed design and performance of grout with respect to mixing variables are given in [3]. The high-shear mixer has a capacity of 20 L 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. Fig. 6 (a) and (b) show the front view of the high–shear mixer and the schematic representation of the mixer and spindle, 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 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 the mixing operation [3].

3.2. Robustness assessment

Robustness was assessed by measuring the changes in the fresh properties (fluidity and bleed resistance) of the TFG with respect to variations in the ambient temperature and the water content. Fig. 7 shows the schematic diagrams of the laboratory tests for measuring fluidity and bleed water resistance. The tests were conducted at two different temperatures (15° and 35 °C) other than the standard temperature (25 °C); at a constant relative humidity of 65 %. Similarly, water content was varied up to ± 10 kg/m^3 of the reference water content of 420 kg/m^3.

3.3. Shelf-life studies

The physical properties of both the pilot productions of the TFG were tested periodically at 0, 3 and 6 months to understand the extend up to which the pre-blended grout material can be used without much variations in the properties. Susceptibility of the grouts to change the physical/chemical properties over time with exposure to surroundings would possibly alter the performance by causing pre-hydration of the portland cement. This could eventually result in the formation of softgrout. Hence, the consistency of various physical properties/parameters of the grout were monitored and documented, with an exposure condition of 25 °C and relative humidity of 50 %. Among the physical characteristics, the mean particle diameter of the grout material was determined using laser diffraction method as per ISO 13320 [37], the specific surface area was measured using Blaine's air permeability test as per IS 4031-Part 2 [38] and the specific gravity was measured according to IS 4031 Part-11 [39]. The fresh properties of the grout were assessed as per EN 445 [4] by testing the fluidity and retention by measuring efflux time and spread diameter; the volume of bleed using wick induced, pressure-induced and inclined tube test; and the initial and final setting times according to ASTM C 953 [40].The physical properties of both the pilot productions of the TFG were tested periodically at 0, 3 and 6 months to understand the extend up to which the pre-blended grout material can be used without much variations in the properties. Susceptibility of the grouts to change the physical/chemical properties over time with exposure to surroundings would possibly alter the performance by causing pre-hydration of the portland cement. This could eventually result in the formation of softgrout [9,41].

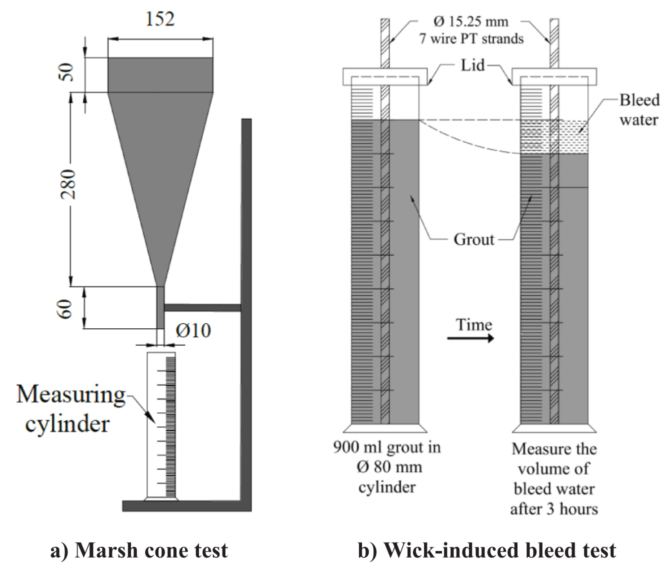


Fig. 7. Laboratory-scale tests to measure fluidity and bleed water volume.

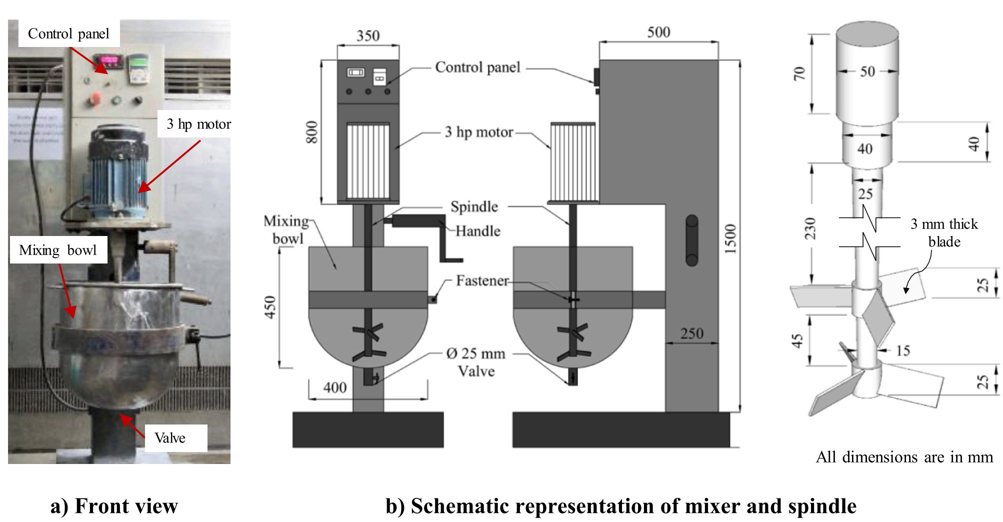


Fig. 6. Custom-made high shear mixer and the details of the blade and spindle.

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3.4. Prototype-scale tendon grouting tests

Prototype-scale tendon grouting experiments were conducted to critically assess the bleed resistance of the grouts. Fig. 8 shows the schematic diagram and the actual setup of the prototype-scale tendon grouting test. Three different tendon profiles (inclined 10°, 30°, and 90° with the horizontal) were mounted on a vertical wall. Each duct has an inner diameter of 70 mm and a wall thickness of 3 mm. The strand area to duct area ratio was chosen to simulate the real conditions in a PT concrete bridge. AASHTO LRFD [42] specifies that the strand area to duct area ratio should not be more than 0.5, while the PTI, ASBI and EN standards specify that the ratio should not be more than 0.4 [32,42,43]. 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 to realistically assess the amount of bleed water due to congested tendon systems usually present in segmental PT bridges. Twelve, seven-wire strands (diameter of 12.7 mm) were inserted in each duct. Fig. 9 (a) shows the details of the 30° angle (with respect to horizontal) tendon grout system, and Fig. 9 (b) shows the actual setup of the duct system used at different inclinations. PT strands can be eccentric at various locations inside the duct due to the prestressing force This eccentricity of strands will make the complete filling/grouting very difficult. To check the ability of grout to fill even at these eccentric locations, the strands inside the duct were raised to the top of the duct using tie wires. This arrangement can closely simulate the real scenario in PT bridges with congested strand systems. Transparent acrylic tubes were used as ducts for better visual observation. A typical SBG was also tested for comparison. Two trials were conducted for each batch of TFG and SBG. After grouting, the ducts were covered with wet cotton cloths to maintain the temperature of the grout in the range of 20 - 25° C. After three days, the tendon-duct system was disassembled and the hardened grout was cut at critical locations where the bleeding was expected to check the presence of voids.

The grout mixing operation was carried by an industrial grout mixer with a maximum mixing speed of 1450 rpm. The details of the industrial grout mixer and blade configuration is shown in Fig. 10. For each trial, 45 L of grout were needed to fill the ducts.

3.4.1. Acceptance criteria used in the prototype-scale testing

Table 3 lists the parameters and assessment methods used for the assessment of the performance of the grouts in the prototype-scale tendon grouting study. Table 3 also gives the performance specifications for each parameter, which can be used to screen out poor-quality grout materials.

4. Results and discussion

4.1. Performance assessment at laboratory scale

Table 4 gives the physical properties of the TFG1 and TFG2. From Table 4, it can be seen that there are no variations in the physical properties even though the TFG1 and TFG2 are produced at two different industrial blenders. The fresh and hardened properties of the TFG1, TFG2 and SBG are given in Table 5. From Table 5, it can be seen that TFG1 and TFG2 exhibited zero bleeding in all the simulated bleed test conditions. On the other hand, SBG exhibited significantly high bleeding in all different simulated bleed test conditions. The lack of bleeding in TFG mixes can be attributed to the presence of cellulose-based viscosity modifying agent and also lower w/b [35].

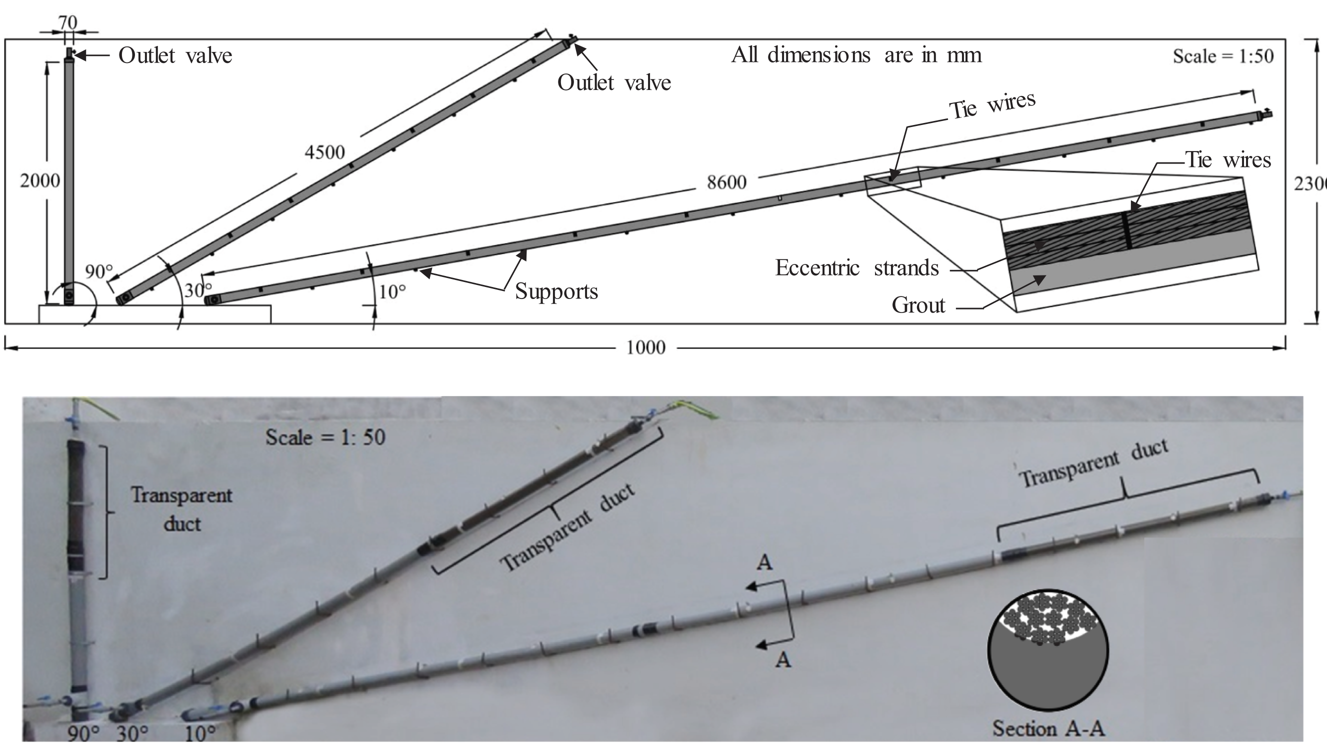
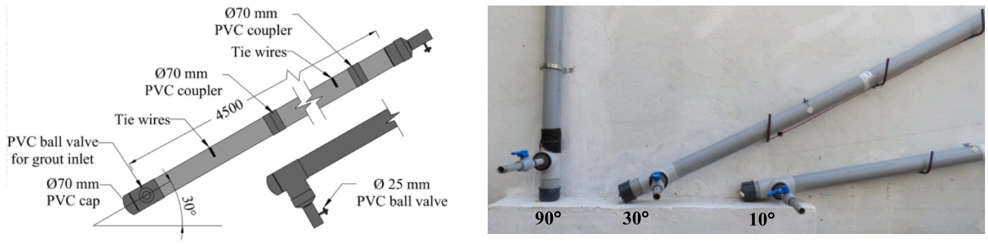


Fig. 8. Prototype tendon grouting test setup.



a) Schematic illustration of the tendon at 30° inclination **b) Actual test setup in 10°, 30°, and 90° inclinations**

Fig. 9. Schematic representation and photograph of the duct system.

Fig. 10. Grout mixer and the blade configuration used for prototype-scale grouting studies.

Table 3
Assessment plan of the grout performance in prototype-scale grouting tests.

Parameter	Test method
$T_{e,\ 1}$ (s)	Marsh cone test as per EN 445 [4]
$BV_{wick\text{-}induced}$ (%)	Wick-induced bleed test as per EN 445 [4]
Volume of softgrout $V_{softgrout}$ (%)	Visual observation on standard bleed test cylinder at 24 h
$BV_{Prototype\text{-}grouting}$ (%)	Measurement of volume of accumulated bleed water at 3 h after grouting
Area of voids at the cross-section, $A_{void,\ x}$	Measurement of the area of voids at the cross-sections of the dissected tendon-duct system

Table 4
Physical properties of the TFG1 and TFG2.

Properties of TFG	TFG1	TFG2
Colour	Grey	Grey
Bulk density (kg/m^3)	2200	2224
Specific gravity	2.8	2.8
Mean diameter of particles (μm)	9.5	9.5
Yield per 25 kg (litre)	16	16

Table 5
Fresh and hardened properties of two pilot productions of TFG and SBG from the laboratory scale experiments.

Parameter	TFG1	TFG 2	SBG
$T_{e,\ 1}$ (s)	17	24	11
$T_{e\ 30}$ (s)	22	25	13
$T_{e,\ 180}$ (s)	24	27	15
$D_{e,\ 1}$ (mm)	159	159	190
$D_{e,\ 30}$ (mm)	148	155	185
$D_{e,\ 180}$ (mm)	134	147	170
$BV_{Standard}$ (mm)	0	0	8
$BV_{Wick\text{-}induced}$ (%)	0	0	10
$BV_{Pressure,\ 350}$ (%)	0.1	0.1	12
$BV_{Inclined}$ (%)	0	0	12
$ST_{Initial}$ (hours)	7.8	3.95	3.5
ST_{Final} (hours)	16.4	21.68	7.6
$\Delta L_{28\ day}$ (%)	−0.016	−0.01	−0.09
$f_{c},\ _{7\text{-}day}$ (MPa)	41	43	18
$f_{c},\ _{28\text{-}day}$ (MPa)	62	62	36
$V_{softgrout}$	0	0	0

4.2. Robustness assessment

4.2.1. Variations in ambient mixing temperature

Depending on the climatic conditions and the quality control measures at the construction field, the ambient temperature of mixing and the amount of water added could vary. The conditions in the construction field are often difficult to control, and therefore, it is anticipated that a good quality grout should also be robust against such possible variations in occur in the field. In this context, the robustness can be defined as the capacity of the PT grout to retain its fresh properties with the small variations in the ambient temperature of mixing and water content. If the variations in efflux time are not exceeding the maximum allowable limit of 25 s and the variations in spread diameter go below the minimum required limit of 140 mm, the grout can be categorised as robust. The fluidity of the fresh grout represented by the variation in efflux time and spread diameter with respect to variations in the ambient temperature of mixing was assessed by a Marsh cone and spread test conforming to EN 445 [4], respectively.

Fig. 11 represents the variations in efflux time and spread diameter with respect to the variations in the ambient temperature at mixing. As the ambient temperature increases, the efflux time decreases, indicating enhanced fluidity. A similar trend was observed with the spread

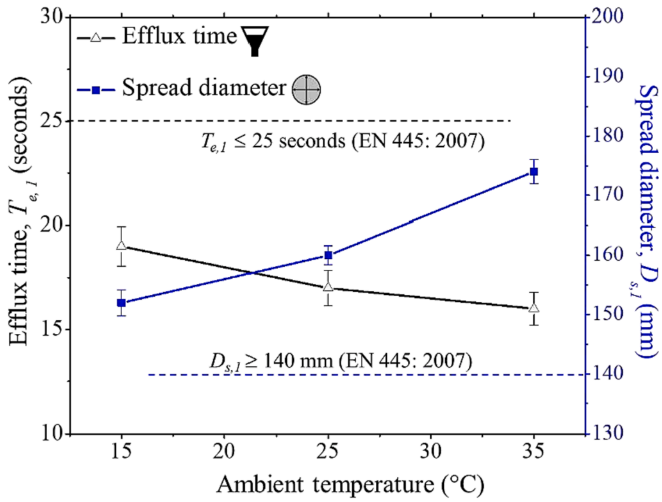


Fig. 11. Effect of changes in ambient temperature on efflux time and spread diameter.

diameter also. At constant relative humidity, when the ambient temperature increased, the variation of fluidity depends on 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 high range water reducer. 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 [44]. Here, the fluidity was enhanced due to the latter mechanism. From Fig. 11, it is evident that the TendonFill satisfies the acceptance criteria – indicating robustness. There was no significant change in the bleed resistance when the ambient temperature was varied.

4.2.2. Variations in water content

Fig. 12 shows the changes in efflux time and spread diameter with the variations in the water content, respectively. As expected, with the increase in water content, the efflux time decreases and spread diameter increases – indicating the enhanced fluidity. From Fig. 12, it is again apparent that the TendonFill satisfies the acceptance criteria, which indicates robustness. Therefore, TendonFill can be used in field conditions without much changes in fluidity.

Often, a combination of both the changes in water content and ambient temperature need to be considered depending on the extreme field conditions. For instance, a grouting operation with a combination of low ambient temperature (15 °C) and low w/b ratio (0.26) can occur. PT grouts should satisfy the performance criteria as per EN 447 [22] (i.e., $T_{e,1} \leq 25$ s and $D_{s,1} \geq 140$ mm) even at such extreme conditions in order to achieve a void free tendon system.

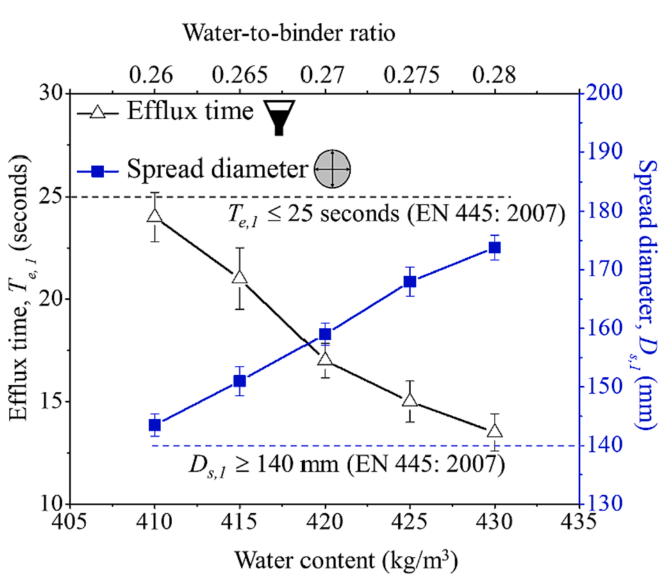


Fig. 12. Effect of changes in water content on efflux time and spread diameter.

4.3. Shelf life assessment

TFG that was aged at controlled conditions in the laboratory was tested for the physical properties and the fresh properties at 0, 1 and 6 months and are given in Table 6. Negligible change in particle size distribution had occurred in 6 months (in mean diameter D_{50}), from the laser diffraction test conducted. No substantial difference was observed between the specific surface area and the specific gravity of the material tested at 1 and 6 months of ageing. All the tested fresh properties, including efflux time, bleed resistance in various tests (wick induced, pressure-induced and inclined tube test) and setting time had the results at 1 and 6 months satisfying the acceptance criteria recommended in the standards followed, and with negligible variations among the results at 1 and 6 months. The assessment indicates the stability of the TFG material up to 6 months, which in turn suggests that the pre-hydration of the surface of anhydrous Portland cement particles have not occurred.

4.4. Prototype-scale tendon grouting studies

TFGs were prepared by blending at an industrial blending facility, packaged in 25 kg bags and transported to IIT Madras. Then, prototype-scale tendon grouting tests were carried out to assess the bleed resistance of TFG on a real scale with congested strand systems. A typical site batched grout (SBG) was also tested in prototype tendon grouting tests to compare the performance.

Prior to prototype-scale grouting tests, the fluidity and bleed resistance of both the grouts were assessed by Marsh cone test and wick-induced bleed test, respectively, as quality checks. SBG exhibited about 6 % volume of bleed water in the wick-induced test and thus, did not pass the acceptance criterion. However, the prototype-scale tendon grouting tests were conducted with both TFG and SBG.

The grouting was carried out as per the guidelines in PTI M55.1–12 [21], at an ambient temperature of 32 ± 5 °C. In order to keep the grout temperature below 30 °C, the mixing water was pre-conditioned at 22 ± 5 °C. Therefore, the temperature of the grout mix at the time of pumping

Table 6
Properties of the TFG material/grout at one month and six months of shelf life.

Parameter	Test Method	Performance criteria	At 1 month	At 6 months
Mean diameter (D_{50}) of particles (μm)	Laser diffraction method as per ISO 13320 [37]	$D_{50} \leq 10$ μm	9.5	9
Specific surface area, SSA (m^2/kg)	Blaine's air permeability as per IS 4031 Part-2 [38]	$SSA_{initial} \geq SSA_{final}$	489	468
Specific gravity	As per IS 4031 Part-11 [39]	$SG_{initial} \leq SG_{final}$	2.8	2.84
$T_{e,1}$ (s)	Marsh cone test as per EN 445 [4]	$T_{e,0} \leq 25$ s	17	26
$D_{s,1}$ (mm)	Spread test as per EN 445 [4]	$D_{s,0} \geq 140$ mm	159	147
$BV_{wick-induced}$ (%)	Wick-induced bleed test as per EN 445 [4]	≤ 0.30 %	0	0
$ST_{Initial}$ (h)	As per ASTM C 953 [40]	≥ 3 and ≤ 12	7.8	11
ST_{Final} (h)	As per ASTM C 953 [40]	≤ 24	16.4	16
$BV_{pressure-induced}$ (%)	Pressure induced bleed as per ASTM C1741 [5]	≤ 0.1 %	0.1	0.08

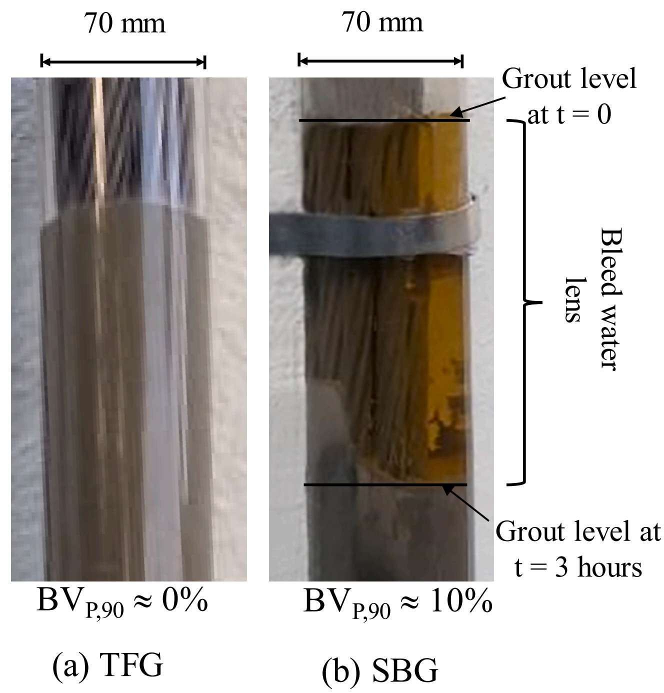


Fig. 13. TFG and SBG at three hours after grouting - showing negligible bleeding in TFG and significant bleeding in SBG.

was 25 ± 5 °C. The grout pumping pressure was fixed at 5 MPa [21]. During the pumping, there will be chances of separation of the aqueous phase from the grout due to the high pumping pressure. This separation of the aqueous phase will be very high in SBG as it has more water content. Therefore, about 3 L of the pumped grout was allowed to overflow through the outlet or until a consistent grout starts to discharge through the outlet. After the grouting, the entire tendon-duct system was covered with wet cotton cloths to avoid moisture loss due to evaporation.

Fig. 13 shows the volume of the accumulated bleed water in TFG and SBG, three hours after grouting. From Fig. 13, it is apparent that SBG exhibited a large volume of accumulated bleed water (about 10 %), while TendonFill grout exhibited zero observable/measurable volume of bleed water. This indicates that one of the typical SBG in India has very low bleed resistance. This bleed water will get evaporated or reabsorbed to the grout later – leaving voids. The presence of voids and exposed strands can later result in the premature corrosion of the strands. Also, it is interesting to note that a similar grout mix to SBG used in this study has been used in the grouting of post-tensioned beams and slabs in Mumbai port trust at Mumbai, India. The use of such very low bleed resistant SBGs can result in the premature corrosion of strands and thus reduce the corrosion-free service life significantly.

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

Parameter	TFG 1	TFG 2	SBG
$T_{e,\,1}$ (s)	19	24	13
$BV_{wick\text{-}induced}$ (%)	0	0	6
$V_{softgrout}$ (%)	0	0	0
$BV_{P,\,90^{\circ}}$ (%)	0	0	10
$BV_{P,\,30^{\circ}}$ (%)	0	0	8
$BV_{P,\,10^{\circ}}$ (%)	0	0	8

Three days after grouting, the tendon-duct system was disassembled and dissected at various locations throughout the length of the duct. Fig. 14 shows the dissected cross-sections of the tendons-duct system inclined at 90°, 30° and 10° to the horizontal. The tendons were cut at two typical locations. At 10° inclination, it is apparent that the SBG exhibited cracks and voids at different cross-sections, while the TFG did not exhibit any voids or cracks. It can be noted that these voids are formed at the top side of the cross-section of the duct. The strands inside the PT duct will be eccentric at different locations. During the pumping, the grout takes the easy pathway (i.e., the bottom portion of the cross-section of the duct) to flow. This will increase the bleeding as the strands are highly congested at the top portion of the cross-section, and only the aqueous phase from the grout can fill there. Thus, due to wick action, the accumulation of bleed water can be more – leaving voids later. These voids can expose the strands to the deleterious ions from the atmosphere and thus, result in corrosion. However, the TFG exhibited excellent bleed resistance, and thus, there were no voids throughout the duct. As shown in Fig. 14, in the cross-sections of the tendon system inclined 30° to the horizontal, the TFG did not exhibit voids throughout the cross-section as in this case also. Similarly, for 90° inclination to the horizontal, the grout present inside the vertical tendon system experiences complete self-weight of the grout column above it. Thus, the tendons aligned vertically to the ground would represent the most critical state of bleeding scenario among all the tendon alignments tested. 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, which can represent a tendon-grout system in a real PT bridge. The tests were repeated with one more batch of TFG blended at another industrial facility. Thus, the results of the total of two pilot studies on the novel TFG was evaluated and compared against the standard requirements on performance. Table 7 lists the results of the SBG and the two pilot studies on the TFG from the prototype tendon grouting test.

4.5. Performance specifications

Grouting is one of the most important operations for ensuring the

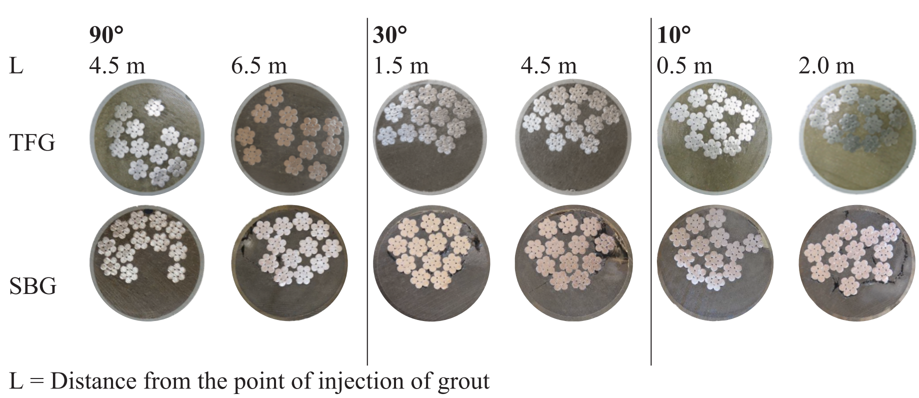


Fig. 14. Cross-sections at various locations along the tendon.

Table 8
Recommended specifications for the PT grouts.

Parameter	Performance	Reference standard
$T_{e,\,1}$ (s)	$T_{e,\,1} \leq 30$	EN 447 and [4]Mohan et al. [35]
$T_{e,\,30}$ (s)	$1.2\ T_{e,\,1} \geq T_{e,\,30} \geq 0.8\ T_{e,\,1}$ & $T_{e,\,30} \leq 25$	
$T_{e,\,180}$ (s)	$1.4\ T_{e,\,1} \geq T_{e,\,180} \geq 0.8\ T_{e,\,1}$ & $T_{e,\,180} \leq 30$	
$D_{s,\,1}$ (mm)	$D_{s,\,1} \geq 140$	
$D_{s,\,30}$ (mm)	$1.2\ D_{s,\,1} \geq D_{s,\,30} \geq 0.8\ D_{s,\,1}$ & $D_{s,\,30} \geq 140$	
$D_{s,\,180}$ (mm)	$1.4\ D_{s,\,1} \geq D_{s,\,180} \geq 0.6\ D_{s,\,1}$ & $D_{s,\,180} \geq 140$	
BV_{Wick} (%)	≤ 0.0 at 3 h	EN 447 [4]
$BV_{Pressure,\,350}$ (%)	≤ 0.0 at 350 kPa	PTI M55. 1–12 [21]
$ST_{Initial}$ (hr.)	≥ 3.0 and ≤ 12.0	PTI M55. 1–12 [21]
ST_{Final} (hours)	≤ 24.0	
$f_{c,\,7\text{-day}}$ (MPa)	≥ 21	
$f_{c,\,28\text{-day}}$ (MPa)	≥ 35	
ΔL (%)	ΔL (%) ≤ 0.1 at 1 day and $-0.2 \leq$ ΔL (%) ≤ 0.2 at 28 days	
$V_{softgrout}$	$= 0$	From the current study and [35]

durability of the PT concrete elements. Unfortunately, it is also one of the most neglected and carelessly carried out operations at the construction site. Even though there exist several standards available today, the specifications are not comprehensive enough. Based on the present study, a set of stringent and comprehensive performance specifications were proposed. These performance specifications are the combination of most stringent specifications, from various standards for grouting of post-tensioned concrete systems and the recommendations from the present study. Table 8 lists the specifications on the properties of the PT grout. The newly proposed specifications are as follows:

- The retention of fluidity should be checked for three hours as the grouting operations in the field can go beyond 2 h. The variation in fluidity after 3 h should not be more than (i) 40 % of the initial fluidity and (ii) 25 s. Both the criteria are required to disqualify PT grouts with low fluidity retention. For instance, a PT grout exhibits an efflux time of 10 s immediately after mixing. After 3 h, the same grout exhibits an efflux time of 22 s. Here, criterion (i) was not satisfied, but (ii) was satisfied. As the grout loses its fluidity by more than 40 %, that indicates the grout may not stay workable under all field conditions.
- The volume of the softgrout should be zero. Currently, there are no standardized test methods available to quantify the softgrout. However, quantifying the volume can be easily done by scraping out the layer of softgrout from the hardened grout after the wick-induced bleed test. If there are inert filler materials with lower density than cement present in the grout, those will remain at the top portion while the cementitious phase hardens.

5. Summary and conclusions

The study presents performance assessment of novel pre-blended cementitious grout at different simulated real conditions and comparing with a commonly used PT grout. The fresh properties, including fluidity, bleed resistance and setting behaviour, were evaluated for two separate batches of the pre-blended grout prepared at different industrial blending facilities and compared with a typical site-batched grout with prototype-scale tendon grouting tests. Also, a set of performance specifications on the grout materials and guidelines for the grouting practices are presented. The conclusions from the study are:

- In the prototype-scale tendon grouting test with congested strands, TFGs exhibit excellent bleed resistance without the formation of softgrout. On the other hand, a typical SBG exhibits very low bleed resistance, even though it can exhibit excellent fluidity.
- For TFGs, a reduction in temperature from 35 to 15 °C can increase the efflux time by 20 %. Similarly, a variation of water content ± 5 kg/m^3 and ± 10 kg/m^3 can result in a maximum of 30 % change in efflux time and 20 % change in spread diameter form of the reference water content of 420 kg/m^3. Also, pre-blended grouts retain its properties for a period of 6 months exhibiting a long shelf-life.
- The time-dependent variation of efflux time is more than the variation of spread diameter, which was supported by the results of the shelf-life study also. This can indicate that the Marsh cone test is more a sensitive test to measure the fluidity retention of grouts used for post-tensioning applications.
- A new set of specifications were proposed on grouting materials and methods, which can provide stringent and comprehensive recommendations on fluidity retention and formation of soft grout.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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