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ABRASION EFFECT OF FLOW ON PIPES

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Abstract

One of the main factors in determining pipe diameter to design of potable water supplying systems is the flow velocity. The design flow velocity cannot be chosen above a certain value since higher velocities cause deterioration of cement mortar lining, additional management costs and destructive water impact. The flow velocity limits noted in the literature are given in a specific range (0,5-3,0 m/sec). However, the mentioned velocity limits can be increased up to a certain value in systems without pumping by decreasing the pipe diameter. Better quality of cement mortar used in the interior lining of the pipes help to increase capacity and thus the cost of the project can be reduced. In this study, an experimental pipeline model was set up from ductile pipes with cement mortar lining in which high velocities were aimed and a series of experiments were conducted. Experimental set up was composed of ductile pipes with four different diameters (Ø200-300-400-450 mm) and water was recycled from a reservoir to the pipe system and back to the reservoir by pumps. The measured thicknesses from the pipes were compared and the changes on the cement mortar lining were observed.

Keywords: Water pipeline, cement mortar lining, abrasion, flow velocity

1. Introduction

In recent years, the quality of concrete coating and water proofing has been increased with the help of adhesion promoters and accelerator additives used in the concrete coating of drinking water distribution pipelines and the design velocity criteria used in drinking water transmission line pipes can thus be increased a little more thereby enabling the use of achievable economic pipe diameters. The economical contribution that would be gained by using smaller diameter sized pipes can not be neglected as the cost of pipe used in drinking water transmission lines is considered to be 60-70% of the total cost of the work.
It is crucial to detect the corrosion effects of water velocity on concrete lining of water transmission pipelines. In practice, the pipe diameter in potable water transmission lines is determined by taking water velocity in the range of 0.5 – 3.00 m/s and then using the continuity equation Q=V.A. Both the steel pipe in the damage of concrete pavement, which should bring additional operating costs due to the increasing impact of the energy losses of the water rapidly increase their impact can not be removed on the grounds that a certain value.
The design flow velocity cannot be chosen above a certain value since higher velocities cause deterioration of cement mortar lining, increase additional management costs due to increased energy losses and enhance destructive water impact. Specified water velocity limit is determined in this range in the literature ([1], [2], [3], [4], [5]). Admissible water velocities are determined in order to prevent precipitation at minimum velocities and to protect the system against corrosion and water hammer at maximum velocities. In literature, various studies are present about corrosion influence on

the concrete lining, noise, impact and cavitation effects caused by large water velocity in the system ([6], [7], [8]).
In this study, pressurized water at low and high velocities was passed through concrete coated pipes for a certain period of time. The aim of the study was to obtain a mathematical relationship between the water velocities used in the experiments and the abrasion rates on the concrete lining. It is considered that if a relationship between the water velocity and the abrasion rate cannot be estabilished, the design velocity criteria used in the potable water supplying systems can be increased by a certain amount taking into consideration the water hammer effects and the pipe diameter which is directly related to the water velocities in the pressurized systems can be reduced. Within the limits of the available experimental facility, water was circulated thorough pipes at low and high water velocities for 3 months and the experimental findings were aimed to be evaluated taking into consideration the actual long durations (40-50 years) in operation of such systems.

2. Literature Review

In the experiments conducted at Department of Mechanical Engineering of Saudi Arabia's King Fahd University [7], a steel pipe abruptly narrowing from 200 mm to 100 mm in diameter and water containing particles of diameter 10 μm - 100 μm - 200 μm - 400 μm at 20 °C was used. The aim of the experiments was to detect corrosion on the pipe walls caused by water flowing at various velocities and with particles of different sizes. For this purpose, water containing particles of different grain sizes and flowing at velocities 1 m/s - 5 m/s – 10 m/s was passed through vertical pipes arranged in an upward direction and abrasion the lining was observed. Experimental results showed that water velocity and grain size play a major role in the formation of abrasion but the water flow direction was found to have little effect on the abrasion. The influence of flow direction was found to have a sensible effect only when water flowed with a velocity of 5 m/s with 400 μm grain size. It was also observed that the abrasion was negligible at water velocities under 2 m/s and with all grain sizes used. The deepest abrasion was identified with the biggest grain size and the highest water velocity at the entrance of the small diameter pipe.
In a study conducted by [6] at Missouri University Mechanical and Aerospace Engineering Department of Industry for ASHRAE, it was reported that the upper limits of the specified flow velocity and/or pressure drops in the closed-looped hydraulic piping systems should be arranged below the upper limits. For example, it was noted that the flow velocity should be 1.22 m/s (4 ft/sec) for pipe diameters 50.8mm (2 inches) and less due to the commonly used pressure drop limits while the flow velocity should be 3.05 m/s (10 ft/sec) for pipe diameters 50.8 mm (2 inches) and more due to the noise rate. Although the study indicated that these limits were not tested against sufficient data they are widely accepted limits. Hence, if necessary measures are taken in order to minimize or eliminate the factors causing the noise, abrasion, corrosion and water hammer, then higher flow velocities can be applicable. During the litreture review, manufacturer's publications, research papers, publications made by governmental agencies, trade and professional publications, books and textbooks were examined. It was concluded that most of the current information about the maximum flow velocity criteria for the abrasion occurred on the pipe systems were obtained either from practical experiences or composed of very old experimental studies. The real source for the velocity criteria is unknown in most cases.
In the literature, there are various upper limits for the water velocity and/or pressure drop in pipes and pipe systems. Some limitations are based on pipe diameter. For instance, the limit for flow velocity is 1.2 m/s for pipe diameters of 5.1 cm (2 inch) and less. The limit for pressure drop is 1.2 m (4 ft) for every 30.5 m (10ft) length of pipe with diameter greater than 2 inch. Other limitations vary depending on the usage or system operating time (Table 1). These limitations are arranged in order to keep the noise levels and the water hammer pressure in pipes and valves or economic factors under

control. [9] proposed that the flow velocity should not overcome 4.6 m/s (15 ft/sec), Table 1. Additional restrictions were formed when the flow velocity was determined either by indirect limitations specified by design engineers who want to stay on the safe side with subjective choises or by limitations put forward with the usage of time-dependent pressure drops on corroded pipes.
Furthermore, in that study, noise, abrasion, water hammer, acceptable reduction in time-dependent discharge capacity and their limitations on the factors causing water flow restrictions as water velocity, usage, pipe type, the number and type of the valves and the fittings, the relationship with the type of the system (closed or open) are included in discussions.

Table 1. Maximum velocity limits in terms of abrasion in pipe [9]

Operation (hr/year)	**Velocity (m/s)**
1500	4,6
2000	4,3
3000	4,0
4000	3,7
6000	3,0

The velocity dependent noise in the piping systems and in the open or closed looped pipes is a result of different parameters such as flow turbulence, cavitation, inlet air release and water hammer. Noise in the turbulent flow occurs as the flow strikes against the pipe walls due to the intense turbulence of the liquid. Various studies were carried out to evaluate the noise levels of different flow velocities at different pipe types and fittings ([9], [10]).
The noise generated by the flow passing through the pipe system increases abruptly in case of cavitation being present in the system or the air entered into the system being realized. In general change in flow direction, high flow velocity or a sudden pressure drop due to an increase in pipe diameter causes cavitation. [8] determined that at a maximum possible flow velocity of 14 m/s cavitation didn't form at straight pipes with diameters ranging from 9.5 to 12.7 mm (3/8-1/2 inches). [8] noted that in a pipe with 2 bents, cavitation didn't develop for up to a velocity of 7 m/s of cold water ([6]). [11], [12], [13] came up with the formation of cavitation at orifices with small areas (1.5m/s at A/8 and 3m/s A/4), but at tested velocities no evidence of cavitation was encountered at valves and fittings along the flow.
[14] found no cavitation in their study. It was thus conluded that the noise caused by the cavitation in a system without a large number of valves, fasteners or orifice wouldn't cause a problem. As air enters into the water, the air found in the system would have a higher partial pressure than water carrying itself. It is therefore likely that noise will still occur due to the release of trapped air even though the flow velocity is small enough to prevent cavitation. [14] proposed that all necessary measures should be taken in order to realese the trapped air present in the pipe system or ensure the minimization of the air entrainment.
Most of the materials and water valves used at residentials move slowly; hence noise of water hammer doesn't occur. As solid particles enter into the flow, abrasion occurs quickly especially at bends in case of high flow velocities presence [15]. Hence, high flow velocities are not suitable for transport system in which sand or other solids are present ([16], [17]).
Water hammer is a pressure surge or wave formed in addition to the normal hydraulic pressure as a result of fluctuations created by a power failure or a sudden opening and closing of water flow. The effect of the impulse depends on the initial water velocity, diameter, length and material of the pipe.

Pulse pressure is computed in widely used water pipes at different flow velocities, while the flow velocity is limited with 1.5 m / s in ABS pipes, 3 m/s in PVC pipes and 10.7 m/s in steel pipes [6]. [18] proposed "Abrasion Velocity" criterion given under the heading "Design Criteria For Two-Phase Gas/Liquid Flows" and the velocity is defined in Eq.(1) as

$$v_e = \frac{c}{\sqrt{g_m}} \tag{1}$$

where v_e: abrasion velocity of the flow, ft/sec, c: ampirical constant, g_m: density of gas/liquid mixture, lbs/ft^3. The minimum velocity at which abrasion starts is computed by Eq.(1) then the components of the reason for the flow abrasion are not known.

Firstly the flow velocity should be considered as the sizing criterion for the flow in the pipe. It was found that the loss in the pipe wall thickness was caused by the process of erosion/corrosion because of high flow velocity, presence of sediment and corrosion components such as CO_2, H_2S and components such as elbows giving negative influence to the flow [19].

Industrial experience shows that for continuous flow the use of c = 100 value and for discontinuous flow the use of c = 125 value is appropriate in clean water without sediment. For clear water without sediment content in which corrosion isn't expected or can be kept under control by corrosion prevention methods, the values of c = 150-200 were used for continuous flows and c = 200-250 for discontinuous flows. If sediment presence is expected in the flow, then the magnitude of the flow velocity is significantly reduced. For flows in which sediment and corrosion components are present or for continuous flows where the c value is taken above 100, the wall thicknesses of the pipes should be checked periodically [19].

According to [18], if the maximum velocity that will not cause abrasion is computed by Eq.(1) for these experiments, then an abrasion velocity value of 7.71 m/s is reached.

In a study conducted by [20]; a pipe system with an elbow was subjected to multiphase flow both numerically and experimentally and the influence of the flow velocity, the size and amount of solid particles, the angle of impact and the gravitational effects on the formation of abrasion and corrosion were examined. In the experimental setup adopted for the study; a multiphase flow consisting of gas, water and fuel was passed through stainless steel and carbon steel alloy pipes of 2 cm in diameter and 0.5 cm in thickness, and solid particles of 400 microns in diameter with an impact speed of 4 m/s was added to the flow.The influences of abrasion and corrosion were investigated by increasing and decreasing the amount of solid particles and the flow velocity. It was determined that the impingement angle of solid particles to the pipe wall, its size, flow velocity and gravitational acceleration is closely related to the abration degree, and this was shown to be tested with graphics and other measurements.

According to the research results conducted by [20], the secondary flow developed due to turbulence affects the dynamics of solid particles, thereby contributing to the formation of abrasion and corrosion. Due to the changes in gravitational and inertial forces and the effects of gravitational forces on the solid particles, bottom surfaces of the pipe bend have more damages than the upper surfaces with high gas content flows. As the flow velocity and the amount of solid particles increase, abrasion also increases. As a result it was concluded that the flow velocity and the impact angle are the most important factors affecting the behavior of erosion / corrosion while the influence of flow parameters and flow phases on the loss effect of corrosion have found to be limited [20].

3. Equations of Energy Head in Pipe Flow

Bernoulli equation expressed in terms of energy per unit weight of water, or the energy head [21]:

$$\frac{V_1^2}{2g}+\frac{P_1}{\gamma}+h_1=\frac{V_2^2}{2g}+\frac{P_2}{\gamma}+h_2 \tag{2}$$

However, a certain of amount of energy loss in Eq.(2) occurs when the water mass flows from one section to another. Figure 1. shows, schematically,the energy heads at two sections along a pipeline. The difference in elevations between points *a* and *a'* represents the head loss, h_L between sections 1 and 2. The energy relationship between two sections can be written in the following form in Eq (3) [21]:

$$\frac{V_1^2}{2g}+\frac{P_1}{\gamma}+h_1=\frac{V_2^2}{2g}+\frac{P_2}{\gamma}+h_2+h_L \tag{3}$$

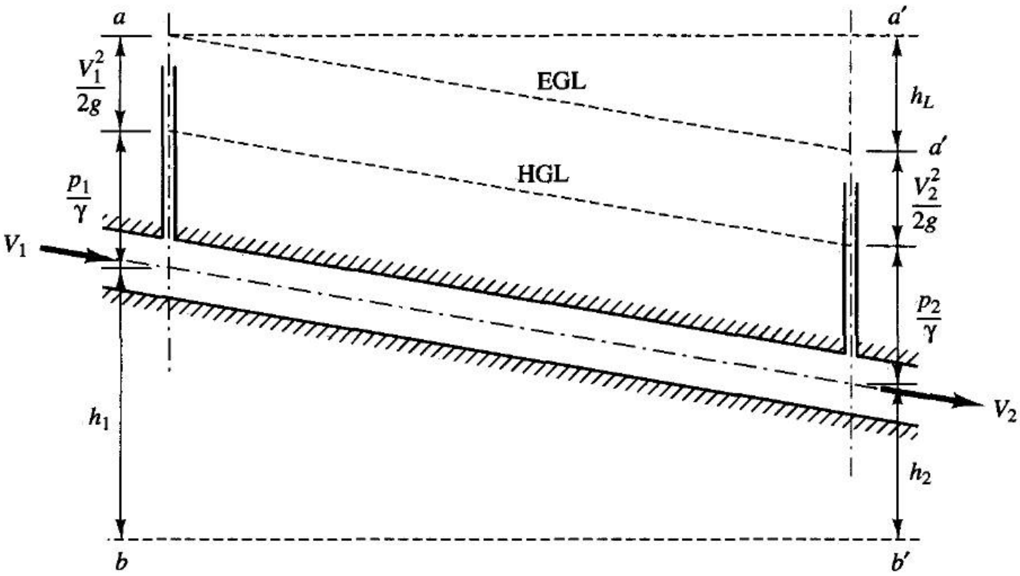

Figure 1: Energy head and head loss in pipe flow [21]

Energy loss through friction in the length of a pipeline is commonly termed the major loss, h_f. (All other losses are referred to as minor.) This is loss of head due to pipe friction and to the viscous dissipation in the flowing water. Most popular pipe flow formula was derived by Henri Darcy [21], and Julius Weisbach. The formula takes the form [21]:

$$h_f=f\left(\frac{L}{D}\right)\frac{V^2}{2g} \tag{4}$$

In laminer flow the friction factor *f* in Eq. (4) can be determined by balancing the viscous force and the pressure force at the two end sections of a horizontal pipe separated by a distance *L*. After some arrangements, friction factor can be formulated as $f=\frac{64}{\text{Re}}$ for laminer pipe flow.

When the Reynolds number approaches higher value, i.e. Re>>2000, the flow in the pipe becomes practically turbulent and the value of *f* then becomes less dependent on the Reynols number but more dependent on the relative roughness, *e/D*, of the pipe. The quantity *e* is a measure of the average roughness height of the pipe wall irregularities and D is the pipe diameter [21].

Based on laboratory experimental data, it has been found that if $\delta' > 1{,}7e$, the effect of surface roughness is completely submerged by the laminar sublayer and the pipe flow is hydraulically smooth. In this case, *von Karman* [21] developed an equation for the friction factor f,

$$\frac{1}{\sqrt{f}} = 2\log\left(\frac{\mathrm{Re}\sqrt{f}}{2{,}51}\right) \tag{5}$$

At high Reynold's numbers, δ' becomes very small. If $\delta' < 0{,}08e$, it has been found that the friction factor, f, becomes independent of the Reynolds number and depends on the relative roughness height. In this case, the pipe behaves as a hydraulically rough pipe, and *von Karman* [21] found that the friction factor f can be expressed as:

$$\frac{1}{\sqrt{f}} = 2\log\left(3{,}7\frac{D}{e}\right) \tag{6}$$

In between these two extreme cases, if $0{,}08e < \delta' < 1{,}7e$, the pipe behaves neither smoothly nor completely roughly. *Colebrook* [21] devised an approximate relationship fort his intermediate range:

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{e/D}{3{,}7} + \frac{2{,}51}{\mathrm{Re}\sqrt{f}}\right) \tag{7}$$

A convenient chart was prepared by *Lewis F. Moody* and is commonly called the *Moody diagram* [21]of friction factors for pipe flow.

4. Experimental Set-up

Experimental setup was constructed at the General Directorate of State Hydraulic Works Water Supply Department within the scope of Research Project within DSI TAKK Department. In this set up a flow of 440 l/s provided by 4 pumps to a pipe system having different diameters with ductile concrete lining was circulated for 3 months at low and high flow velocities. The pipe sytem is a loop sytem in which pipes with 4 different diameters are interconnected. The intention of setting up such a system was to have 4 different flow velocities within the same system [22].

In drinking water supply pipe lines steel, ductile and HDPE pipes are mostly used. The internal lining of steel and ductile pipes is concrete coating which is the most appropriate material health wise. Diameters and the wall thicknesses of the ductile pipes used are given in Table 2, while the general properties of the ductile pipes are given in Table 3 [22].

Table 2. Ductile pipes used in the experiments [22]

Mentioned diameter(mm)	**External diameter(mm)**	**Internal diameter(mm)**	**Thickness (mm)**	**Thickness of interior concrete pavement (mm)**
450	480	452,80	8,6	5
400	429	402,80	8,1	5
300	326	303,60	7,2	4
200	222	201,40	6,3	4

Table 3. Material properties (Ductile Iron Pipe and Fittings, SMS Catalog) [22]

Pipe	Ductile cast iron pipe, Min. Tensile strength 420 MPa
Muff Interior Lining	200 micron epoxy coating
External Lining	200 gr/m^2 ,70 micron bitumen coating on zinc coating, ISO 8179. 400 gr/m^2 70 micron bitumen coating on Zn-Al coating, (optional)
Fittings	Ductile cast iron, Min. tensile strength 420 MPa
Inner Lining	epoxy coating, adequacy report on drinking water concrete lining (optional) – ISO 4179 – centrifugal method
External	200 gr/m^2 70 micron bitumen coating on zinc coating 400 gr/m^2 200 micron epoxy coating on Zn-Al coating

The Reynolds numbers are found to change in the range $1.22x10^6 - 2.78x\ 10^6$ considering the pipe diameters and discharges used in the tests. The turbulent flow is thereby formed in all pipes. Therefore, the minimum distance required to be a uniform flow recommended for turbulent flows [23] is given by:

$$\frac{L_e}{D}=4{,}4x\sqrt{\mathrm{Re}} \quad (8)$$

From Eq. (8) L_e=49,39xD is determined. Length of an edge is taken as L_e=60xD to stay on the safe side of the cycle. The minimum pipe lengths should thus determined as 27 m, 24m, 18m and is 12 m respectively for pipe diameters 450 mm, 400 mm, 300 mm and 200 mm, respectively, in order to obtain uniform flow (Fig.2). Ductile pipes were obtained and the experimental setup was established by taking into consideration of those values. 4 pumps of 50 kW power each were connected first two series with the two pumps each and then these two series were connected in parallel pumping a discharge of 440 l /s flow to a height of H_m=28 m, thereby circulating water from the pipe with diameter Ø 450 mm to Ø 200 mm and then back to water tank. In order to measure the discharge passing through the system as accurately as possible a flowmeter was fitted on pipe of diameter Ø 400 mm (Fig.3). The water velocity in each pipe was determined after discharge reading from flowmeter and using the continuity equation as V=Q/A. Furthermore, measurement pipes of 2 m in length were attached at the end of aforementioned pipe lengths and at the end of each month these pipes were removed from the set up to enable the measurement of the thichness of the concrete lining. Installation of ductile iron pipe connections was first made by bellmouth fittings, however due to the difficulties in re-installation of the measurement pipes to the system pipes, flange connection was later adopted. Two control valves, one located at the output of pumps and the other located in front of the flowmeter were installed to enable air release from the system. Thus, a proper operation of the pumps is enabled giving the opportunity to take accurate measurements from the flow meter. Moreover, two pressure gauges attached one at the beginning and one at the end of the lineto measure the pressure in the system.

Figure 2: Experimetal set-up [22]

Figure 3: Flowmeter [22]

4.1. Experiments and observations

The first measurements were taken by removing measuring pipes before any discharge is pumped into the system. Measurements were taken for a total of 3 times in 3 periods. During the first 30 days period of the experiments, the turbidity values in the analysis conducted on the well water used found to be low (14.6 NTU). By increasing the turbidity values in the second period, the aim was to reach turbidity values of crude water in operation. Of considering that treatment plants already in operation can purify crude water with turbidity value of up to 500-600 NTU, 305 kg of clay and silt material that can stay in suspension were added to the tank to blur the water [22].
Concrete lining measurements are taken from four points around the pipe section, from both inlet and outlet parts of the pipes and at a distance of 40 cm from the inlet of the stationary pipe. Measurements taken by the ultrasonic thickness measuring device has a sensitivity value of 1: 1000 millimeteres. The study herein is aimed to investigate the effects of high flow velocities on the concrete lining of pipes by using concrete lined ductile pipes with four different diameters. Examples of changes on interior concrete in the operational period (before and after the experiment) are given in Fig. 4-7 [22].
At the beginning of experiments, measurements of concrete lining thickness were taken and changes in the thickness of concrete coating were thus determined. Firstly, the thickness measurements in concrete coating were compared with each other to identify whether or not any abrasion occurred during this period due to high flow velocity (Table 4 and Table 5). Then the damages on the concrete coating were examined in order to identify what type of physical factors caused them and finally tried to determine whether any deterioration was present due to the chemical and biological characteristics of water. Physical and chemical analyzes of the water used in this context were performed at DSI TAKK Department and results were assessed.

Table 4. Concrete lining thickness changes in the Ø 200 mm pipe [22]

INTERNAL CONCRETE PAVEMENT THICKNESS (μm)			
Ø200 mm - ENTRANCE			
Measurent Po.	1. Measurement	2. Measurement	3. Measurement
A	4279	3906	3794
B	3964	4080	3981
C	3822	3542	3439
D	3539	3635	3572
Ø200 mm -EXIT			
Measurent Po.	1. Measurement	2. Measurement	3. Measurement
A	3463	3205	3272
B	3478	3358	3389
C	2905	3927	3893
D	4012	2795	2663 EXIT
Ø200 mm –PIPE (in Middle)			
Measurent Po.	1. Measurement	2. Measurement	3. Measurement
A	2391	2485	2497
B	2569	2257	2194
C	2485	2301	2265
D	2571	2560	2428

Table 5. Concrete lining thickness changes in the Ø 450 mm pipe [22]

INTERNAL CONCRETE PAVEMENT THICKNESS (μm)			
Ø450 mm - ENTRANCE			
Measurent Po.	1. Measurement	2. Measurement	3. Measurement
A	6769	3732	3860
B	5581	4827	5077
C	5886	5601	5933
D	5910	5753	5564
Ø450 mm - EXIT			
Measurent Po.	1. Measurement	2. Measurement	3. Measurement
A	4612	4871	4793
B	4460	5916	5663
C	4461	6540	6538
D	3955	5651	5976
Ø450 mm - PIPE (in Middle)			
Measurent Po.	1. Measurement	2. Measurement	3. Measurement
A	3662	3674	3662
B	4225	4307	4285
C	5152	4989	4574
D	4988	5137	5211

As a result of water velocity experiments performed in ductile iron pipes, some damages on the inner concrete lining of the ductile pipes occurred, as seen in Fig.6 and Fig.7. For instance, the initial manufacturing cracks (see Fig. 4 and Fig.5) present on the concrete coating at different locations of the pipes were seen to get enlarged, while places of abrasion and loss of concrete were seen on a thin layer of cement accumulated on the outer surface as in the process of concrete pouring by centrifuged (tossing) method and especially at locations close to pipe entrance and around cracks, formation of partial rust thisckness and change in color of the surface of the concrete to a yellowish color were observed. Causes of the formation of those damages were investigated by using previous conducted studies and interviews with related manufacturers, implementation engineers and academics. Causes of the formation of cracks in the concrete lining may be caused by a number of reasons. For example, cracks may occur on the inner lining of the pipe due to the external factors (such as temperature differences etc.) because of the difference in elasticity of the pipe lining material from the elasticity of the concrete used in the inner lining of the pipe. Another reason for these cracks is thought to occur due to the non-fulfillment of the concrete curing conditions during manufacturing of the concrete. Because those cracks are longitudinal cracks, which are likely shrinkage cracks that occured during concrete curing. Moreover, it is likely that the pipes would be exposed to tensile stress during transportation of the manufactured pipes from factory to the location where the field experiments were conducted and during assemble of the pipe system. Since the inner lining concrete is very suitable to cracking and breaking, it can be considered that the circular cracks of the aforementioned ones to be formed as a result of exposure to tensile stress. Although the longitudinal cracks on the inner lining of the pipes were observed frequently, the same can not be said for the circular cracks.

Figure 4: Interior concrete lining of the pipe from factory,[22]

Figure 5: Concrete lining from factory,[22]

Figure 6: Inner concrete lining after three months test (Ø400) V=3.45 m/s, [22]

Figure 7: Inner concrete lining after three months test (Ø200) V=13.81 m/s,[22]

According to the observations, it was conluded that the water in the pipe penetrated to the concrete lining through cracks present in the coating, reaching up to the ductile material where corrosion started on the ductile pipe extended to the concrete surface through the same cracks and thus forming a rust layer. From the interviews and information exchanges with manufacturers and construction engineers working on site it was concluded that during the preparation of the inner lining of the concrete the additives (AGAPOL) used only enhanced adhesion and accelerated hardening of the concrete whilst not any measurements were taken to evaluate whether it has any concrete strength-enhancing feature or not. Properties of the additive (AGAPOL) can be found from [24].
According to the information obtained from the manufacturer regarding to the properties of the internal concrete and to the ISO 4179 standards, it was noted that the 28-day compressive strength of the concrete should be in the range of 52-55 MPa, so that this value corresponding to the concrete of C50 class having a low slump value, while according to the standards the maximum crack width allowed to occur in the concrete is stated to be a maximum of 1.5 mm.
According to the results of chemical analysis of the well water that was used in the concrete during experiments, not any findings present in the water were found to cause any damages to the concrete. The pH level of water was found to be 8.58 and chemicals such as sulfate, ammonium, magnesium, etc. were found to be below the limit values. It was therefore concluded that the reason for coloring of the concrete, cracking, falling and rusting was not originated from the chemical properties of the water.
Within the scope of this study, ductile pipes that have been in practice for many years in the drinking water supply lines in Ankara by ASKİ were examined [22]. The damages observed on the concrete lining of the ductile pipes that were taken out of service for any reason by ASKİ were compared with the damages caused on the concrete lining observed in the experiments of this study. Comparisions showed that the inner surface layer of the concrete pipes that are used by ASKİ changed color without any large degree of cracks or concrete losses on the inner lining [22]. However, no information about the durations of the pipes being in operation, for how long they have been out of service or the properties of the water they carried was avaibale.Though this prevents a reasonable comparison of the experimental results with those obtained from the pipes taken out of service from a scientific point of view, they were thought to be in service for 10 – 15 years and have been in the open for quite a long time, though their interior concrete lining was found to be in better shape than the pipes used in the experiments.
Another factor that causes abrasion on concrete surfaces that are in contact with water due to flow velocity is cavitation. Cavitation is the sudden evaporation of water in areas where the pressure falls below vapor pressure [24]. When the water vapor bubbles move to an area with a higher pressure, they vigorously collide with each other and explode resulting in cavitation. This can give a fairly large damage to the structure in that area. Flow velocity is also a factor in the formation of cavitation. Since the flow velocities encountered in the experiments are (2.73 m / s - 13.81 m / s) higher than the design velocities (0.5 m / s - 3.0 m / s) formation of cavitation is considered to be among the reasons that caused abrasion on the inner concrete coating of the pipes. However, since the conditions that may cause cavitation are known earlier, necessary measures against cavitation were taken when the experimental setup was designed. Cavitation is therefore not considered as a reason for abrasion. However, it should be kept in mind that the possibility of small air bubbles transported in the flow could still make some damages to the concrete lining even it is very small.
Furthermore, when the cracks formed in the inner concrete lining are considered, the stress occurring along the pipe wall also considered to be effective. Two types of stress along the pipe wall, namely longitudinal and tangential stress, form. In particular, for pipes with the ratio of the radius of the pipe to the wall thickness are greater than 10 ($r/t \geq 10$) the stresses would be directly proportional to the radius and the internal pressure while it is inversely proportional to the wall thickness [25]. While those tangential stresses caused longitudinal cracks, the longitudinal stress causes cracks in the

tangential direction as well. Therefore, the amount of longitudinal cracks on the inner concrete coating of large diametered pipes being more than the amount of longitudinal cracks of small diametered pipes shows that especially tangential stresses are directly related to the radius of the pipe.

5. Conclusions

When the experimental procedure is analyzed, it is observed that same amount of damage as mentioned above is perceived approximately in all pipes independent of the pipe diameter and/or flow velocity. As the thicknesses of concrete coating presented in Table 4 and Table 5 are examined, it is seen that the rate of change is computed by using the maximum difference between the initial and final measurements of thicknesses and the change in the concrete lining thickness is to be in the range of 4-5% at most. However, the changes in thickness in all pipe diameters is found to be approximately in the same proportions, thus the results are independent of the flow velocity criteria used in the experiments.

In this study, experiments were conducted in a closed pipe system to identify the damages that may develop at high flow velocities and by taking into consideration that the water used in the experiments have similar values with those of crude water, the abrasion on the inner concrete lining is found to be independent of the flow velocity criteria adopted in the experiments where the abrasion effects due to high flow velocities found to be at negligible levels [22]. Therefore, the maximum design velocity of 3 m/s which is accepted as the design criteria adopted in potable water systems could be increased to a value of 14 m/s without considering the abrasion possibility on the inner concrete lining with the elimination of other factors that could cause abrasion on the concrete. However, this issue should be determined by taking into account the water hammer impacts, cavitation and energy losses and an optimum solution should be reached.

It is therefore suggested that in future experiments all these factors should be taken into consideration in a similar manner but with much longer experimental durations and the potable water supply systems already in operation should be monitored for comparison of the experimental findings.

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Notations

c	empirical constant
D	pipe diameter
e	average roughness height of the pipe wall irregularities
f	friction factor
g	acceleration of gravity
g_m	density of gas / liquid mixture
gr	gram
h	elevation
h_L	head loss
Hr/yr	hour/year
l	liter
L	pipe length
Le	distance required to achieve uniform flow
NTU	turbidity units (Nephelometric Turbidity Unit)

P	Pressure
pH	acid and alkalinity unit
Re	Reynolds number
s	second
Q	discharge
V	velocity
v_e	wear(abrasion) rate of flow
w/c	water/cement ratio
µm	micrometer
δ'	the thichness of the laminar sublayer
γ	specific weight

Abbreviations

ASKİ	Ankara Water and Sewerage Administration
API RP 14E	American Petrolium Institute Recommended Practice for Design and Installation of Offshore Production Platform Piping Systems
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
AWWA	American Water Works Association
DSİ	The State Hydraulic Works
TAKK	Technical Scientific Research Quality Control Department (DSİ)

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