


THE IDENTIFICATION OF VARIABLE SHEAR STRENGTH OF PARTICLES DEPOSITED ON DRINKING WATER PVC PIPES AFTER THE PASSAGE OF A SUSPENDED PARTICLE PLUME IN A FULL-SCALE LABORATORY SYSTEM

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Abstract

Understanding the adhesion properties of sediments that accumulate on the wall of drinking water pipes is an important step in the development of mitigation strategies to prevent the formation of deposits and protect drinking water. Research based on flushing of operational pipe mains that mobilized particulate sediments from isolated pipe sections has shown that fine iron oxide particles are a recurrent major component of these deposits. In addition, it has been established that adhesion forces proportional to the flow wall shear stress (WSS) develop between the pipe wall and accumulated particles, which prevents the washing-off of particles during common conditioning flows and provokes a rapid resuspension during high-flow events that cause water discoloration. Discolouration models have also showed that sediments have a variable shear strength, and, therefore, a fraction of material may resist a first increase in WSS but then be mobilized after a second increase in WSS. To explain the variable shear strength of layers, researchers have hypothesized that sediments accumulate as cohesive layers, which might be explained by the growth of biofilm among particulate material. Although current models have successfully explained sediment mobilization during flushing, the prediction of material accumulation and its shear strength is more challenging due to the lack of a comprehensive understanding about the accumulation process.

The aim of this paper is to examine how particulate iron oxide that are rapidly deposited on PVC pipes develop variable shear strength under common hydraulic conditions found in drinking water distribution networks. A set of experiments were performed in a full-scale laboratory facility, where selected iron oxide particles were controlled and used to amend the feed water at the entrance of a 200 m pipe loop during a short period of time to create a suspended sediment plume with constant concentration. Experiments were realized at three different concentrations and three different velocities. In each set, three sequential plumes were used to accumulate particles on the pipe walls, followed by three sequential flushing steps used to mobilize the particulate material. The deposition of iron oxides in the PVC pipes were assessed indirectly through suspended sediment concentration (SSC) and turbidity data. Results showed that iron oxide particles predominantly accumulated in the first sections of the pipe wall. Most sediments were found to have weak shear strength and were easily mobilized with the first flushing step. However, the mobilized load from the second and third flushing steps revealed a consistent mobilization of sediment with higher shear strengths. These shear strengths were higher in the experiments with a higher inoculation concentration, and they were lower in experiments performed with a higher conditioning fluid velocity. The results suggest that variable shear strength can develop without biofilm. Additional long-term experiments are still required to evaluate the evolution of sediment shear strength which possibly can increase with time.

Keywords

Discolouration, Pipe Flushing, Iron Oxide Particles, Shear Strength, Wall Shear Stress.

1 INTRODUCTION

Pipe flushing is an established method in the drinking water industry to recover accumulated materials on the internal surface of pipe walls before they can have a negative impact on drinking water quality and cause customers complaints [1-3]. However, the practice of flushing operations by water utilities is not yet standardized and rely mostly on local empirical experience, where results from previous attempts are generally used as a guidance to determine key control variables for new pipe flushing. Research shows that the fluid velocity and wall shear stress (WSS) are the most important parameters that have an impact on material mobilization [4]. But it is well known that material accumulation is dominant in old cast iron pipe sections due to corrosion processes [5], and prolonged periods of time without flushing that produce larger material loads [6, 7]. In this context, a water utility's challenges consist of optimizing flushing operations in terms of intensity (e.g., flushing duration, fluid velocity/WSS) and recurrence, to reduce their elevated cost and water consumption.

During flushing, the increase of the WSS over the pipe walls promotes the mobilization of material accumulation. This implies that there is an adhesion force that binds the accumulated materials have an to the pipe wall that prevents their mobilization under regular flow demands. This concept is named *material shear strength* and it was first quantified by the *prediction of discolouration events in distribution system* (PODDS) model [8]. PODDS hypothesized that accumulated material have a finite shear strength, and material can be mobilized if the WSS exceeds the shear strength of that material. In addition, the fraction of material within each shear strength layer was pre-defined based on the assumption of a linear decrease in material load according to their shear strength. However, later research showed that the highest WSS levels achieved on flushing of DWDSs are often below the ultimate shear strength of accumulated materials [7, 9], and that material strengths at all levels are developed simultaneously without conforming to the constraints imposed by the PODDS framework [10]. In practice, these findings revealed that pipe flushing has a limited capacity to remove material from pipe walls, and that the effectiveness of such operations is strongly determined by the material shear strength.

Inspired by the PODDS concept, research has focused on determining the shear strength of accumulated materials to better estimate optimal flushing levels [4, 6, 7, 10]. Researchers have proposed that material shear strength is conditioned by the daily peak flow, although substantial differences between the shear strength behaviour for different pipe materials are also reported and yet not fully explained [7, 9]. In this context, the known contributions of biofilm for material accumulation in drinking water pipes [11] motivated the explanation of material shear strength based on cohesiveness and high-adhesion properties of extracellular polymeric substances (EPS) that form biofilms [12, 13]. Biofilm may explain the occurrence of materials with high shear strength that are able to resist elevated WSS during flushing, and these are hypothesized to assist in the deposition of iron oxide particles – commonly released during discolouration events [14] – by enhancing pipe wall adhesion properties [15]. By comparison, recent research realized under controlled laboratory conditions that prevented biofilm formation observed iron oxide deposits on PVC pipes with shear strength that was able to resist a WSS of 5 Pa [16]. Microscopy observations of the particles also revealed that the particles with the highest shear strength were small (<2 μm) and were uniformly distributed, rather than aggregated, along the pipe wall. The findings suggest that cohesion was not responsible for the variable shear strength, but rather that shear strength originates from the placement of the particles in microscopic 'valleys' of the pipe wall roughness that shield them from the wall shear stress.

Despite the current advances in understanding material accumulation shear strength, several questions remain unanswered. Specifically, differences in the mechanisms of particulate material accumulation of low and high shear strength are not yet explained. The aim of this paper is to examine how particulate iron oxide that are rapidly deposited on PVC pipes develop variable

shear strength under common hydraulic conditions found in drinking water distribution networks. The research was completed by means of a series of experiments where iron oxide was introduced into a full-scale laboratory system to produce controlled plumes of particles that were conveyed through the system to simulate the occurrence of a discolouration event in a DWDS. Five experiments independently tested three different suspended sediment concentrations (SSC) and three different conditioning fluid velocities. The shear strength of particle deposits was assessed through their mobilization using three incremental flushing stages realized after the pipes were conditioned.

2 METHODS

The experiments were realized in the Drinking Water Distribution Laboratory (DWDL) at Queen's University, using a full-scale pipe loop rig that simulates the operation of drinking water mains. The pipe laboratory system is comprised of a water tank with a volume of 3.6 m³, two variable speed centrifugal pumps and 11 loops of IPEX Blue Brute PVC pipe Class 235 (DR18) with an internal diameter of 108 mm, and a total length of 193 m. During the experiments, the pipe loop system was operated in a non-recirculatory manner, where drinking water from the City of Kingston was continuously added to the tank, pumped through the pipe system, and discarded at the outlet of the loop. Previous assessment of the local drinking water suggests a negligible amount of SSC (<0.1mg L⁻¹).

For the experiments, the incoming drinking water that was constantly fed into the inlet of the pipe loop was amended with iron oxide particles. This feed location was located after a straight pipe section of approximate 2 m reserved for the stabilization of the flow velocity profile. A chemical grade of red iron oxide powder from Alpha Chemicals, with a composition of 82% of Iron (III) oxide – Fe₂O₃, was chosen as the source of particles for the experiments due to their representativeness of iron oxide particles found in DWDSs and their stable particulate form and insolubility in water. To guarantee the repeatability of the powder particle size distribution (PSD), the full iron oxide sample was sent to a commercial laboratory to split it into sub-samples of 50 g using a mini rotary splitter from Retsch company model PT100. The PSD of two sub-samples picked at random was analysed with a Malvern Mastersizer 3000 particle size analyser (laser diffraction).

A total of five experiments were performed with a variable concentration of suspended particles (F1C1, F2C2 and F1C3 in Table 1) and a variable conditioning flow rate (F1C1, F2C1 and F3C1 in Table 1). Each experiment was divided into three independent sub-stages (P1, P2 and P3), where plumes of suspended particles were produced at the inlet of the pipe loop and transported to the pipe loop outlet before the introduction of the next plume in the next sub-stage. Each plume was created by injecting a known volume of a concentrated solution of iron oxide particles (CSIOP) at the inlet of the pipe loop with a known SSC over an injection period equal to the time required for the water to travel 60 m downstream of the injection point given the prevailing flow rate in the pipe loop. A diaphragm pump was used to pump water from the bottom of the CSIOP tank (approximately 10 cm away from the tank walls) from a position of intense mixing between two of the four vertical baffles. This water was injected at a constant flow rate at the inlet of the pipe loop at the centreline cross-sectional position of the pipe. At the end of each injection period, the steady flow conditions were maintained in the pipe loop for an additional period required to refresh the equivalent of 1.5 pipe loop volumes to guarantee that all suspended particles from the sediment plume had exited the pipe loop.

At the end of the conditioning stage of each experiment (passage of the three sequential plumes P1, P2 and P3), the system was flushed with three independent incremental steps at different intensities (FS1, FS2 and FS3 at Table 1) to assess the mobilization of particle deposits from the pipe walls. The first flushing step had a WSS of 1.2 Pa, which was previously suggested as an

ultimate shear strength for materials accumulated in plastic pipes [7]. By comparison, the last flushing step produced an elevated WSS of 5.0 Pa, that is not commonly achieved in DWDSs even under fire fighting/flushing conditions [4]. After the end of the flushing phase, and before starting a new experiment with a specific set of conditions, the pipe system was flushed and cleaned at the highest achievable flow rate of 16 L s⁻¹ (slightly above the flow of the FS3) for 5 minutes to establish identical initial condition for all the experiments.

Table 1. Hydraulic and water quality conditions for the experiments.

Experiment	SSC^a (mg L⁻¹)	Flow (L s⁻¹)	Velocity (m s⁻¹)	Reynolds Number	WSS^b (Pa)	Pipe loop RT^c (min)
F1C1	20.0	0.60	0.07	7 000	0.02	50.9
F1C2	40.0	0.60	0.07	7 000	0.02	50.9
F1C3	60.0	0.60	0.07	7 000	0.02	50.9
F2C1	20.0	1.80	0.20	21 000	0.11	17.0
F3C1	20.0	2.75	0.30	32 000	0.24	11.1
FS1	-	6.5	0.71	76 600	1.20	4.7
FS2	-	11.0	1.20	129 700	3.09	2.8
FS3	-	14.3	1.56	168 600	4.96	2.1

a. Suspended solids concentration.

b. Wall shear stress based on the Darcy-Weisbach equation.

c. Pipe loop residence time (RT) calculated by dividing the pipe loop volume of 1.7 m³ by the flow rate.

During all the experiments, the pipe flow rate and turbidity were continuously monitored at a sampling frequency of 1 Hz using two Sierra InnoVaSonic® 205i Ultrasonic Flow Meters ($\pm 0.5\%$) and two online Hach TU5300sc turbidimeters (± 0.01 NTU). The turbidimeters were configured to monitor turbidity at the inlet (7% of the pipe length) and outlet (98% of the pipe length). Turbidity was measured from water continuously sampled from the centre of the pipe at a constant sampling flow rate. Following each injection, grab samples were collected at the inlet and outlet sampling port locations to determine SSC at those locations and to assess changes in the particles in suspension after the passage of each plume through the pipe loop. The collection of grab samples was synchronized with the fluid velocity in the pipe loop to collect 4 L of water from the centre of the passing sediment plume. During the flushing phase, SSC grab samples were synchronized to collect water from the centre region of the pipe loop that corresponded to a region between $\frac{1}{4}$ and $\frac{3}{4}$ of the total pipe loop length. The SSC of the grab samples was determined using a dry-weight method, by filtering the sample volume with pre-weighed 0.45 μm glass microfiber filters, drying the filters at 105°C for 1 hour, and weighing them again after drying with a precision scale. Additional details of the experimental design can be found in Braga and Filion [17].

The continuous turbidity data of the conditioning and flushing phases of the experiments was offset by the background turbidity of the local drinking water and converted to SSC data through the calibration of linear conversion coefficients κ (mg L⁻¹ NTU⁻¹). For the conditioning phase, the constant source of particles and steady flow resulted in very stable relationships between SSC and the turbidity increase caused by the iron oxide particles addition [17]. It is noted here that the calibration of two different coefficients for the inlet and outlet positions was required due to changes in the PSD during the passage of the plume through in the pipes. A coefficient $\kappa = 0.24$ mg L⁻¹ NTU⁻¹ was obtained for the inlet, and $\kappa = 0.15$ mg L⁻¹ NTU⁻¹ was obtained for the outlet. In the case of the flushing stage of the experiment, the PSD of the particles mobilized from the walls was not stable and varied across each flushing step, experimental condition, and position of the pipe where particles were mobilized. To a reliably convert turbidity data into SSC data, it was

assumed that each flushing step produced a similar PSD, and coefficients κ were calculated through the average of individual SSC grab sample coefficients from all experiments for each flushing step. A $\kappa = 2.5 \text{ mg L}^{-1} \text{ NTU}^{-1}$, $\kappa = 6.0 \text{ mg L}^{-1} \text{ NTU}^{-1}$, and $\kappa = 5.2 \text{ mg L}^{-1} \text{ NTU}^{-1}$ were obtained for the FS1, FS2 and FS3, respectively. The average error of the coefficients is approximately 30%.

Following the conversion of the continuous turbidity data (TURB) to SSC data using the constant coefficients κ for each conditions highlighted above, a continuous particle mass flux Q_{SS} (mg s^{-1}) was obtained by the product of the instantaneous flowrate Q (L s^{-1}) and the SSC (mg L^{-1}) (Equation 1). A mass balance analysis of the continuous particle mass flux at the inlet and outlet of the pipe loop made is possible to estimate the mass of iron oxide particles that remained attached to the pipe walls during the conditioning phase and the mass of iron oxide particles that were mobilized during the flushing phase.

$$Q_{SS} = Q \times SSC = Q \times (\kappa \times TURB) \quad (1)$$

3 RESULTS AND DISCUSSION

The results of the iron oxide particle mass flux produced by the passage of the plumes during the conditioning phase of each experiment is presented in Figure 1 and highlights the differences between the plumes at the inlet and outlet positions of the pipe loop. Figure 1a shows the three experiments at different SSC, where an evident decrease of the particle mass flux occurred between the inlet and outlet. The results among the three experiments were consistent and they point to a decrease of 46% of particles between the two turbidimeter positions (22% of the injected particle load). However, it was previously estimated that 55% of the particles remained in the short length of pipe between the particle injection point and the inlet turbidimeter for these 3 experiments [17]. The combined total fraction of the particles injected in the pipe loop that accumulated in the pipes for the F1C1, F1C2 and F1C3 was estimated to be 75%.

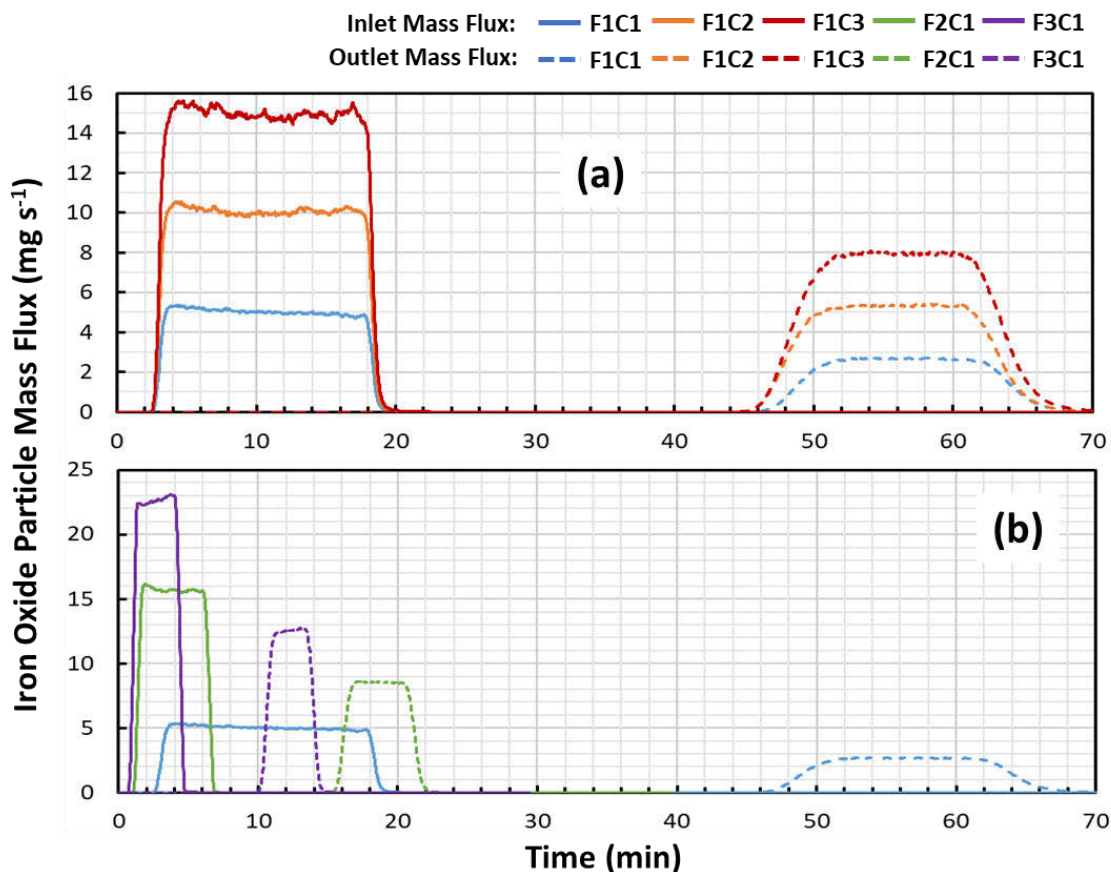


Figure 1 – Iron oxide particle mass flux of the suspended sediment plumes produced during the conditioning phase of the experiments at the inlet and outlet positions during the a) three experiments at different SSC and constant velocity (F1C1, F1C2, F1C3); and b) three experiments at different velocities and constant SSC (F1C1, F2C1, F3C1).

In the case of the experiments with different fluid velocities and constant SSC (Figure 1b), the decrease in the peak of the particle plume mass flux is even more evident in experiments F2C1 and F3C1 which were notably different than F1C1. Note that even if the SSC between the experiments is similar, the particle mass flux of the experiments at higher fluid velocities is substantially higher due to their higher flow rates. In terms of the mass balance for F2C1 and F3C1, a similar constant reduction fraction of 46% was obtained between the turbidimeters locations (in this case representing 25% of the injected particle load). However, a slight decrease of the particle fraction in the initial pipe length to 44% caused a reduction of the total load accumulated in the pipes to 69%. These results suggest that the main difference in the particle deposition load between the experiments at higher velocities occurred in the initial pipe sections.

Further, the results for the particle mass flux at the pipe outlet during the flushing phase of the experiments is presented in Figure 2. Substantial particle loads were mobilized during the three sequential flushing steps. The highest load was observed during flushing step FS1 (Figure 2a), and smaller loads were observed during the subsequent flushing steps FS2 (Figure 2b) and FS3 (Figure 2c). The results provide evidence that: i) the particles accumulated in the pipes had different shear strengths, and ii) these material deposits were produced after the rapid passage of particle plumes and not as a result of a continuous particle load as reported in the literature [16, 18]. However, in comparison to previous experiments that tested for chronic loading of particles, the results of FS1 in Figure 2a shows unusual peaks in the particle mass flux around 5 min, which corresponded to the initial pipe sections where most of the accumulation occurred.

The results suggest that this fraction of accumulated particles likely settled onto the invert of the pipes once the conditioning velocity was not able to maintain their suspension and were held to the pipe wall by weak adhesion forces [16]. In addition, the peak in particle mass flux in flushing step FS1 decreased in the experiments with higher velocities and this agrees with the observed reduction of particle fractions that accumulated on the initial pipe lengths in these experiments.

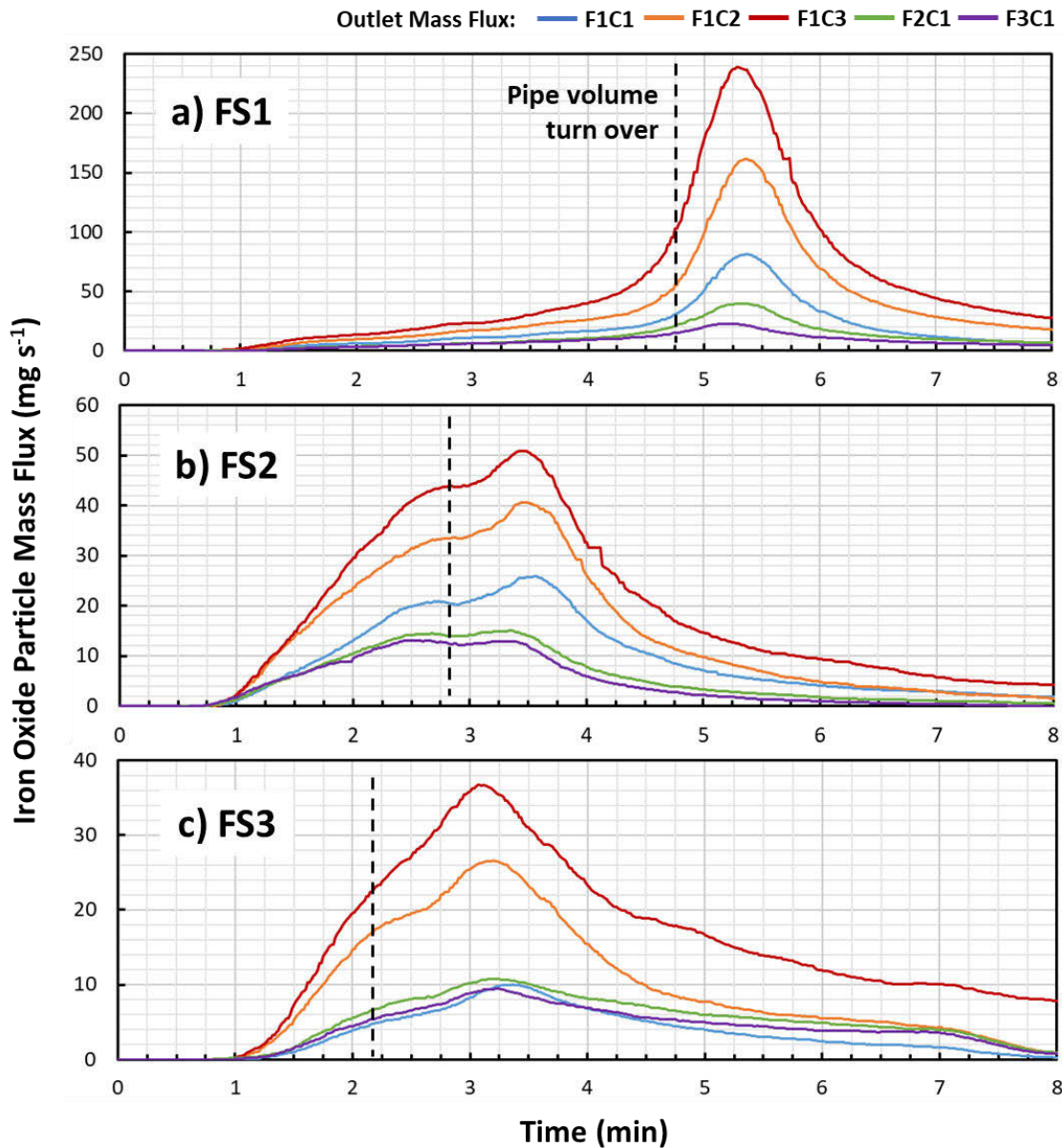


Figure 2 – Iron oxide particle mass flux observed at the outlet turbidimeter location of the pipe loop during the three flushing steps (FS1, FS2 and FS3) for all experiments.

Higher loads of mobilized particles for all flushing steps were observed for the experiments at higher concentrations (F1C2 and F1C3) that produced higher loads of deposited particles on the pipe walls. By comparison, differences between the three experiments at similar SSC (F1C1, F2C1 and F3C1) were larger for the FS1 (Figure 2a), where the F1C1 had the larger mobilized load of particles. However, these differences tapered out for the FS2 and FS3. The particle mass flux peaks of the flushing steps FS2 and FS3 (with corresponding to the initial pipe sections) was also substantially reduced in comparison to the flushing step FS1 (Figure 2bc). This demonstrates that particle attachment with higher shear strength occurred for longer lengths of the pipe loop rather

than predominantly at the first sections. However, the particle mass flux profiles of the flushing steps FS2 and FS3 also shows a slight increase towards their peaks (slightly after the pipe loop volume turn over) rather than stable level. This result suggests that the accumulated particle load decreased along the pipe loop length. Previous analysis of the data proposed that only a finite fraction of particles was suitable for attachment on the pipes in each experimental condition [17]. For this reason, the depletion of the particle fraction along the plume passage explains the decrease in mobilized particles in downstream sections of the pipe loop (firstly measured by the outlet turbidimeter between the times of 1 and 3 minutes in Figure 2bc).

Lastly, the difference between the load of accumulated and mobilized particles in Figure 2 revealed that a consistent fraction of 31% of the accumulated particles were not mobilized during the flushing in the F1C1, F1C2 and F1C3 experiments. The non-mobilized fraction of particles increased to 39% and 52% in the F2C1 and F3C1 experiments, respectively. Although previous research suggested that the last flushing step at a WSS of 5.0 Pa was insufficient to mobilize all particles from the pipe loop [16, 17], it is unlikely that the remaining particle load in the pipes totalled 30% of the inoculated load. It is also unlikely that the non-mobilized fraction of particles increased for experiments with higher velocities. In this case, the discrepancies are better explained by errors in the particle load estimations of the flushing stage based on turbidity data. Since the collection of only one grab sample per flushing step was feasible to analyse SSC due to the requirements of a large sample volume. This sample corresponded to the middle section of the pipe loop, and it is likely that the SSC peak (corresponding to the initial pipe sections) was underestimated. A better estimation of the particle load during flushing would require a higher resolution of SSC data, specifically during the passage of the particles mobilized from the initial pipe lengths where a variable PSD is expected. Alternatively, constant turbidity to SSC calibration factors may be obtained inversely from the assumption that all attached particles during the conditioning phase were mobilized. But this approach would average the differences of PSD along the mobilization profile, and still be inaccurate to investigate the rapid dynamics of SSC during the flushing operations.

4 CONCLUSION

The aim of this paper is to examine how particulate iron oxide that are rapidly deposited on PVC pipes develop variable shear strength under common hydraulic conditions found in drinking water distribution networks. A series of controlled laboratory experiments in a full-scale system were completed in which selected particles were inoculated in the system under steady conditions and rapidly deposited on the pipe walls of the system through the controlled passage of a sediment plume that simulated a discolouration event. Three different SSC and three different fluid velocities were tested. After the pipe wall conditioning through the sediment plume passage, the pipes were flushed at three incremental steps with WSS of 1.2 Pa, 3.1 Pa and 5.0 Pa to mobilize accumulated particles to test their shear strength resistance to the imposed WSS.

The results showed that large fractions of the inoculated particles (69% – 75%) remained in the pipe loops after the passage of the concentrated sediment plume. The predominant fraction of the accumulated particles occurred in the initial pipe sections of the system, and experiments with higher velocities ($>0.2 \text{ m s}^{-1}$) produced only a slight decrease in particle accumulation. Data obtained from the flushing stage of the experiments confirmed that most of particles were accumulated in the initial pipe sections of the loop and revealed that a considerable fraction of the accumulated particles developed a higher shear strength. Particle mobilization profiles from the second and third flushing steps showed that particles with higher shear strength accumulated through longer pipe sections, but progressively decreased with the pipe length. This behaviour agrees with a previous hypothesis that a finite pool of particles amenable to pipe wall attachment is determined by the conditioning fluid velocity.

The experimental results presented here were obtained from conditions that only partially represent operational DWDSs. However, the results contributed to substantial improvements in the understanding of particulate deposit formation and have the potential to also contribute to the better management of material accumulation in operational systems. Further research is required to examine the current results against more complex conditions of DWDSs and connect them to concurrent material accumulation processes.

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