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Factors affecting the performance characteristics of cementitious grouts for post-tensioning applications

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HIGHLIGHTS

- Commercially available grouts for post-tensioning applications were characterized.
- Flow cone test should not be used as a screening test for post-tensioning applications.
- Increase in fineness can increase the flow retention & bleed resistance of PT grouts.
- Increase in fineness is critical for enhancing the fillability in post tensioned systems.
- Mixing speed and ambient temperature significantly influence the grout performance.

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ABSTRACT

In grouted post-tensioned (PT) systems, cementitious grouts are supposed to completely fill the interstitial spaces between the strands and act as the 'last line defence system' against corrosion. However, use of poor quality grout materials and grouting practices result in voided grout systems, ultimately leading to premature failure of tendons in many bridges around the world. To ensure an intact system, the grout must have excellent fresh properties, in particular the flow properties. Such high-performance grouts are not available in many developing countries, where grouting for post-tensioned structures is still a nascent technology. In this research, a two-stage test program was carried out to evaluate the fresh and hardened properties of seven commercial grouts, which includes three Pre-Packaged Grout mixes (PPG); three Site-Batched Grout mixes (SBG) and one standard Ordinary Portland Cement grout mix (PCG). Further, one PPG mix and SBG mix were chosen and their properties were evaluated for three levels of mixing speed and two ambient temperature conditions. Fresh properties such as wet density, efflux time and its retention, standard bleed, wick-induced bleed and pressure bleed, as well as set/hardened properties such as setting time, compressive strength and volume change were evaluated. Three batches of grout were tested for each grout material, to ensure reliability of results. The influence of binder fineness on the performance of grouts was also evaluated. The study serves as a strong evidence in substantiating that the most commonly used grout materials for PT system in developing countries, fail to meet the standard requirements and even the manufacturer's own specifications. It is also found that the performance of the grout is influenced by mixing speed, ambient temperature, and fineness. The study emphasises that the evaluation of the grout behaviour under simulated field conditions is essential to ensure void free and durable PT systems.

1. Introduction

Prestressing technology, conceived and developed by Freyssinet in the 20th century is considered as one of the most significant breakthrough technologies in construction. Widespread use of this technology, especially post-tensioning (denoted as 'PT', herein), began in the 1950s and 60s with the construction of many long span bridges in Europe and the United States of America (USA).

Abbreviations: % bvog, percentage by volume of grout; ASTM, American Society for Testing and Materials; C, cement; EN, European Norms; F, fly ash; FHWA, Federal Highway Administration US; HRWR, high range water reducer; IBG, interground blended grouts; IMG, in-situ mixed grouts; PB, pressure bleed; PCE, polycarboxylate ether; PCG, plain cement grout; PPG, pre packaged grouts; PT, post-tensioned; RH, relative humidity; SB, standard bleed; SBG, site-batched grouts; U, ultra-fine fly ash; UK, United Kingdom; US, United States of America; VMA, viscosity modifying agent; w/c or w/b, water cement ratio or water binder ratio; WB, wick-induced bleed.

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Over the past 60 years, PT has found wide applications in the construction of long span bridges, marine structures, nuclear pressure vessels, water retaining structures, oil exploration structures, etc. Based on these young structures, PT systems were believed to be inherently maintenance free. But the collapse of a few PT bridges in the Europe [1,2] shed light on the potential long-term risk associated with these systems. Thus, an enhanced focus on the tendon system becomes essential because of its importance in PT structures. This becomes more critical in developing countries, where major infrastructure development is taking place and is being planned for the coming decades.

1.1. Lessons from past failures

Several failures of the tendon systems have been observed in the last 20 years. Following the failure of Bickton Meadows footbridge in 1967 and Ynys-y-Gwas Bridge in 1985, a ban on the construction of PT bridges (1992–1996) was imposed in the United Kingdom (UK). This ban brought to light the potential problems and triggered investigations in other countries like France, Switzerland, Austria, Korea, US etc. [1–3]. Many failures were found to be a result of poor grout materials, poor workmanship or quality control during construction [1,4,5].

1.2. Voids in grouted PT system

The stressed strands in a PT system are provided with various levels of protection systems, as shown in Fig. 1. As evident from the figure, the grout material that is in direct contact with the stressed strand acts as the last line of defence system. The grout creates an alkaline environment, forming a passive layer on the steel surface thereby preventing corrosion [5–7]. Hence, long term protection of PT strands necessitates the complete filling of the ducts with high performance, flowable grout [1,3].

Many investigations have reported that the presence of unwanted air voids in the PT system is an important cause of strand corrosion [2,3,5,8–10]. In voided tendons, the presence of moisture or standing water creates a GAS (Grout-Air-Strand) interface. The location and orientation of this interface, especially in the anchorage zone of tendons plays an important role in strand corrosion, thereby affecting the structural and service reliability of the bridge systems [9]. The major reasons for the formation of these unwanted voids include poor fluidity, significant bleeding and evaporation of bleed-water, poor grouting, poor construction practices, or a combination of these [11–13]. Fig. 2 shows the typical cross-section of ducts with strands and voids along the length of a PT bridge girder.

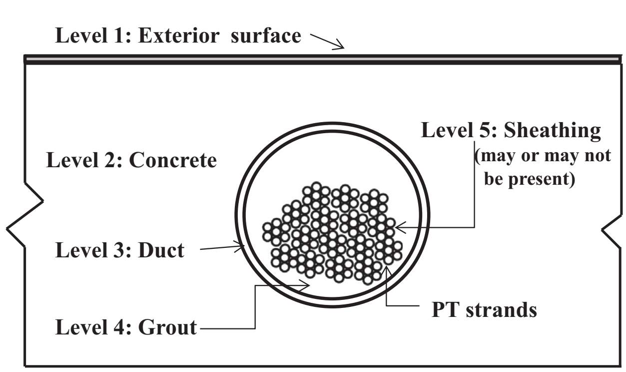


Fig. 1. Levels of protection in typical PT systems (adapted from [5]).

1.3. Fluidity and bleed resistance of PT grouts

Significant work on the performance of masonry grouts are available in literature. For example, the performance of masonry grouts made using superplasticizers, fly ash, and silica fume under different temperature conditions have been reported [14,15]. Later, similar effects on masonry grouts and how these can influence the injectability has been reported [16]. However, limited information is available on the performance of highly flowable post-tensioning (PT) grouts. Following is a discussion on some of these fresh properties (say, fluidity and bleed resistance).

The ability of grout to penetrate the interstitial spaces between the strands and the duct, as shown in Fig. 1, to ensure complete filling is controlled mostly by its fluidity and fluidity retention. For enhanced pumpability, fresh grouts should have low viscosity (an indicator of fluidity) and adequate fluidity retention. Fluidity can be enhanced by the addition of superplasticizer [17]. However, uncontrolled enhancement of flow will lead to bleeding, sedimentation and segregation. Fluidity of PT grouts can be determined using flow cone or Marsh funnel test [17,18].

If excess water is added to the grout, the cement particles can flocculate and settle under gravity; and the water moves up and gets collected at the top. This water is called as 'bleed water'. It results in anisotropic behaviour of the grout, causing segregation [10]. This excess water gets collected at high points of tendon profiles (say, at anchorage zones) and later evaporates or gets reabsorbed into the grout, leaving large voids and exposed strands [19]. Bleed is quantified by standard bleed and wick-induced bleed ("SB" and 'WB', respectively) tests based on ASTM C 940-2010 and EN445 Part-3 (2007), respectively [20,21]. WB is usually higher than SB due to the capillary movement of water through the space between the wires in a strand in the former (see Fig. 3(a) and (b)). The third bleed test is the Schupack Pressure Bleed Test (see Fig. 3 (c)), which can be carried out when the tendons have significant slope or are vertical in profile leading to considerable static water pressure [11,22].

1.4. Factors affecting the properties of grout

1.4.1. Ambient temperature

Temperature of the ambient environment, water and the grout materials can significantly influence the fresh properties [8,18,23,24]. Grout mixes subjected to elevated temperature show rapid reduction in viscosity due to accelerated reactions between cement particles leading to workability loss. Plastic viscosity can decrease with increase in temperature until about 35 °C [8]. At more than 35 °C, there can be a significant workability loss (increase in viscosity) [8].

Similar is the case with setting time, which is prolonged at low ambient temperature; at higher temperatures it is shortened, due to accelerated hydration [23]. Expansion of grout at about 10 °C (i.e., low temperature) can be very slow [25]. Achieving acceptable range for mechanical properties like compressive strength and modulus of elasticity can be difficult when the ambient temperature is less than 10 °C [25].

1.4.2. Fineness of grout

The particle size distribution of all the cementitious materials or binders in the grout is an important factor that controls the rheological and mechanical behaviour of grouts and the complete grout filling [5,26]. Efforts have been made to extend the injectability range of suspension grouts by developing materials with very fine gradation, resulting in "micro-fine" ($D_{95} < 20$ μm and Blaine fineness over 800 m^2/kg according to EN 12715) and "ultrafine" (D_{95}

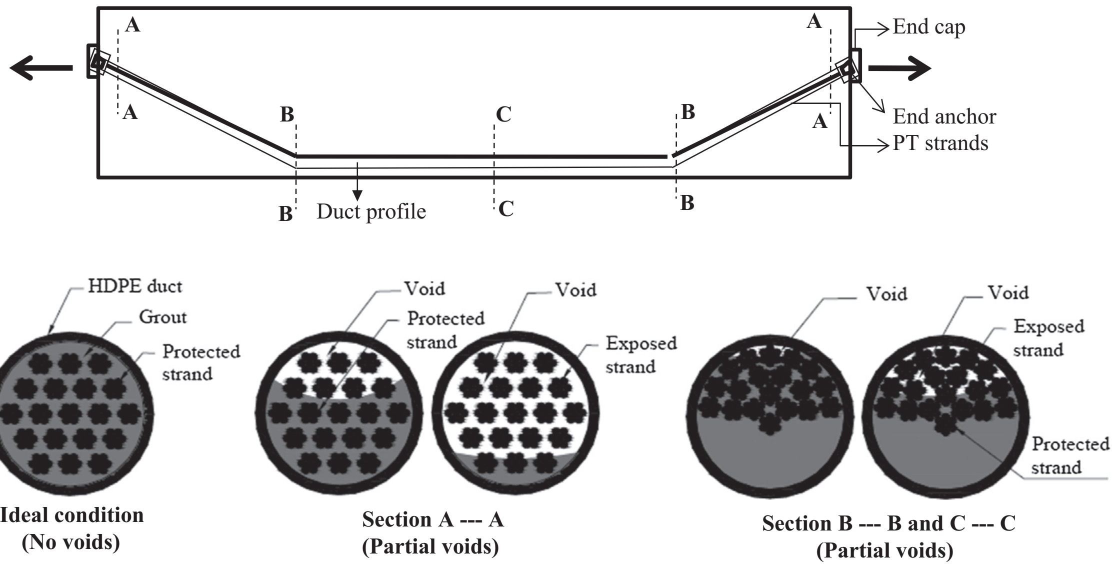


Fig. 2. Simplified schematic of a typical tendon profile in a segmental bridge and presence of voids at different locations of duct profile.

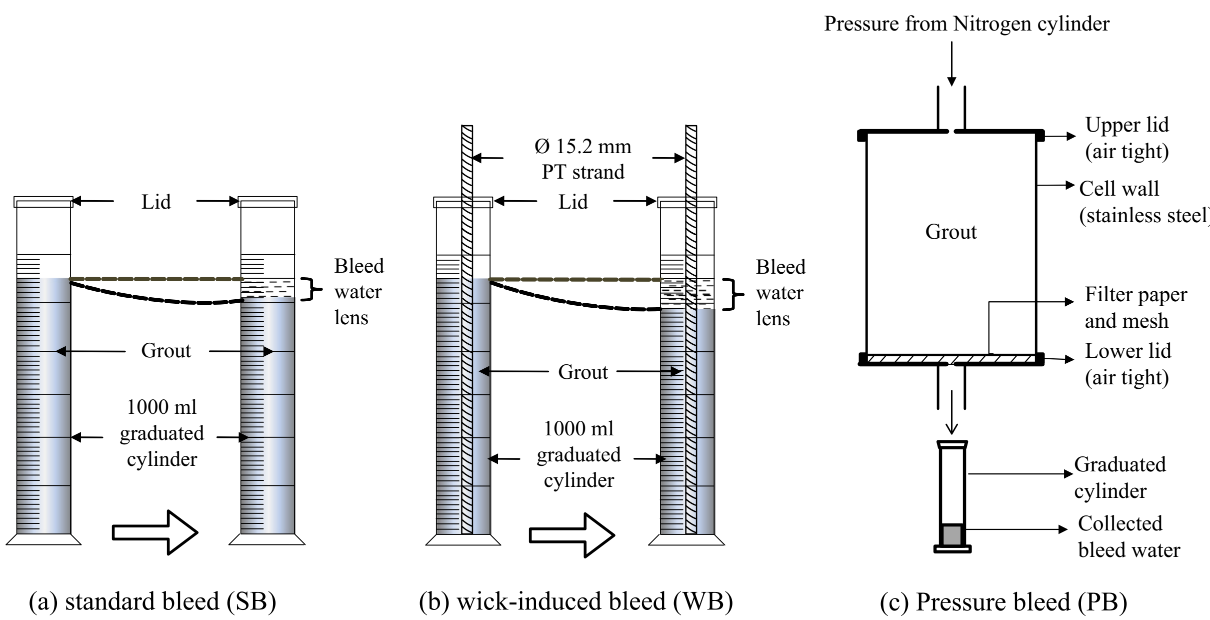


Fig. 3. Experimental setup for various bleed tests.

< 15 µm or D_{max} < µm) cement grouts [27,23]. However, this has adverse effects on the viscosity and rheology [28–30]. Use of 'micro-fine' grout materials can improve stability against suspension even at increased water content. It can also decrease the setting time and reduce the permeability [5,29]. Bleed resistance can be affected more by cement size than its composition [29]. The use of 'ultrafine' materials can result in increased compressive strength and reduced shrinkage due to better packing efficiency [30]. Higher fineness helps in achieving high strength with low porosity and high durability.

1.4.3. Mixer and mixing procedure

Even grouts prepared with the same type and particle size distribution of materials can have different bleed resistance due to differences in the mixer type, batch volumes and the mixing techniques [25]. Dispersivity of grout particles depends on the time of exposure, power, and the angular frequency (speed) of mixing. There exists an optimal speed at which maximum dispersion can be achieved. If the particle size increases, the mixing speed corresponding to the maximum dispersion can reduce [31]. However, longer mixing times may not significantly improve the grout fluidity [7]. The type of mixing or the mixer (say mixing energy) may also affect apparent viscosity and yield stress [31,32]. From a practical point of view, optimal mixing helps in attaining a particular penetrability at a lower water and super plasticiser content. It also produces a homogenous, stable, lump free grout, that enables proper pumping and filling of grout.

2. Research significance

Corrosion failures of tendons are attributed to the formation of voids, resulting from inadequate grouting, poor grout materials and inappropriate grout formulation. Pre-packaged grouts (referred herein as 'PPG') that are used in developed countries to prevent such failures are not easily available in the developing nations. Drastic infrastructure development demands a large volume of grouting. The present study shows that the grouts widely used in the developing countries for post-tensioned systems are not satisfactory. In the current scenario wherein PT construction is gaining a huge momentum in the developing world, it is critical to sensitise on the quality of grout materials available in the market and the associated premature corrosion problems. There is a dire need to focus on the indigenous development of high performance grouts and grouting practices. Otherwise, it would result in huge spending for the unavoidable repair and maintenance of these PT systems.

3. Experimental program

3.1. Overview of the study

In this study, the following five types of grout mixes were used and all the tests (in 3 phases) were done inside a walk-in chamber (RH 60 ± 10% and at pre-defined temperature).

i. PCG – Ordinary Portland Cement +0.4 w/b ratio;
ii. PPG – Commercially available Pre-Packaged Grout;
iii. SBG – Site Batched Grout with commonly used property enhancing admixtures;
iv. IMG – In-situ Mixed Grout (IMG); and
v. IBG – Inter-ground Blended Grout (IBG)

- Phase 1 – To assess the performance of commercially available grouts used for PT applications. This was done by analysing their critical fresh and hardened properties and comparing it with their manufacturers' specifications and codal standards.
- Phase 2 – To assess the effect of site-dependent parameters (i.e., mixing speed and temperature) on the properties of grout.
- Phase 3 – To assess the effect of fineness of binder on the fresh properties of grout.

3.2. Mixing procedure

All the materials used for the preparation of grout mixes were stored under their corresponding test temperature for 24 h prior to mixing. The mixing was done in a custom-made high-shear mixer (see Fig. 4) having a speed regulator (digital meter) with a maximum speed of 3000 rpm and a bowl capacity of 20 L.

Grout mixes were prepared in batches of 14 L each. In Phase 1, mixes were prepared following the procedure recommended by the manufacturer. In Phase 2 and 3, a mixing procedure was developed based on the recommendations from ASTM C305 and other literature [7,8,33,34] and the general site practices followed in India. In this mixing procedure, at first, three-fourth of the water required for the mix was placed in the mixer. Then, keeping the mixer at a speed of 200 rpm, the dry grout materials were added gradually into the mixing bowl within 30 s. The gradual addition was done to avoid formation of lumps and settling of powder at the bottom of the bowl. Chemical admixtures, if any, required for the mix were added into the mixture followed by addition of the remaining water. The mixing speed was gradually increased to the specified value, i.e., 500 rpm, 1500 rpm or 2500 rpm, in the next 30 s. Mixing at the specified speed was continued for additional three minutes and then the mix was kept in agitation at 200 rpm for the remaining test duration (i.e., three hours).

3.3. Experimental program and testing procedures

In all three phases, the grout mixes were subject to a two-stage testing program by following the procedures recommended by the codal standards as shown in Table 1.In every phase, three trial batches of each grout mix were prepared and tested to be able to assess the mean and standard deviation of the results obtained. The relative humidity was maintained at 60 ± 10% throughout the study.

In Phase 1, seven commercially available grout materials (PCG, SBG – 1/2/3 and PPG – 1/2/3) were subject to the two stages of testing. Here, SBG and PBG grout mixes were prepared under controlled temperature condition of 25 °C, following the manufacturers' recommendations on mixing procedure, mixing time and mixing speed; and for PCG, the standardised mixing procedure as discussed in Section 3.2 was adopted.

For Phase 2, two comparatively better performing grouts from Phase 1, (one each of SBG and PPG) were selected for the studies on effect of site-dependent parameters (i.e., mixing speed and temperature) on the properties of grout. Here, six types of grout mixes based on all possible combinations between mixing speeds of 500, 1500 and 2500 rpm and ambient temperature conditions of 15 °C and 30 °C, for each grout type (SBG and PPG) were prepared.

In the Phase 3, two grout mixes – IMG and IBG, were formulated based on particle packing method. The binder for IMG was prepared by mixing the cementitious (ordinary Portland cement) and pozzolanic materials (fly ash and ultrafine fly ash) in a high shear mixer. For IBG, it was prepared by inter-grinding the dry binder constituents (same as that of IMG) in a laboratory ball mill for 4 h. At the end of 4 h (found by several trials), IBG attained double the specific surface area of IMG. The optimal dosage of superplasticiser and viscosity modifying agent for these two binders were obtained through various trials based on the bleed water collected at different compositions. The final composition of these mixes that were adopted for study is shown in Table 2. All the tests were carried out at a temperature of 25 °C.

4. Results of Phase 1 – commercially available grouts

For this phase, one plain PCG mix, three SBGs and three PPGs, were used. These seven grouts were checked for their compliance with the specifications by the manufacturers and the codal standards, as shown in Table 3. The raw material characteristics (i.e., specific gravity, specific surface area (SSA) and particle size distribution (PSD)) of these materials were determined and are listed in Table 4. Critical fresh properties such as flowability or fluidity and bleed resistance were determined for each of the PT grout materials following the procedures as per Table 1. Wet density was also evaluated as an additional check for the quality and consistency of grout mixes prepared for the study.

4.1. Fluidity

Fig. 5 shows the comparison of efflux time of the commercial grouts as a function of time elapsed after the mix preparation. Since in the Fig. 5(a), the curves of all the grout mixes except that of PPG 1 and PPG 3 are overlapping, an enlarged view of these curves are presented in Fig. 5(b) for clarity. In general, for most of the grout mixes, it was observed that initially there was an increase in the efflux time followed by a negligible decrease or change (say, dormant period), after which, it gradually increased as a function of time (see Fig. 5(a)). This is as expected because the mix thickens due to reaction between the grout constituents as time passes. The efflux time of PPGs was significantly higher than that of PCG grout and the SBGs. This may be due to the lower w/c and higher specific surface area (SSA) of PPGs. Hence, for better clarity, the efflux time variations of SBGs are shown in Fig. 5(b). The efflux time of PPG 1 and 3 exceeded the 25 s upper limit set by EN 445:2007 [21], and the mixes stopped flowing through the

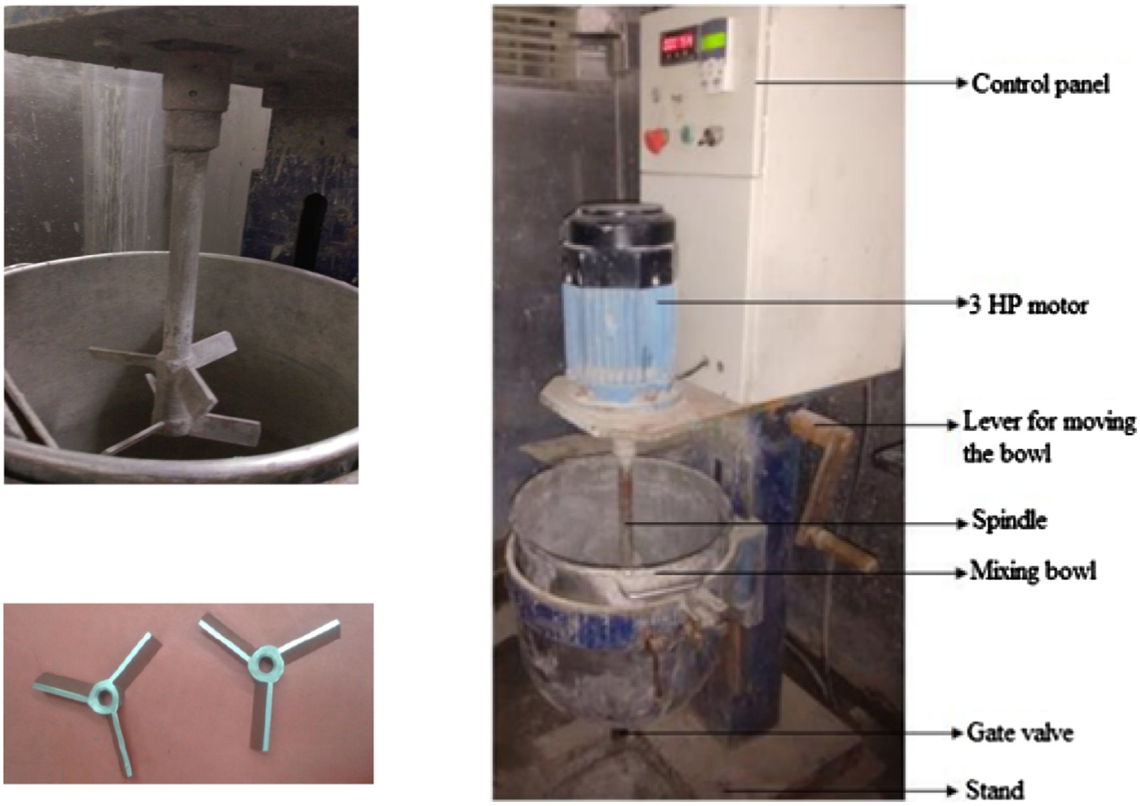


Fig. 4. Custom-made high-shear mixer and a close-up view of the spindle.

Table 1
Two stage test programme.*

Stage	Test/Property	Reference standard adopted
Stage 1	Flow cone	EN 445: 2007 [21]
	Standard bleed	ASTM C940: 2010 [20]
	Wick-induced bleed	EN 445: 2007 (modified) [21]
	Pressure bleed	ASTM 1741: 2012 (modified) [35]
	Wet density	API RP (13B-1): 2010 [36]
Stage2	Hardened volume change	ASTM C1090: 2010 [37]
	Setting time	IS: 4031 (Part 5): 1988 [38]
	Compressive strength	ASTM C942: 1986 [39]

* For all three phases of the study.

Table 2
Composition of IMG and IBG.

Constituents	IMG	IBG
*Cement-OPC	56%	56%
*Fly Ash	24%	24%
*Ultra-fine Fly Ash	20%	20%
**Super Plasticiser – PCE based (solids content)	0.21%	0.42%
**Viscosity Modifying Agent	0.5%	0.5%
**Water-Cement ratio	0.3	0.3

Note: IMG and IBG have similar compositions except for superplasticiser content owing to increased fineness of IBG.
* Volume replacement.
** Weight replacement.

8 mm orifice of flow cone at about 3 h after mixing. This may be due to their higher fineness, which could have resulted in their faster reaction rate and the subsequent loss of fluidity. Here, it is to be noted that, the use of 8 mm orifice as a measure of fluidity may not be representative of the real-time behaviour of thixotropic grouts flowing through the PT duct system. The interstitial space between the congested strands and in many locations of the PT system (say, near deviator blocks or where there is a change of profile) is very narrow. Hence, the evaluation with respect to smaller diameter orifices is necessary for a better assessment of the real-time performance of PT grouts. However, this is not the focus of this study.

4.2. Bleed resistance

The average cumulative bleed water collected at the top of the grout column in the form of bleed water lens (see Fig. 3(a) and (b)) at three hours after the mixing of grouts (in terms of percentage by volume of grout (%bvog)) is shown in Fig. 6(a). While all the grouts except for PPG 1 failed to meet the SB and WB specifications (see Table 3), PPG 3 satisfied only the SB criteria of 0%bvog bleed at 3 h.

To evaluate the applicability of the grouts for vertical PT systems, Schupack Pressure Bleed test [11,13] was conducted (see Fig. 3(c)). The average pressure sustained in 'psi' by different grout mixes under study and the bleed water collected (%bvog) at the corresponding pressures are presented in Fig. 6(b). It indicates that neither the PCG grout nor the SBGs can be used when the variation in elevation is more than 7 m (assuming average grout density as 2100 kg/m^3). The PPG 1 exhibited highest pressure sustenance capacity of 50 psi (indicating its suitability for nearly 16 m vertical application). Only PPG 1 was found to have less than 2% bleed at the corresponding pressure sustained. However, none of the grout mixes could meet with their own manufacturers' specifications (Table 3) on pressure bleed values. It was observed that PPG 2 contained ultra-fine sand (size < 600 μ) that resulted in a segregating non-homogenous mix leading to clogging of mesh in the pressure cell. Therefore, PPG 2 was eliminated from further studies in Stage 2 of Phase 1. This also raises a serious concern that grouts with ultrafine aggregates may not be suitable for PT applications.

Table 3
Compliance of commercial products with standards and specifications.

Property/Test		Specifications from standards*	Manufacturers' Specifications			Compliance***						
			PPG			PCG	SBG			PPG		
			1	2	3		1	2	3	1	2	3
Flow/efflux time (s)		≤25 (After 10 min.)	7–20 s	–	–	✓	✓	✓	✓	X	✓	X
Mini slump (mm)		>140	–	–	–	✓	✓	✓	✓	✓	✓	✓
Standard bleed (%)		0 at 3 hr	0–2 at 3 hr	–	–	X	X	X	X	✓	X	✓
Wick induced bleed (%)		≤2	0 at 4 hr	–	–	X	X	X	X	✓	X	X
Pressure bleed (%)		≤2 at 50 psi	0 at 100 psi	–	–	X	X	X	X	✓**	–	X
Wet density (kg/m^3)		Not available	2000	2150 to 2250	2050	No specification by manufacturer			✓	✓	✓	✓
Hardened volume change (%)		0 to 0.1 in 24 hr ≤0.2 in 28 days	0 to 0.2 at 28 day	0	0	✓	✓**	✓**	✓**	✓	X	✓**
Setting time (hr)		>3 but <12	–	3–4	–	✓	X	✓	✓	✓	–	✓
Compressive strength (MPa) at	3 day	–	34	60	–	✓	✓	✓	✓	✓**	–	✓**
	7 day	21	48	70	40							
	28 day	35	80	>100	60							

* Values correspond to those standards identified to be stringent among those specified in EN 445:2007, MORTH, PTI, JSC and FIP [21,40,41,42,43].
** Results comply with standards but not manufacturer specifications.
*** Compliance of test results observed in this study with both standard and manufacturers' specification.

Table 4
Raw material characteristics.

Binder type	Specific gravity	Specific surface area (m^2/kg)	Particle size (μm)		
			D10	D50	D95
OPC	3.14	312.75	7.44	25.71	88.04
PPG 1	2.99	572.62	6.76	27.64	160.3
PPG 3	3.02	411.53	6.90	26.21	133.5
FA	2.19	312	6.71	38.76	126.9
UFA	2.49	592	2.29	4.19	12.53
IMG	2.94	344	Not Determined		
IBG	2.95	738	Not Determined		

OPC: Ordinary Portland Cement; PPG: Pre-Packaged Grout.
FA: Fly Ash; UFA: Ultra-fine fly ash; IMG: Inter-Mixed Grout.
IBG: Inter-Blended Grout.
D_{10}, D_{50}, D_{95} – corresponds to size of particles that are over 10%, 50% and 95% of the total material.

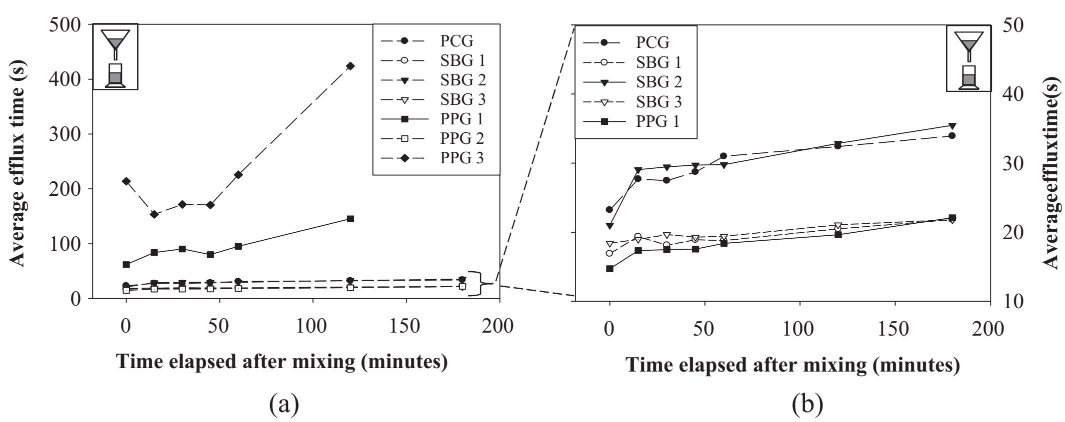


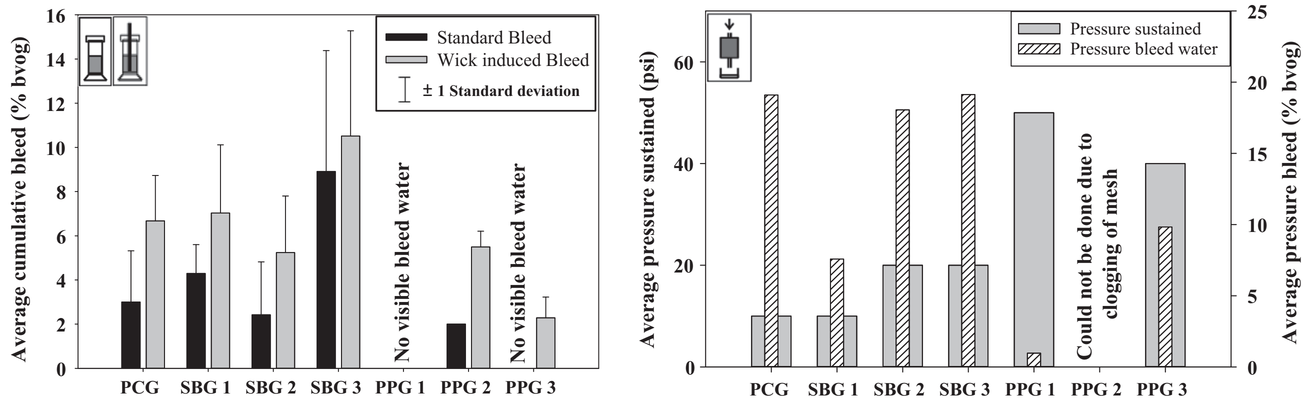
Fig. 5. Comparison of (a) flow time of commercially available grouts and (b) enlarged graph of the same.

However, this requires further investigation which is not in the scope of this study.

Setting time and compressive strength (IS: 4031 (Part 5) – 1988 and ASTM C942 respectively) are currently considered as qualifying parameters for any grout mix before their use at site [38,39]. Table 5 shows that all the materials met with the standard specifications as per Table 3. Shrinkage was observed in all the grouts (see Table 5) and the performance of PPG 1 was better than better than PPG3, PCG and the SBGs. Hardened properties were not determined for PPG 2, as it resulted in a non-homogenous mix (segregation of ultra-fine sand from paste).

4.3. Compliance with standards and specifications

The results obtained from the current study were compared with the specifications given by the corresponding grout manufacturers and the standard recommendations listed in Table 3. Most of the materials failed in the bleed parameters, which is critical from the durability point of view as it is an indication of the probability of void formation. PPG 1 and PPG 3 were found to have better bleed performance as per Table 3, but then their efflux time was very high. In the present state, efflux time is the main or the only parameter measured at the Indian construction sites. However,



(a) (b)

Fig. 6. Comparison of (a) Standard Bleed (SB); (b) Wick-induced Bleed (WB); and (c) pressure sustained and the corresponding bleed water collected for commercial grouts.

Table 5
Set and Hardened properties of grouts.

Phase	Grout	Set property	Hardened properties	
		Set time (hr:min)	Compressive strength (MPa) (7 days)	Shrinkage (%) (28 days)
1 & 2	PCG	05:00	21.2	0.08
	SBG 1	12:05	22.3	0.09
	SBG 2	10:55	23.5	0.09
	SBG 3	10:45	23.5	0.08
	PPG 1	07:35	34.9	0.05
	PPG 3	06:00	25.3	0.18
3	IMG	13.45	30.3	0.049**
	IBG	12.30	40.5	0.046**

*PPG 2 was eliminated from study of hardened properties as it resulted in a non-homogenous mix.
**Corresponds to 7th day values.

current results show that it is not appropriate to use efflux time as the deciding parameter in the selection of PT grouts. Further, the test of fluidity by using flow cone of a larger orifice (say, 8 mm) may not be representative of the real-time scenario as discussed previously. Hence, this test must be modified for use of smaller orifices, as this can lead to a realistic estimation of the filling ability of the thixotropic grouts flowing through long, small interstitial spaces of the congested PT strand system.

5. Results of Phase 2 – influence of site conditions

Based on the performance in Phase 1, SBG 2 and PPG 1 were selected for Phase 2 analysis.

5.1. Effect of site conditions on fluidity

Fig. 7(a) and (b) shows the average efflux time(s) variation at different time elapsed (minutes), after mix preparation. The solid and hollow markers of the same type indicate the grout mixes prepared at 15 °C and 30 °C respectively. It is observed that the efflux time decreased with increase in mixing speed for the SBG and PPG. While the change was significant when the speed was increased from 500 to 1500 rpm, it was not significant when increased from 1500 to 2500 rpm. This may be attributed to the better dispersion of the particles at high speed shear mixing action. Also, as a common trend, the efflux time immediately after mixing was lesser at 30 °C than at 15 °C (i.e., lower temperature). But as the time elapsed, due to stabilisation of the grout temperature, higher average efflux time was observed at 30 °C. This is in accordance with the fact that, the viscosity of cement paste increases with increase in temperature as there is a reduction in the water content available for lubrication of the particles. Similar patterns of variation were followed in SBG and PPG at different temperatures for all speed variations as evident from Fig. 7(a) and (b). Understanding the reason behind this pattern requires greater depth of study in the areas of rheology and cement chemistry. In general, a steep increase in the efflux time was observed after one hour of the grout mix preparation in both the SBGs and PPGs. This is of great importance in deciding the pot life of the grout mix at a particular temperature condition and mixing speed. At the ambient temperature of 30 °C, for all mixing speeds, the flow of PPG through the EN 445 cone (8 mm orifice)stopped by the third hour of the time elapsed after mixing. For the SBG and the PPG mixes prepared at 30 °C and 15 °C respectively, it was observed that there was no flow through the cone at the third hour, when a mixing speed of 2500 rpm was adopted.

5.2. Effect of site conditions on bleed

The average cumulative bleed (%bvog) at three hours, increased with increasing mixing speed at 15 °C for the SBG, under both standard and wick-induced conditions as shown in Fig. 8(a) and (b) respectively. While this increase was not very appreciable, it was observed that there was a drastic decrease in the bleed (both SB and WB) with increasing speed at 30 °C. These effects can be attributed to the fact that at lower temperature, the rate of binder reaction is low even under higher particle dispersion. However, a combination of high temperature that facilitates faster reactivity, along with greater dispersion of the particles at higher mixing speeds (which facilitates availability of more surfaces for reaction), results in the reduction of the water available for bleeding (as more water is engaged in the cementitious reaction itself). In general, for

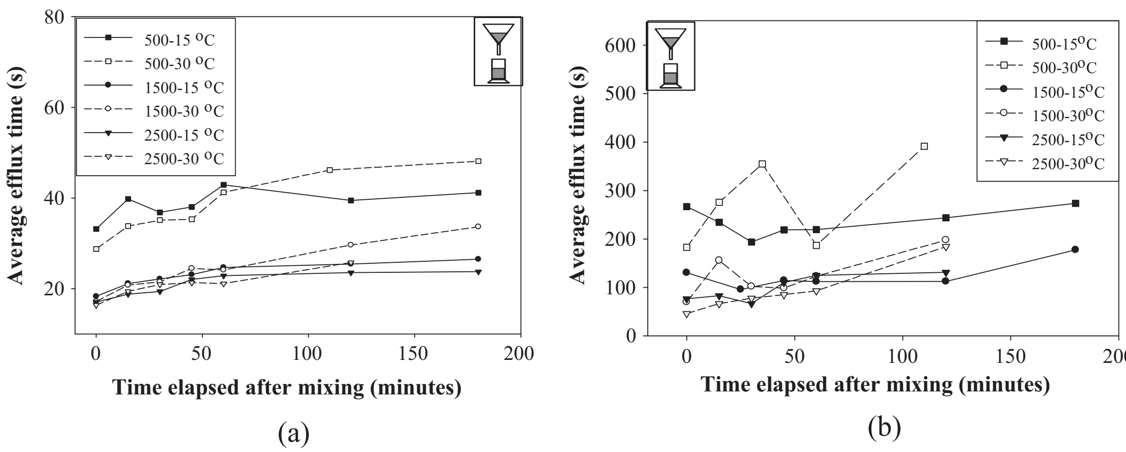


Fig. 7. Effect of mixing speed and temperature on efflux time of (a) SBG and (b) PPG.

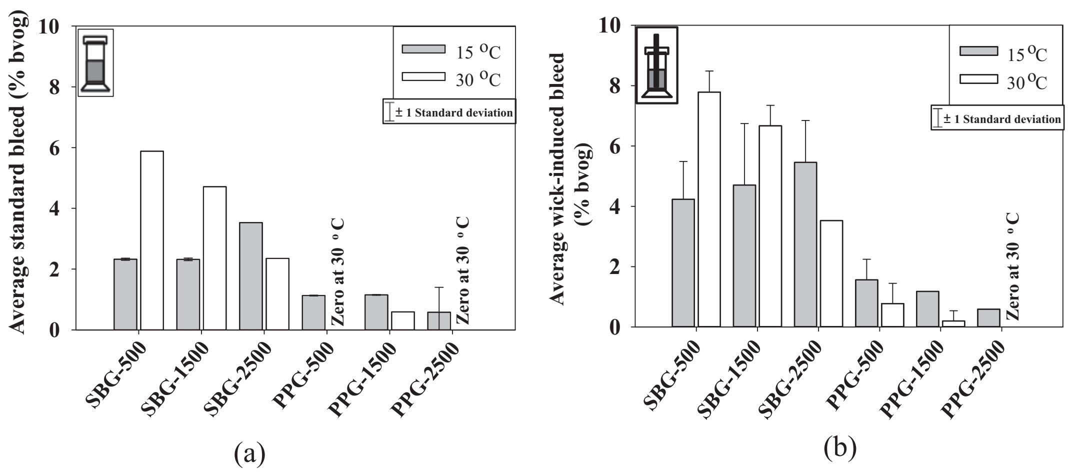


Fig. 8. Effect of mixing speed and temperature on (a) SB and (b) WB at the end of 3 h.

PPGs, the cumulative bleed for three hours (both SB and WB) decreased with increasing mixing speed both at 15 °C and 30 °C. This may be due to the higher fineness of PPGs when compared to the cement used in the SBG mix, providing for a greater surface area for faster reaction. However, the reduction in bleed was drastic at 30 °C, which is attributed to the faster reaction rate at higher ambient temperature. It was observed that there was no bleed (both SB and WB) at 30 °C for the PPG mixed with a speed of 2500 rpm. The reason for zero bleed of the PPGs at 30 °C even when mixed at 500 rpm requires further study.

For vertical grouting applications, Fig. 9 shows the trend of pressure sustained (psi) (in the left ordinate) and the corresponding bleed (in %bvog) (in the right ordinate) at different mixing speeds. The solid and hollow markers represent this variation for the same grout mixes prepared at 15 °C and 30 °C respectively. It was observed that, in general, the pressure sustained for a particular grout mix remained almost the same across the three mixing speeds and the two temperatures, but there was a change observed in the bleed values. Bleed of PPG was lesser when compared to that of SBG, irrespective of the temperature and the mixing speeds. It was observed that there was no significant change in the bleed of PPG with the speed and temperature variations. However, it was the lowest at 2500 rpm. In the case of SBG, as observed from Fig. 9, there were significant changes in the bleed with respect to the temperature and mixing speed. At 15 °C, the bleed of SBG increased with increasing mixing speed. The bleed at 30 °C was higher than that

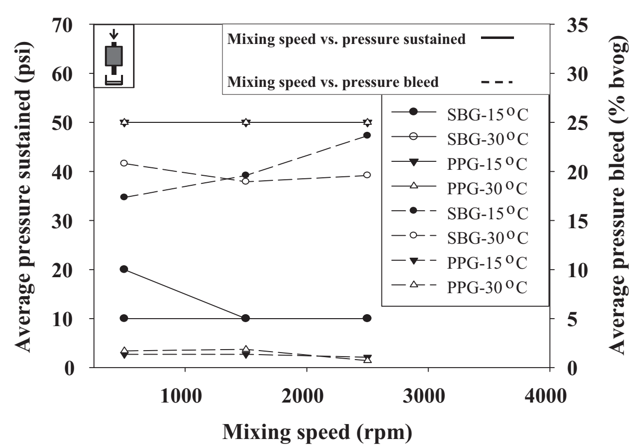


Fig. 9. Effect of mixing speed and temperature on the pressure sustained and the corresponding bleed.

at 15 °C for 500 rpm. However, it gradually reduced at higher speeds for 30 °C with no significant difference between 1500 and 2500 rpm and reduced to a value below that observed for 15 °C at the corresponding speeds. This can be owed to the higher reaction rate due to combined effects of higher temperature and enhanced dispersion of particles at higher mixing speeds.

5.3. Effect of site conditions on set and hardened properties

A study of the influence of the selected parameters on set time and critical hardened properties was undertaken following the procedure listed in Table 1. The results for change in average setting time (in hr) with respect to different mixing speeds (rpm) are presented in Fig. 10(a). Similarly, variations in average compressive strength (in MPa) and average volume change (in %) as a function of mixing speed are represented in Fig. 10(b) and (c) respectively. For all these parameters analysis was done for mixes prepared at both 15 °C (solid marker) and 30 °C (hollow marker).

It was observed in general that, these hardened properties do not change with the variation in the mixing speeds, but there was a drastic effect of temperature change. Increase in temperature can increase the rate of cementitious reaction and result in faster setting. Therefore, greater strength was attained in a shorter duration, which is evident from Fig. 10(a) and (b). However, Fig. 10 (c) shows that the volume change (only shrinkage was observed) was uniform in all the mixes and was not affected much by either of the parameters.

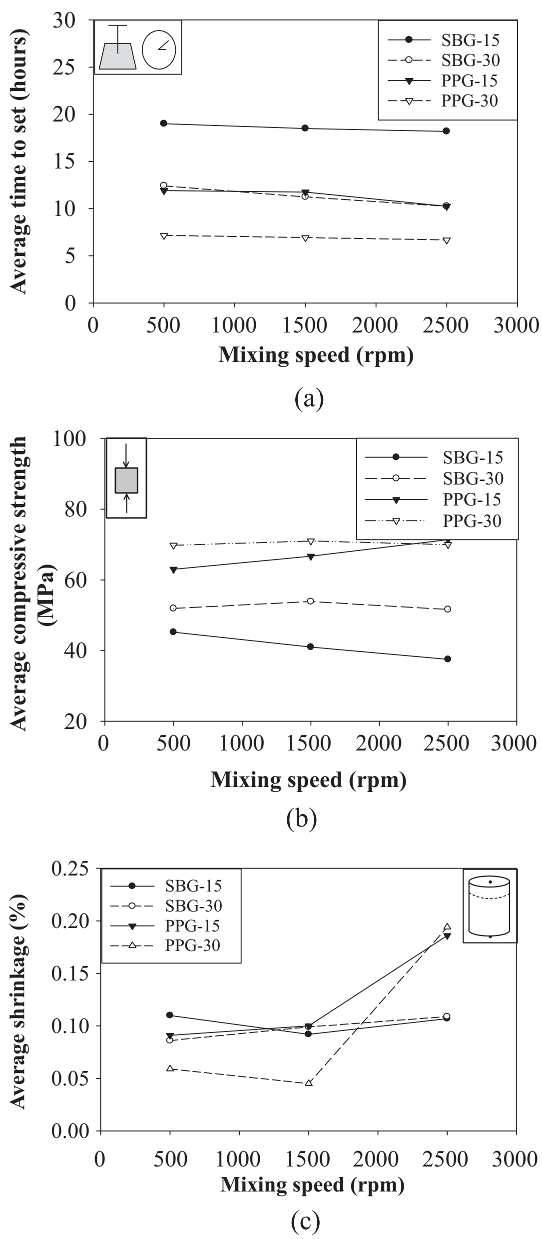


Fig. 10. Effect of mixing speed and temperature on (a) Setting time; (b) Compressive strength (28 days); and (c) Volume change (shrinkage at 28 days).

6. Results of Phase 3 – influence of fineness

The effect of fineness of binders on the fresh and hardened properties of the grout was studied based on the tests performed on In-situ Mixed Grout (IMG) and Inter-ground Blended Grout (IBG) (composition is as per Table 2) and comparing their performance. The basic raw material characteristics i.e., specific gravity and SSA were determined for the dry binders and these are listed in Table 4.

6.1. Effect of fineness on fresh properties

As observed from Fig. 11(a), both IMG and IBG exhibited only a marginal change in the efflux time with time elapsed, indicating better flow retention properties. Note that the efflux time of IBG was slightly higher (about 5 to 10 s) than IMG. This may be because of the higher fineness (i.e., greater surface area) of the IBG, which uses more water and super plasticizer in the mix to wet the surface of binders than that of IMG. As a result of this, viscosity increases, leading to longer efflux time. However, longer efflux time should not be considered as an indicator of poor performance (in terms of fillability).

It is a general trend that the Wick-induced Bleed (WB) is usually more than Standard Bleed (SB) and this was observed in both IMG and IBG (see Fig. 11(b) and (c)). Further, due to the effect of grinding and blending the SB and WB of IBG has reduced by 56 and 68% respectively, when compared to that of IMG. The same trend was followed in Fig. 11(d), where the Pressure Bleed (PB) corresponding to 50 psi had reduced from 1% in IMG to 0.65% in IBG. This corresponds to about 45% reduction in PB of IBG when compared with IMG. In addition, the pressure sustained at failure by IMG was 60 psi and by IBG was 65 psi However, for comparison of pressure bleed performance, the pressure sustenance up to 50 psi is only represented in Fig. 11(d).

Increased pressure sustenance and the improved bleed resistance of IBG can be attributed to its increased fineness and higher packing density, which consequently leads to an increase in the water retention capacity of the mixture - a desired behaviour to minimize void formation.

6.2. Effect of fineness on set and hardened properties

Table 5 summarises the experimental results of setting time, compressive strength and volume change of IMG and IBG mixes. It can be observed that the setting time criteria (see Table 3) was not satisfied by both the mixes. This may be due to the effect of dosage of superplasticiser (0.2% in IMG and 042% in IBG) and hence, may require the addition of accelerators to the formulated mixes. However, in general, the setting time of IBG was lesser than that of IMG by about one hour. This is expected due to its larger specific surface area and hence, the probability of higher reaction rates.

IMG and IBG had very low compressive strength (around 11 MPa for both) on the 3rd day, as the presence of fly ash usually delays the strength gain at early stages. However, both had attained strength greater than 21 MPa on the 7th day (see criteria in Table 3) and it was seen that inter-grinding resulted in an increase in the compressive strength of IBG. This was more evident at a later age (7th day). The average shrinkage (in %) of IMG and IBG on the 7th day is given in Table 5. The shrinkage of IBG was found to be lesser than that of IMG, but, the difference was only marginal.

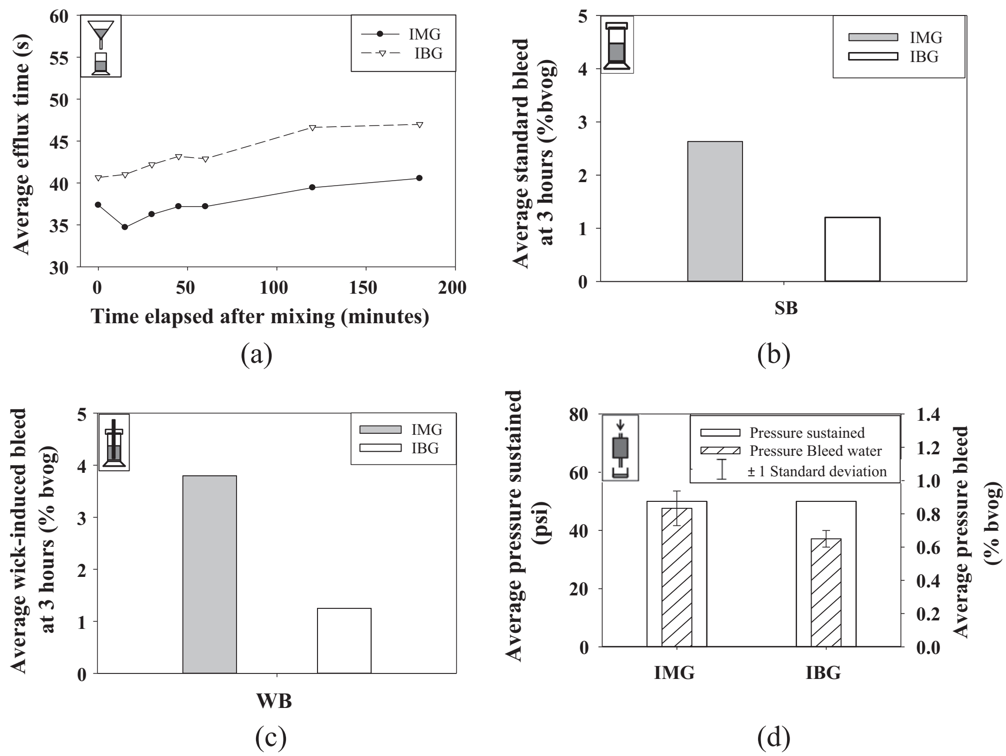


Fig. 11. Comparison of performance of IMG and IBG (a) Efflux time; (b) Standard Bleed (SB); (c) Wick-induced Bleed (WB); and (d) Average pressure sustained and the corresponding bleed collected.

7. Limitations of the research

This research serves as an indicator of the quality of grout materials that are currently being used for PT applications and; the importance of site parameters and fineness on grout performance. The research was done using the most common commercially available PPGs and SBGs. Behaviour of these grout mixes were studied only under two temperature conditions of 15 °C and 30 °C and three different mixing speeds of 500, 1500 and 2500 rpm using a custom made high shear mixer. For the analysis of SBGs, only a single batch of OPC-53 grade cement was used throughout the research. The effect of fineness was studied based on a single source of binder. The inter-grinding/blending was done in a laboratory ball mill. However, large scale pilot studies are required for more realistic performance of grouts in the field.

8. Conclusions and recommendations

Based on the experimental work, the following conclusions are drawn

1. The most commonly used PT grouts in many developing countries (i.e., Plain Cement Grout (PCG), Site-Batched Grouts (SBGs) and some recently developed Pre-Packaged Grouts (PPGs)) fail to meet the requirements of PT grout standards, and even the specifications given by the manufacturers.
2. Efflux time determined using a flow cone cannot be used as a screening parameter to select thixotropic grouts for PT applications.
3. A change in ambient temperature from 15 to 30 °C can result in significant change in bleed resistance. However, the magnitude of this change can vary for different grout materials.
4. For SBG and PPG, the optimal mixing speed was found to be 1500 and 2500 rpm, respectively.
5. Setting time and compressive strength of grouts are affected only by the variation in the ambient mixing temperature (at 15 and 30 °C) and not mixing speeds (until 2500 rpm). Hardened volume change is not affected at ambient mixing temperatures of 15 & 30 °C and mixing speed.
6. Increase in fineness can increase the flow retention and bleed resistance of grouts, which are critical in influencing complete grout fillability and reducing void formation.

Based on these, it is recommended that:

1. Flow cone alone should not be used for assessing the fillability of thixotropic grouts for PT applications.
2. High-performance grouts and suitable grouting practices need to be developed to ensure that the PT systems will actually meet their desired long service life.
3. The performance of grout mixes under simulated site conditions must be evaluated prior to their large-scale use in the field.

9. Conflicts of interest

There are no conflict of interest.

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