INLINE MONITORING OF GROUT DENSITY DURING PUMPING

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Cementitious grout has proven to be an effective corrosion protection method in post-tensioning systems. While successful grouting has been used in numerous post-tensioned (PT) bridges, quality control of the material and placement in the field remains a challenge. During the grouting process on site, ensuring that the grout being placed in the tendon is representative of the intended grout design is critical for the performance of the system. Inconsistencies in the placed grout can be attributed to varying mixing procedures used in the field (such as the addition of water above the design value). Advancements in the quality of in-place grouts can be made by refining specifications and developing a procedure to continuously measure the density of the grout as it is pumped into the tendon. This paper focuses on the results of testing of an in-line density meter for nearly continuous monitoring and recording of grout density and temperature.

Keywords:
density meter; flow meter; grout density; grouting; specifications.

INTRODUCTION

Cementitious grouts for post-tensioning have a good track record when a quality grout is used under well-controlled construction conditions. However, during grouting in the field, ensuring that the prequalified product is the actual end product being injected into the tendons can be difficult. The reason is twofold: the product material may differ from that tested in a laboratory setting and the actual procedures (including addition of water and mixing) on site may vary from best practice. The single biggest downfall for a good prequalified material is the over-addition of water.

Over the past nearly 20 years, considerable effort has been spent in developing specifications for grouting materials and testing as well as training for grouting crews. However, tendons with grout voids that appear to be directly related to a material, mixing, or pumping failure continue to exist. An area that can produce a major advance in quality of the in-place grout material is to develop a procedure to measure the density of the grout continuously as it is pumped into the tendon. Information for contractors and education of construction and inspection practices has increased dramatically over the past two decades; however, the test requirements have seen less evolution. Flow cones, mud balances, and other test methods are nearly the same as they were 20 years ago. With the technology available today, easier and more effective quality control measures are possible and needed in the field to help the inspectors and grout operators produce more consistent grout that is representative of the material developed to pass the specification.

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RESEARCH SIGNIFICANCE

This research provides the foundation for use of an inline density meter that can be specified for quality control during grouting in the field. The proposed device can be used in place of mud balance testing at the inlet and could also be used for the outlet.

TESTING APPARATUS: INLINE DENSITY METER

The inline density meter tested in this program is a Coriolis flowmeter and is one of several brands available commercially. The meter used was a Krohne OPTIMASS 1400C S25 flowmeter as shown in Fig. 1. It is a twin straight-tube Coriolis mass flowmeter consisting of two measuring tubes, a drive coil, and two sensors positioned on either side of the drive coil. When the meter is energized, the drive coil vibrates the measuring tubes, causing them to oscillate producing a sine wave. The sine wave is monitored by the two sensors. As the grout passes through the tubes, the Coriolis effect causes a phase shift in the sine wave that is detected by the sensors. The phase shift is directly proportional to the mass flow. Density measurement is made by evaluation of the frequency of vibration and temperature measurement is made using a Pt500 sensor. Live inline density and temperature measurements provide instantaneous feedback via readout screen. The meter is also equipped with a data recorder that saves the measurements onto a micro SD card that allows a record of the data that can be analyzed further via a standard program such as Microsoft Excel. The meter for this testing was set to eight samples per second. A higher sampling rate is available on the meter but is not necessary for this application.

TEST PLAN

The goal of testing was to evaluate an inline density meter for field use including a comparison to values from the mud balance test.[1,2] The mud balance device is shown in Fig. 2. The wet density is measured by filling the cup and weighing it with the provided balance. The test is straightforward, but accuracy depends on several factors, including calibration, operator consistency, and cleanliness of the device (even a small amount of hardened grout on the device will skew the weight measurement). While the value may not be highly accurate, it does provide a way to give a relative comparison to the inline device while also comparing current methods to the proposed method.

Given the goal of the research, the testing focused on pumping a wide range of densities of grout for comparison. Testing was conducted on two types of prepackaged grouts to evaluate full batches in a standard grout plant. Any reasonable formulation of grout (including non-prepackaged) could be used for the density correlation testing and the results are not intended to compare the two grout formulations. The goal of testing was to have grouts commonly used in the field used at a wide range of water-solids ratios to correlate the inline meter results to mud balance results. The grouts were purposely over-watered to achieve a wide spread of data and thus results are not indicative of properties expected when using the recommended water-solids ratio.

Table 1 shows the water dosage used during testing. Mixtures were tested on various water dosages to verify the changes in the grouts' properties due to changes in the water content. The water demand varied based on the manufacturer's dosage recommendations. The recommended and maximum water dosages were tested as provided by the manufacturers as well as overwatering at 10%, 25%, 45%, and 65% over the manufacturer's maximum suggested water dosage to determine the sensitivity and range of the density meter.

The test protocol includes mixing full-scale batches in a high-shear commercial grout pump that includes a mixer and agitating tank. A schematic of the setup is shown in Fig. 1. The grout was initially batched at the manufacturer's recommended level and moved to the agitator (holding) tank after mixing. The grout was then pumped out through the inline meter and back to the holding tank so that a continuous circulating flow was maintained. The grout was pumped for approximately 25 minutes, during which time the following were tested:

- Modified flow cone test[3]: one per water level;
- Mud balance test: one every 5 minutes (four per water level); and
- Continuous collection of density and temperature readings via density meter.

At the completion of testing at the initial water level, the grout was transferred back to the mixing tank, where the correct volume of water was added to bring the grout to the next water content to be tested. The grout was mixed for 45 seconds with the additional water and then transferred to the holding tank for the next round of testing. This was repeated until all levels were completed, resulting in the grout being pumped over the course of approximately 2.5 hours. Each of the two prepackaged grouts was run through all water levels twice for a total of four individual pumping tests at multiple water levels. It is important to reiterate that this procedure and water contents are not those that would be used to qualify a grout or use a grout in the field. This procedure was developed specifically for comparing to methods of wet density measurements.

RESULTS AND ANALYSIS

Table 2 shows the flow cone results for each grout at each water level during testing. These values are shown only for reference and not indicators of density or other grout performance characteristics. As expected, flow times increase as water content increases. The flow times for the two different batches of the same grout varied in both cases.

Figures 3 through 10 show plots of the data from the density meter. The raw data is easily imported into a spreadsheet/graphing program for manipulation. The density plots show results from the density meter in lb/gal. (equivalent to 120 kg/m^3) averaged over a minute for each point and are

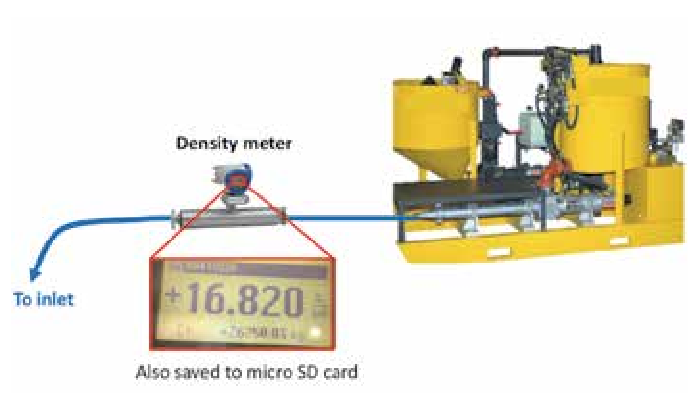

Fig. 1—Coriolis inline density meter setup.

plotted in blue. The mud balance results are plotted in green and include an error bar that represents the range of values taken on the grout at the same water content during pumping. The technician taking mud balance measurements was kept consistent throughout testing. The x-axis on each plot represents the time during pumping. For the density plots, the left y-axis represents the density in pounds per gallon, and the right y-axis shows the value in terms of specific gravity. Each density plot is followed by the correlating temperature plot during mixing.

Fig. 2—Mud balance.

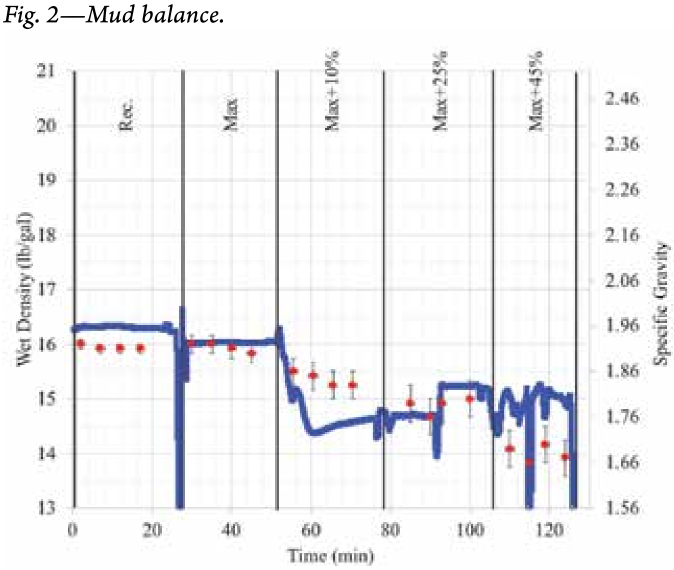

Fig. 3—Grout 1, Test 1 density results.

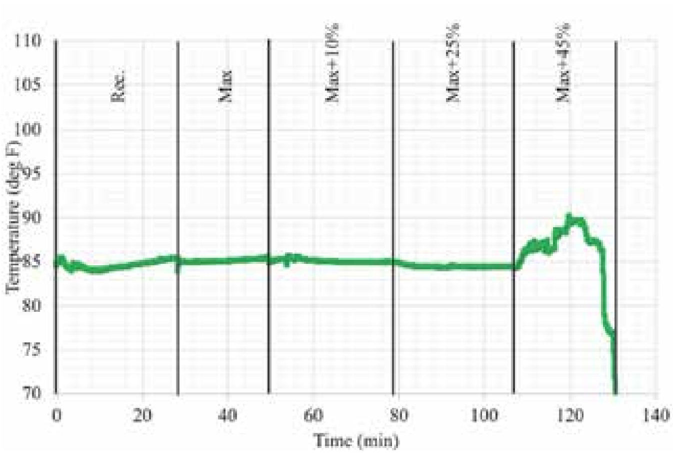

Fig. 4—Grout 1, Test 1 temperature results.

Figure 3 shows Grout 1 during the first testing run. In this batch, the same unhydrated clumps of material were retained on the screen between the mixer and tank, causing some fluctuation in readings. These clumps were added back in to the next mixture. The data is still presented because it still provides a comparison to how this is recorded by the density meter and by the mud balance. It is always important to avoid clumping, which can cause blockages in the pump and lines. After completion of testing, some clumped material was also found in the density meter. This can alter results, can be removed during water flushing of the pump and grout hoses after grouting. The plot shows that both the mud balance and density meter measurements decrease with increasing water content. The density meter plot shows consistent values through the first two water ranges but the clumping in the meter likely occurred during this stage. Clumping eventually became an issue with continued pumping as the pumping pressure began to increase significantly, followed by a blockage. The pump was turned off and on to push the blockage through and this can be seen directly in the inline density readings in the last portion of the plot. Mud balance readings had increasing variability because the sample tested likely varied due to clumping. In the field, this batch of grout would not have been used due to the lack of sufficient mixing (clumping) but the data is included to show

Table 1 – Water content of prebagged grout mixtures

Water content	Grout 1		Grout 2	
	Volume, gal.	*w/s*	Volume, gal.	*w/s*
Recommended	1.5	0.25	1.5	0.26
Maximum	1.7	0.28	1.6	0.28
Max + 10%	1.9	0.31	1.8	0.30
Max + 25%	2.1	0.35	2.0	0.35
Max + 45%	2.5	0.42	2.3	0.38
Max + 65%	2.8	0.47	2.6	0.43

Note: 1 gal. = 3.78 L.

Table 2 – Efflux time by modified flow cone method

w/s	Efflux time, seconds			
	Grout 1, Test 1	Grout 1, Test 2	Grout 2, Test 1	Grout 2, Test 2
A	12.5	21.4	No flow	+ 60
B	7.2	8.1	+ 60	48.0
C	5.8	7.0	+ 60	8.1
D	5.4	6.1	30	6.6
E	4.4	5.2	12.7	5.1
F	Test stopped	4.3	9.7	4.9

how fluctuations in continuous pumping affect the data. No other tests during this program had clumping issues. The corresponding temperature data is shown in Fig. 4. Temperature values remained steady up until the time of the blockage, where a jump in temperature was recorded prior to flushing the mixer with cool water at the end of testing.

Figure 5 shows a new run of Grout 1. Results show clear and consistent drops in density measurements at each water content for both the density meter and the mud balance. A short downward spike is evident in the density meter data between each water content change. This is due to the short shutoff of the pump during the transfer of the grout to the mixer and then back to the holding tank. Figure 6 shows the temperature measurements that slowly drop as additional cool water is added.

Figure 7 shows the density results from the first test of Grout 2. The grout was exceedingly thick at the recommended water content and would not pass through the flow cone, so the initial mixture was batched directly at the maximum recommended dosage. The mud balance was consistent and well-aligned with the inline density meter for the high-water-content grouts, but was significantly higher with the low-water-content grouts. The grout was thick and tended to block the weep hole on the top of the device, which the testing technician did not realize at first. This produced an error in the mud balance results from a larger volume of grout in the device. It is very important that the weep hole is clear and that the cap fits securely so that the correct volume of grout is in the cup. Figure 8 has the temperature data for this grout. Temperature rose quickly above 100°F (38°C) with this grout, which is in alignment with the lack of fluidity of the mixture during inital mixing.

The second run with Grout 2 is shown in Fig. 9 and 10. The behavior was similar to the first run, and though temperatures were not as high. Some clumping occurred with this mixture but was not retained in the density meter

It is important to note that the relationship between measured density (or specific gravity) in the field and water content is not consistent between different grouts or even under different grouting conditions. Significant changes in water content can result in relatively small changes in the specific gravity of the grout (on the order of 0.1). However, the in-line density meter is a vast improvement

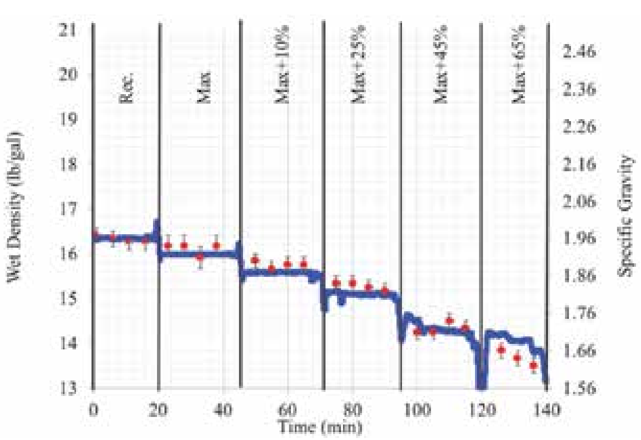

Fig. 5—Grout 1, Test 2 density results.

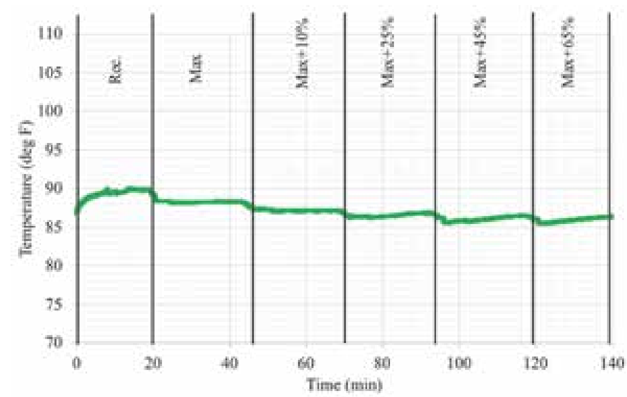

Fig. 6—Grout 1, Test 2 temperature results.

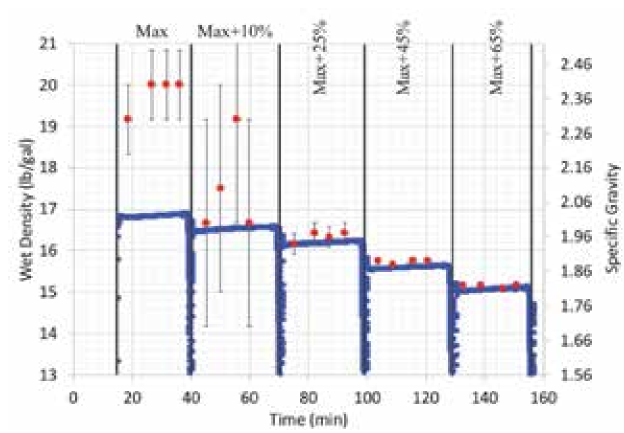

Fig. 7—Grout 2, Test 1 density results.

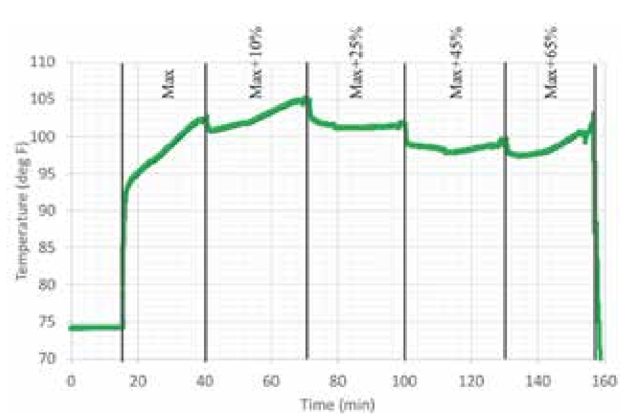

Fig. 8—Grout 2, Test 1 temperature results.

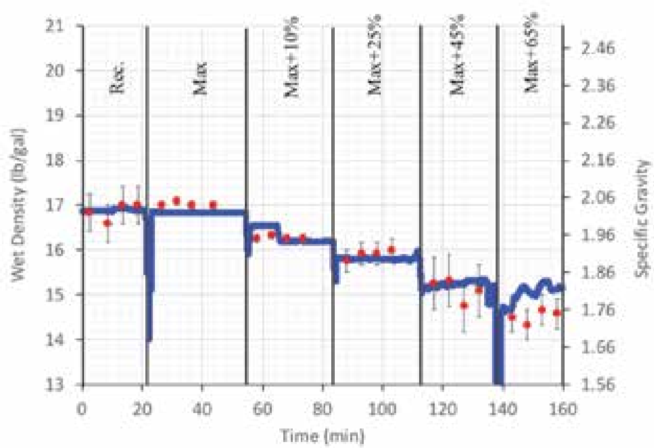

Fig. 9—Grout 2, Test 2 density results.

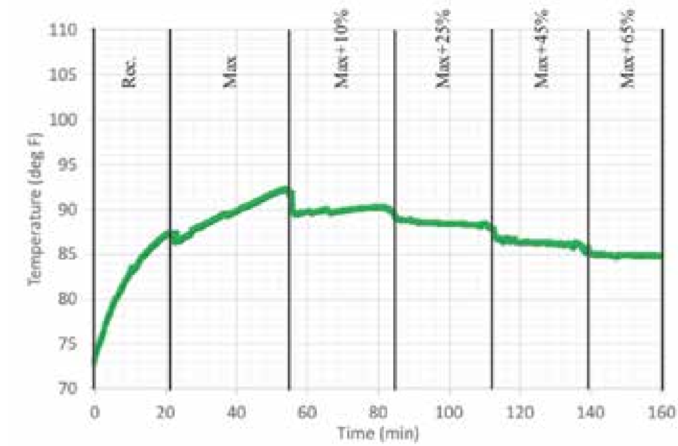

Fig. 10—Grout 2, Test 2 temperature results.

on the mud balance given the inconsistency in the mud balance from either operator error or in acquiring a representative sample. The inline meter accurately and continuously provides density readings throughout pumping and provides a real-time visual indicator of changes in density that may indicate issues.

SUMMARY AND RECOMMENDATIONS

Based on the results of this study, there is a clear benefit to using a flow meter inline during field pumping of post-tensioning grout. The mud balance method that is currently used provides only a snapshot in time, is more prone to operator error, and is not practical to use for frequent measurements during pumping of a tendon. The inline flow meter provides nearly continuous measurement and provides a real-time readout for the grouting crew and inspector. Additionally, the data for both density and temperature can be downloaded as an electronic record of the full grouting procedure. Ideally, a density meter should be used on both the pumping end and the outlet to measure potential addition of water trapped in the tendon due to poor protection. However, if the tendon is properly protected, the pumping (inlet) flow meter would be a major step in combating the main construction issue in grouting PT tendons.

Given that the density meter has the potential to provide a single indicator during construction of grout performance of a pretested grout, it is recommended that density meter is used on every grouted PT tendon that is using the grout as a protection level, including all bridge tendons. For pretested grouts, this test could potentially replace the flow cone and mud balance tests. Before the grout hose is attached to the tendon, flow meter readings would be taken. This also allows an indication of when any water in the mixing plant or hose is cleared from the line. Pretested grouts would then establish a window of acceptable density for approved use.

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