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EFFECT OF TIME ON PIPE ROUGHNESS

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ABSTRACT: This paper presents the results of laboratory measurements conducted on pipes of different materials to investigate the increase of pipe roughness with the age of pipe. The pipe roughness after time t years would be simply defined as half the average decrease in the effective pipe diameter, $0.5(D_0-D_t)$, where D_0 is the pipe original diameter at time t equal to zero and D_t is its diameter at time t. The samples of pipes tested varied in age from zero to 50 years. Pipe samples included lined and unlined Cast Iron, Steel, Reinforced Concrete, Asbestos Cement, and Plastic. Two sets of samples were tested. The first set was for pipes used for filtered water and the second included those used for raw water.

It was found that the pipe roughness increased with time in a parabolic trend. The effect of time on pipe roughness was found to be larger in case of pipes prone to rust like Cast Iron and Steel pipes. Plastic pipes showed minimum response to time due to the plastic mixture nature, plastic smoothness, and plastic resistance to rust. After fifty years, the absolute roughness of the PVC pipes was only about 1.5 times its original value while that of steel pipes was about forty times its original value. Also, pipes of the same material were affected more if used to carry raw water than the case of filtered water. The value of the absolute roughness in raw water relative to that in filtered water was found to change with pipe type and time. After fifty years this value was equal to 10 for PVC pipes while for other types was in the range of 2 to 3. Curves and statistical equations were introduced for design purposes.

1. INTRODUCTION

Pressurized pipe networks have been widely used in engineering practice. Water supply systems, pressurized irrigation systems, hydropower transmission systems and the like are practical examples of these pressurized networks. In planning and design of these systems, it is important to know their hydraulic performance not only when the pipes are new but also all along the life time of these systems. It is practiced in pipe networks that the carrying capacity of pipes decreases with time. For the pipe to regain its original capacity, differential head should be increased to allow for the increase in the friction head loss due the reduction of the pipe diameter. This is caused by the increase in the absolute roughness of the inner pipe surface with time. Hence, to keep these pipe systems as efficient as they were originally, variation of the absolute roughness of these pipes with time should be determined.

(Echavez 1997) examined 2-inch diameter pipes of ages between 15 and 50 years made of galvanized iron and copper. He reported that the copper pipes were not affected by time whereas the galvanized ones were severely affected. His experimental results showed that the variation of pipe roughness with time was parabolic in shape. (Massimo and Giuseppe 1999) introduced a new approach for calibrating hydraulic network models using a nonlinear optimization algorithm and a network solver and applied their method to some sample networks. (Rhodes and Senior 2000) conducted finite volume numerical study to

locate the rough wall origin in both shallow and deep pipe flows where the traditional logarithmic approach was not applicable. (Walter and Chaudhry 2001) presented an energy dissipation model for the computation of unsteady friction losses in cases of transition and fully rough pipes. They used a mixing-length turbulence model, used previously for small pipes, to account for the effect of roughness.
The effect of water quality on the roughness of pipes is also of great importance. (Song et al. 1998) studied experimentally the effect of bed load movement on the flow friction factor. They found that the ratio of friction factor to the so-called clear water friction factor increased with the concentration of bed load.

In the present study, an extensive set of experimental data was analyzed to investigate the relation between time and absolute roughness for some of the well-known types of pipes. Analysis was carried out for the two cases of water conditions; filtered water and raw water. The results of such an analysis are presented in this paper with the hope that this work will facilitate the design of successful pipe systems.

2. THEORETICAL CONSIDERATIONS

The head loss that results from the wall shear in a developed flow is related to the friction factor f by the well-known Darcy-Weisbach equation.

[1] $$h_L = f\frac{L}{D}\frac{V^2}{2g}$$

where h_L is the head loss due to friction over a length L, V is the average velocity, D is the pipe diameter, and g is the acceleration due to gravity. The friction factor f depends on the various quantities that affect the flow, written as

[2] $$f = \phi_1(\rho, \mu, V, D, k)$$

where k is the average wall roughness height and accounts for the influence of the wall roughness elements. Using the Pi theorem, it can be shown that

[3] $$f = \phi_2\left(\frac{\rho VD}{\mu}, \frac{k}{D}\right)$$

where $\rho VD/\mu$ is the Reynolds number R and k/D is the relative roughness. Because of the extreme complexity of naturally rough surfaces, most of the advances in understanding the basic relations have been developed from experiments on artificially roughened pipes. (Moody 1944) has constructed one of the most convenient charts for determining friction in clean, commercial pipes.

For a given wall roughness, measured by the relative roughness k/D, there is a sufficiently large value of R above which the friction factor is constant, thereby defining the completely turbulent regime. In this regime, the average roughness element size k is substantially greater than the viscous wall layer thickness, so that viscous effects are not significant. The resistance to the flow is produced primarily by the drag of the roughness elements that protrude into the flow. The following empirical equation represents the completely turbulent zone in Moody diagram.

[4] $$\frac{1}{\sqrt{f}} = -2\log\frac{k/D}{3.71}$$

For the smaller relative roughness k/D values, it is observed that, as R decreases the friction factor increases in the transition zone and eventually becomes the same as that of a smooth pipe. The roughness elements become submerged in the viscous wall layer so that they produce little effect on the main flow. The following equation represents the transition zone.

[5] $$\frac{1}{\sqrt{f}} = -2\log\left(\frac{k/D}{3.71} + \frac{2.51}{R\sqrt{f}}\right)$$

If the average roughness element size k is smaller than the viscous wall layer thickness, viscous effects dominate and the pipe becomes hydraulically smooth with no effect of roughness on friction. The following empirical equation represents the smooth pipe flow.

[6] $$\frac{1}{\sqrt{f}} = 2\log R\sqrt{f} - 0.8$$

Selection of the proper value for the coefficient of roughness of a pipe is essential in evaluating the flow through piping systems. An excessive value is uneconomical and results in over sizing of pipes, on the other hand a low value can result in a hydraulically inadequate pipe. The k values in Moody diagram are for new pipes. With age, a pipe will corrode and become fouled, changing both the roughness and the pipe diameter, with a resulting increase in the friction factor. Such factors should be included in design considerations.

3. EXPERIMENTAL ARRANGEMENT AND EXPERIMENTS

Used pipes were collected from many working sites. The nominal original diameter, D_0, for all samples was 100 mm. The ages of the collected samples ranged between zero and 50 years. The fifty years age was chosen to comply with the proposed pipe lifetime as stated in the Egyptian Code of Practice for Pipe Design. The main objective was to study the effect of time on pipe roughness and its influence on the flow characteristics (flow velocity, discharge, head loss, etc.).

In this study, pipe roughness after time t years, k_t, was defined as half the difference between the initial pipe diameter, D_0, and the measured pipe diameter after t years, D_t. Pipe samples collected were all from the common pipe types known in the market. Samples collected included Cemented mortar lined Cast Iron (CCI) pipes, unlined Cast Iron (CI) pipes, Reinforced Concrete (RC) pipes, Asbestos Cement (AC) pipes, Plastic (PVC) pipes, and Steel (S) pipes. For every pipe type, samples were collected of pipes used for raw water as well as filtered water.

Every sample was cut to a length of 0.5 m and was marked with its year of fabrication, its material, and its original roughness set by the manufacturer in the year of fabrication, k_0. Then, every sample was filled with mercury that was chosen to guarantee no adhesion with the interior pipe walls. The mercury filling the pipe was then collected and measured volumetrically using a graduated glass cylinder. The average cross section area of the pipe, A_t, was calculated by simply dividing the measured volume ∇ by the pipe length L (0.5 m). Knowing the pipe cross section area, the diameter D_t was calculated. Finally, the absolute roughness, k_t, was determined.

The set of equations used are as follows

[7] $$A_t = \frac{\nabla}{L}$$

[8] $$D_t = \sqrt{\frac{4A_t}{\pi}}$$

[9] $$k_t = \frac{D_0 - D_t}{2}$$

4. ANALYSIS OF EXPERIMENTAL RESULTS

4.1. Effect of pipe material

Figures 1 and 2 show the experimental data for the variation of the relative pipe roughness k_t/k_0 with relative time, t/T, for every pipe material examined. Figure 1 shows this relation for filtered water while raw water is shown in Figure 2. The value of absolute roughness at time t is k_t, and it was related to the original roughness marked by the manufacturer on the pipe when fabricated, k_0. The time, t, was related to the pipe lifetime according to the Egyptian Code of Practice for Pipe Design, T = 50 years.

A number of interesting observations could be made from a study of Figures 1 and 2. First, for all pipe types, the relative pipe roughness k_t/k_0 increased with relative time t/T. For example, for t/T = 0.4, relative pipe roughness in cases of AC pipes, RC pipes, CCI pipes, CI pipes was approximately the same and the absolute pipe roughness, k_t, was about 3 times its original value k_0. When the pipe systems got older, the effect of time became more severe depending on the type of the pipe. Second, the rate of the relative roughness k_t/k_0 increase increased with time. Third, comparing the experimental data of the different pipe materials for both filtered and raw waters, it was found that PVC pipes had the minimum response to time while steel, S, pipes had the maximum response. The minimum response of PVC pipes to time might be due to the nature and the high factor of homogeneity of the PVC mixture. At t = T = 50 years Figure 1 shows that, while the pipe roughness of PVC pipes was only about 1.5 times its original value, roughness of steel pipes, S, became more than 40 times its original value. The order of the other four pipe materials was AC, CCI, RC, and CI pipes (if arranged from a minimum to maximum response to time). For raw water, Figure 2 shows that pipes may be sorted in three groups. The first group included the PVC and AC pipes and they had the minimum response to time. The middle group included the CCI, RC, and CI pipes and they had a moderate response to time. The third group included only steel, S, pipes which had the maximum response to time. Fourth, rate of increase of the relative pipe roughness k_t/k_0 with time was found to be higher in rust prone pipes than in pipes that don't rust. Fifth, after 50 years, the effect of raw water, compared to filtered water, on pipe roughness was tremendous as pipes in raw water suffered the mutual effect of sediments carried by water as well as rust. For PVC pipes k_t/k_0 increased from 1.5 for filtered water to about 15 for raw water while for steel, S, pipes k_t/k_0 increased from about 40 to 100.

The above discussion shows that considering time effect on pipe roughness while designing a pipe system carrying filtered or raw waters, would be essential.

4.2. Effect of transmitted water quality

Figures 3 to 8 show the variation of k_t/k_0 with t/T for filtered as well as raw water for each individual pipe. A review of Figures 3 to 8 reveals the fact that, with time, raw water affected pipe roughness more than filtered water due to the existence of sediments in raw water which accumulate on the pipe inner walls with the aging of pipe. This complies, in a way, with the results of (Song et al. 1998) who noticed the increase of pipe roughness due to bed load. The value of the absolute roughness in raw water relative to that in filtered water, k_R/k_F, was found to change with the pipe material and time. At t = 50 years, the value of k_R/k_F was equal to about 10 in case of PVC pipes while for other pipes it was in the range of 2 to 3. This shows that effect of raw water on pipe roughness was worst for PVC pipes.

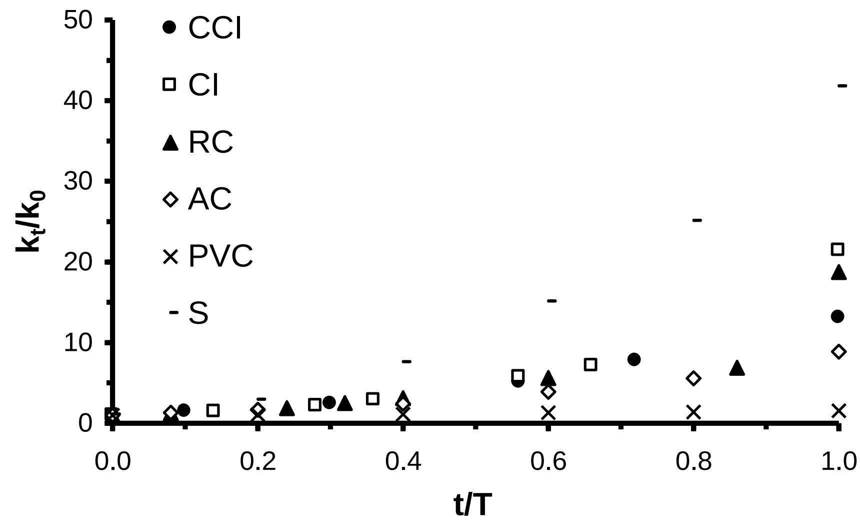

Fig. 1 Variation of relative pipe roughness k_t/k_0 with relative pipe age t/T (Filtered Water)

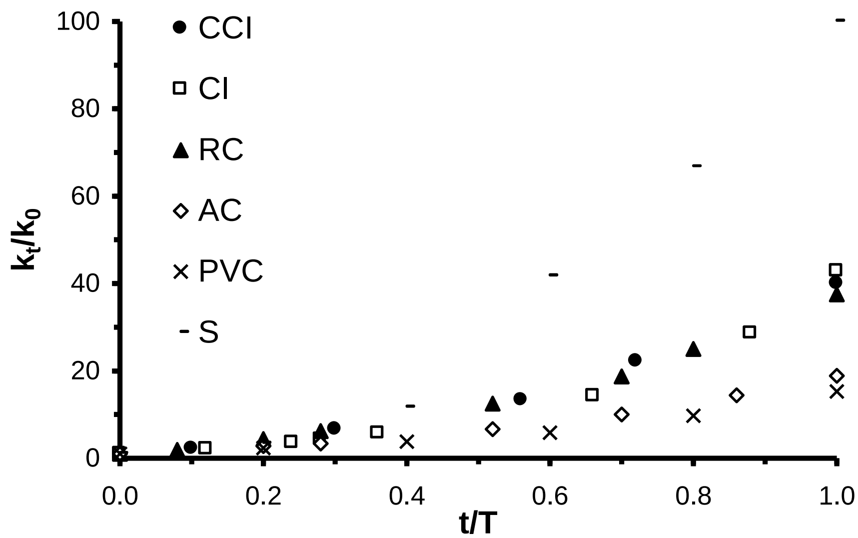

Fig. 2 Variation of relative pipe roughness k_t/k_0 with relative pipe age t/T (Raw Water)

4.3. Statistical analysis and trend function

As mentioned before, Figures 3 to 8 show the variation of the relative pipe roughness, k_t/k_0, with relative time, t/T. Each figure introduces this relation for some examined pipe material in the two cases of filtered and raw waters. In all figures, the symbols show the experimental data while the solid and dashed lines show the best fit relationship.

Statistical analysis showed that a parabolic function would best describe the relation between k_t/k_0 with t/T with a relatively high correlation coefficient, r, for the two cases of filtered and raw waters. This complies with the results of (Echavez 1997) who also suggested a parabolic function for the variation of pipe roughness with time. The parabolic function suggested by this study may be written as

[10] $$\frac{k_t}{k_0} = C_1\left(\frac{t}{T}\right)^2 + C_2\left(\frac{t}{T}\right) + C_3$$

where C_1, C_2 and C_3 are coefficients that were found to vary with the pipe material and water condition whether filtered or raw. The values of these coefficients together with the value of the correlation coefficient for every case are given in table 1.

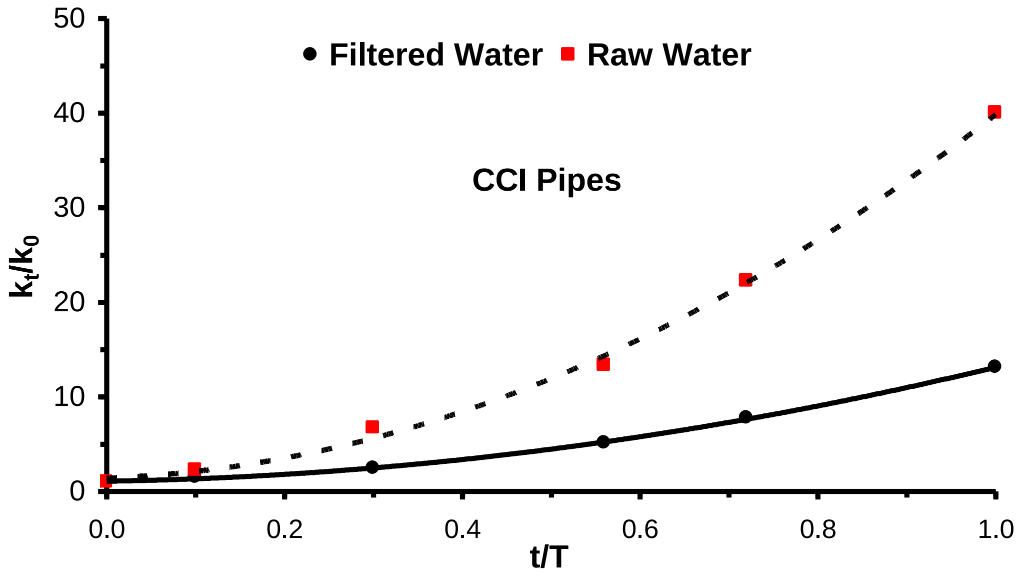

Fig. 3 Variation of relative pipe roughness k_t/k_0 with relative pipe age t/T, for CCI pipes

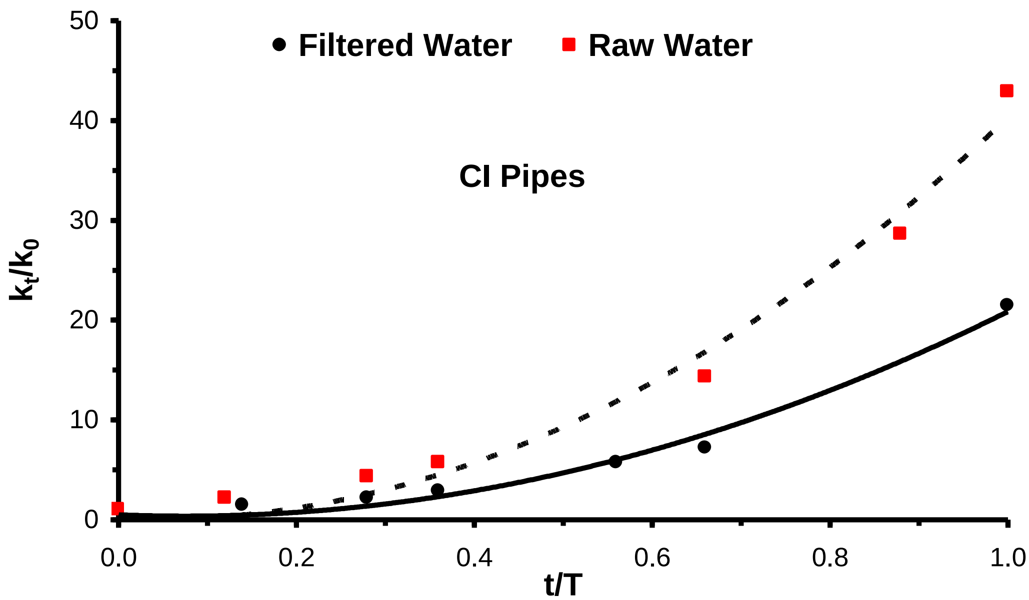

Fig. 4 Variation of relative pipe roughness k_t/k_0 with relative pipe age t/T, for CI pipes

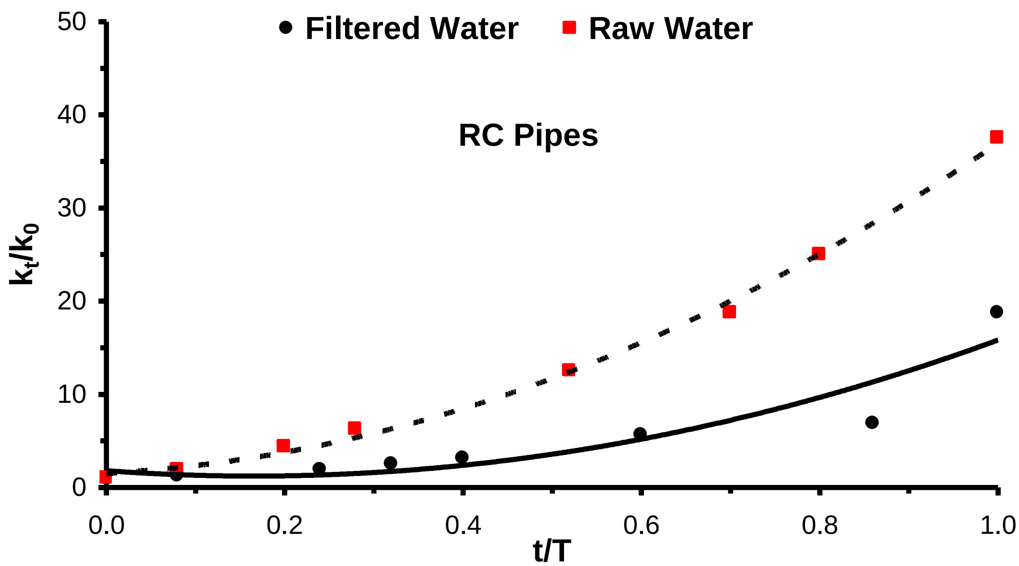

Fig. 5 Variation of relative pipe roughness k_t/k_0 with relative pipe age t/T, for RC pipes

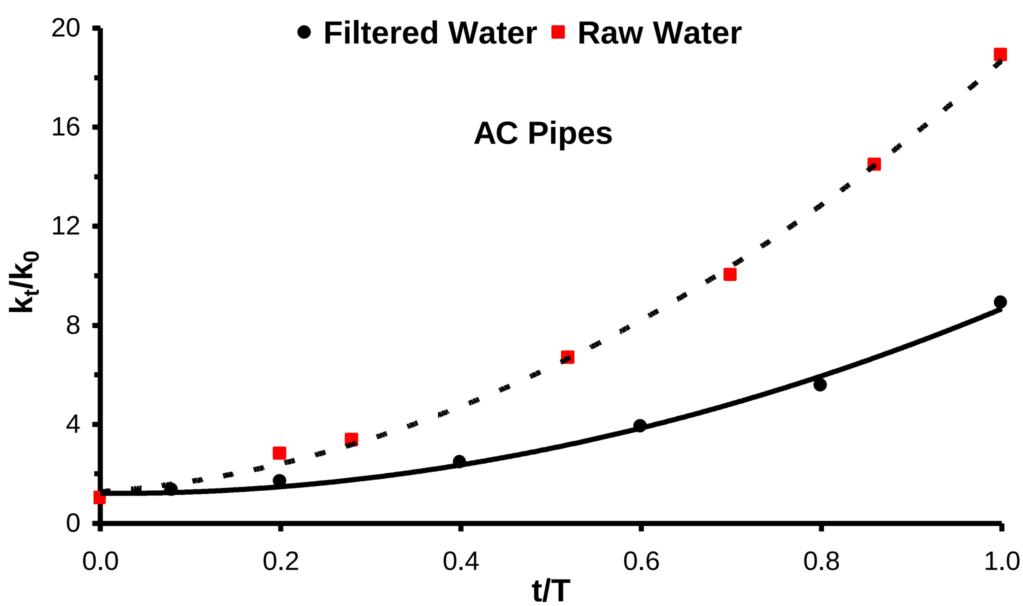

Fig. 6 Variation of relative pipe roughness k_t/k_0 with relative pipe age t/T, for AC pipes

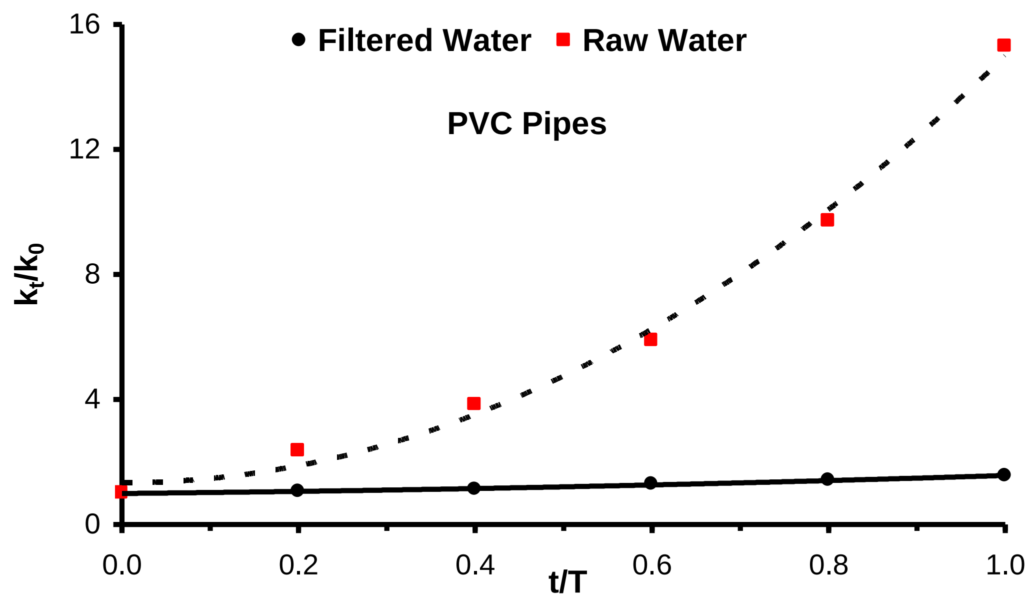

Fig. 7 Variation of relative pipe roughness k_t/k_0 with relative pipe age t/T, for PVC pipes

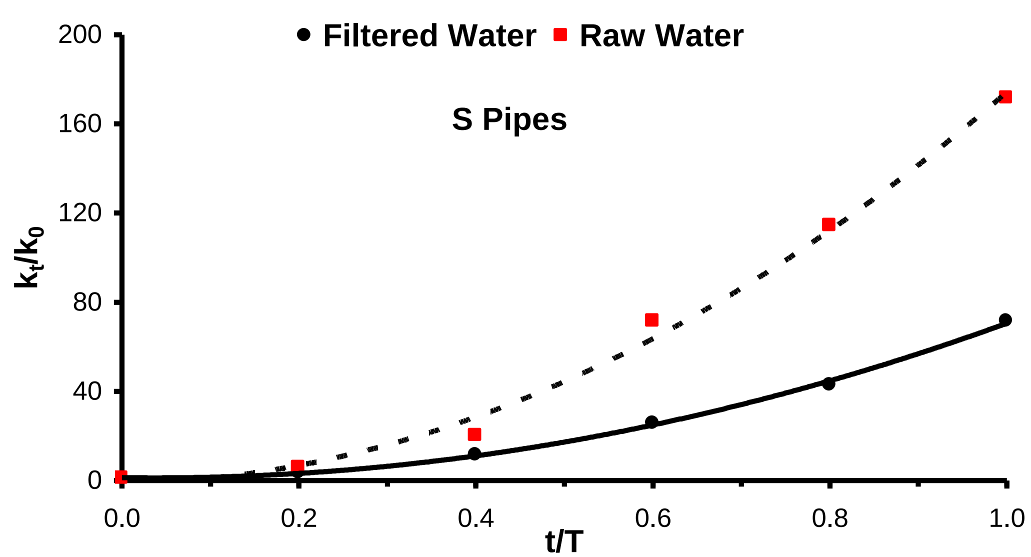

Fig. 8 Variation of relative pipe roughness k_t/k_0 with relative pipe age t/T, for S pipes

Table 1 Values of C_1, C_2, and C_3 and r^2 for all studied cases:

Type of Pipe	Water transmitted	C_1	C_2	C_3	r^2
CCI	Filtered Water	10.533	1.523	1.084	0.999
CCI	Raw Water	34.744	3.701	1.400	0.998
CI	Filtered Water	23.920	-3.558	0.500	0.986
CI	Raw Water	43.602	-3.414	0.100	0.975
RC	Filtered Water	20.962	-6.933	1.801	0.873
RC	Raw Water	30.134	5.312	1.517	0.997
AC	Filtered Water	7.627	-0.171	1.211	0.994
AC	Raw Water	14.666	2.755	1.272	0.998
PVC	Filtered Water	0.302	0.274	0.993	0.991
PVC	Raw Water	13.655	0.000	1.336	0.994
S	Filtered Water	74.681	-5.436	1.311	0.999
S	Raw Water	168.050	7.564	-1.424	0.994

4.4. Limitations

Due to the nature of the present research work that was time dependent as pipes with variable ages were examined, the authors find it important to point out the limitations to the research results especially when used in design purposes.

First, it should be noted that, with time, the material from which pipes were fabricated changed a lot despite the fact that the said pipe type is the same. This was very much clear in case of PVC pipes where much development in the material and pipe fabrication technology were introduced to PVC pipes in the last 50 years.

Second, as pipes were of different ages and were collected from different places, raw waters transmitted by them were not necessarily of the same physical and chemical characteristics. Same applies to filtered waters.

However, these limitations were not to be overcome as this would imply the consistency of the experimental setup (pipes and water quality) for more than 50 years.

5. CONCLUSIONS

An experimental study was conducted to investigate the effect of time on pipe roughness for different pipe materials used to transmit filtered water and raw water. Pipe types tested were Cemented mortar lined Cast Iron (CCI) pipes, unlined Cast Iron (CI) pipes, Reinforced Concrete (RC) pipes, Asbestos Cement (AC) pipes, Plastic (PVC) pipes, and Steel (S) pipes. For every pipe type, samples were collected of pipes used for filtered as well as raw waters. Samples tested varied in age from zero to fifty years.

Based on the laboratory study and bearing the limitations of the study in mind, the following conclusions could be made. For all pipe types, the pipe roughness increased with time. PVC pipes had the minimum response to time while steel S pipes had the maximum response to time. After fifty years the absolute roughness of the PVC pipes was only about one and half times its original value while that of steel pipes was about forty times its original value.

Raw water appeared to have more severe effect on pipe roughness than filtered water. The value of the absolute roughness in raw water relative to that in filtered water changed with pipe type and time. After fifty years, this value was equal to 10 for PVC pipes while for other types was in the range of 2 to 3.

Statistical analysis showed that the pipe roughness increased with time in a parabolic trend. Coefficients of the parabolic equation along with the correlation coefficient changed with pipe material and water condition, whether filtered or raw. Values of these coefficients were determined and presented.

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