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Pipe Materials Selection for Water Networks

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Abstract— *Currently different pipe materials are used in a variety of applications in municipal water networks such as DI, ST, PSC, GRP, HDPE, and uPVC. Recently, many problems have emerged because of the use of an inappropriate pipe material in a certain application. The objective of this paper is to develop an algorithm that can be used for the selection of the most appropriate pipe material in a certain application of water networks taking into consideration design parameters, local experience, environmental conditions, construction, operation, maintenance, and financial evaluation. Technical evaluation considers structural properties, environmental conditions, construction, operation, and maintenance. The impact of these parameters varies from project to another depending on project severity factor. Financial evaluation considers the cost of supply and installation for all the selected pipes*.

Keywords— *Ductile Iron, Steel, Pre-Stressed Concrete, Glass Reinforced Plastics, High- Density Polyethylene, unPlasticized Polyvinyl Chloride, Pipe Selection, Water Networks*.

I. INTRODUCTION

Nowadays, the most commonly used pipe materials in water networks are Ductile Iron (DI), Steel (ST), Pre-Stressed Concrete (PSC), Glass Reinforced Plastic (GRP), High-Density Polyethylene (HDPE), and unPlasticized Polyvinyl Chloride (uPVC). Each pipe material has its own characteristics, advantages, and limitations which may or may not make it suitable for a particular application. But recently many problems have emerged because of the use of an inappropriate pipe material in certain application, resulting in cracks, explosions, breakage and frequent maintenance which led to service unreliability and disruption.

The objective of this research is to develop an algorithm that can be used for the selection of the most appropriate pipe materials in a certain application of water networks taking into consideration design parameters, local experience, environmental conditions, construction, operation, maintenance, and financial evaluation.

Trew et al. (1995) (1) presented a selection manual for pipe materials, that discussed characteristics of different pipe materials used in water networks, advantages and limitations, pipe sizes, working pressures, installation techniques, bedding requirements, repair methods, joints, and corrosion protection requirements for each pipe. A technical selection chart is presented for case studies, some pipe materials are selected and other pipe materials are excluded. Cost comparison is conducted among the selected pipe materials and the cheapest pipe material is selected.

Alferink, (1998) (2) reported that the pipe installation is the most important parameter affecting deflection. The depth of cover comes second in importance order, followed by pipe stiffness.

The failures of the buried pipes can occur in various forms and by different causes. Rajani and Kleiner, (2001) (3) presented three major causes for physical failure in pipelines:

- Pipe properties, material type, pipe-soil interaction, and the quality of installation.
- The internal loads due to operational pressure and the external loads due to traffic loads, soil overburden, frost loads, and the third-party interference.
- Material degradation due mainly to internal and external chemical, biochemical and electrochemical environment.

El Khadem, (2001) (4) presented analysis for the main problems that are observed repeatedly when GRP pipes are used and presented the solution for each problem to prevent from recurring in future projects. These problems were use of Gibault joints, use of gravel and stones as backfill in high water table areas, using GRP-coated flanged steel fittings with GRP pipes, and connection of GRP pipes to concrete structures without using short flexible pipes.

Drew et al. (2002) (5) discussed many advantages for using HDPE pipes in water networks and introduced solution for the problem of water loss by using welded HDPE pipes, which provide a leak free joints, HDPE pipes do not corrode or rust and it has a high resistance to build up or scale and does not rupture at sub-zero temperature conditions.

Abdel-Razik, (2004) (6) discussed the different factors that affect deflection of GRP pipes. Sensitivity analysis is implemented to evaluate the relative importance of each factor and concluded that in order to ensure that deflection does not exceed limit of 5%, the following parameters should be taken into consideration: backfill soil type, backfill soil compaction, cover depth, native soil type, pipe stiffness, and trench width.

Merah et al., (2006) (7) conducted fatigue crack propagation tests on HDPE specimens at temperatures of -10, zero, 23, 40, and 70◦C at frequencies of 0.1, 1, and 50 Hz. The analysis showed that fatigue crack growth rate for HDPE increased at temperature up zero◦C, when the temperature increased the crack propagation resistance and total life reduced, the change of temperatures from -10 to zero◦C had no effect on crack growth rate. Fatigue crack propagation rate decreases with the increase of loading frequency because of localized crack tip heating.

Gargari, (2006) (8) discussed the most commonly used pipe materials in the water networks of the large European cities (GRP, uPVC, ST, DI and PSC pipes). Gargari presented a case study of transmission line with inner diameter 2000 mm and describing the procedure followed to select the best pipe types to be used by visiting and studying several water networks in European cities. The final decision was exclusion

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of GRP and uPVC pipes while PSC, DI, and ST pipes were selected for the project.

Farshad, (2006) (9) presented the main causes of failure in flexible pipes representing in buckling, fracture, weather conditions, voids, fatigue and corrosion, and the clogging of the pipe system.

Wols et al. (2014) (10) reported that differential settlement may damage pipe network. A probabilistic model is proposed for pipe failure and implemented in GIS environment.

II. METHODOLOGY

The methodology followed for the selection of the most appropriate pipe material to be used in a certain application of water networks is conducted in four steps and presented in Fig. (1).

Step (1) - Exclusion Diagram

The exclusion diagram is developed to choose the acceptable pipe materials that can be used for a certain application, taking into consideration as presented in Table (1):-

- Design parameters (diameter and pressure)
- Local experience

Step (2) - Technical Evaluation

Technical evaluation is conducted among selected pipe materials, taking into consideration:-

- Structural Properties: including lifetime, resistance to internal pressures, resistance to external pressures, and resistance to shock loads.
- Environmental Conditions: including resistance to soil corrosion, resistance to groundwater corrosion, resistance to internal corrosion, and resistance to stray currents corrosion.
- Construction, Operation, and Maintenance: including route width, need for specific bedding, need for thrust blocks, ease of jointing, ease of leakage detection, ease of repair, and weight.

Each pipe material takes a score from 1 to 5 based on technical evaluation, as presented in Table (2).

Table (3) presents the proposed weighting factor and score for each technical criterion. It is noted from the general technical evaluation that HDPE is the best pipe material followed by DI, PSC, uPVC, ST, and then GRP pipe. However, this conclusion applies only when all technical criteria are taken into consideration, i.e. worst technical conditions. For a specific project, the score of each pipe material may vary depending on the severity of each technical criterion as discussed below.

Technical Evaluation for a Specific Project

The weighting factors and scoring may vary from case to another according to the specific characteristics of the project under study.

For example, considering the internal pressure parameter, uPVC pipe takes a score 1 of 5 if the working pressure is 16 bars, but would take a higher score if the working pressure is 6 bars.

The following formula is applied to estimate the adjusted score of each pipe material in a specific project.

$$S_{adj} = 5 - (5 - S)X$$

Where,

- S_{adj}: Adjusted technical score for each pipe material in a specific project
- S: General technical score for each pipe material as presented in Table (3)
- X: is a Project Severity Factor ranging from 0 to 100%, presenting the severity of each technical parameter under specific project conditions, as presented below in Fig. (2).

- X = Project lifetime /50 year
- X = Working pressure / Maximum working pressure of pipe (%)
- X =Percent of route under heavy traffic load (%)
- X =Percent of route exposed to shocks (%)
- X =Percent of route with aggressive soil (%)
- X =Percent of route with groundwater above pipe (%)
- X =Percent of route exposed to stray currents (%)
- X =Percent of route with insufficient pipe trench (%)
- Need for thrust blocks (X = No. of fittings per km/20) (%)

Step (3) - Financial Evaluation

Financial evaluation is conducted among pipe materials resulting from the exclusion diagram. Pipe material selection is normally shall be based on a comparison of the cost of supply and installation of selected pipe materials. In the current study, financial comparison is introduced as a relative cost parameter as presented in Table (4).

DI pipe is the most expensive pipe material followed by PSC, ST, GRP, HDPE, and then uPVC. The proposed relative cost may vary from project to another depending on pipe availability in the market, cost of supply & installation, etc.

Fig. (3) shows a comparison among general technical and financial scores of pipe materials.

Step (4) – Overall Evaluation

Technical and financial evaluations are merged for the final selection of the most appropriate pipe material for a certain application. There are two commonly applied methods for merging technical and financial evaluations as follows:

Method (1) - Using a Specific Merging Ratio

A specific merging ratio is proposed to calculate the general pipe score as follows:

$$S_G = S_T \times W_T + S_F \times W_F \text{ , and } W_T + W_F = 1.0$$

Where:

- S_T, S_F, S_G are technical, financial, and general score for pipe material (%).
- W_T and W_F are the specific merging ratio of technical and financial scores.

In water supply projects technical evaluation is commonly given a higher weighting factor than financial evaluation, most commonly with range W_T = 60-70% and W_F = 40-30%.

Fig. (4) shows merging the general technical and financial evaluations at different merging ratios. It is noted that pipe ranking varies significantly depending on the proposed merging ratio.

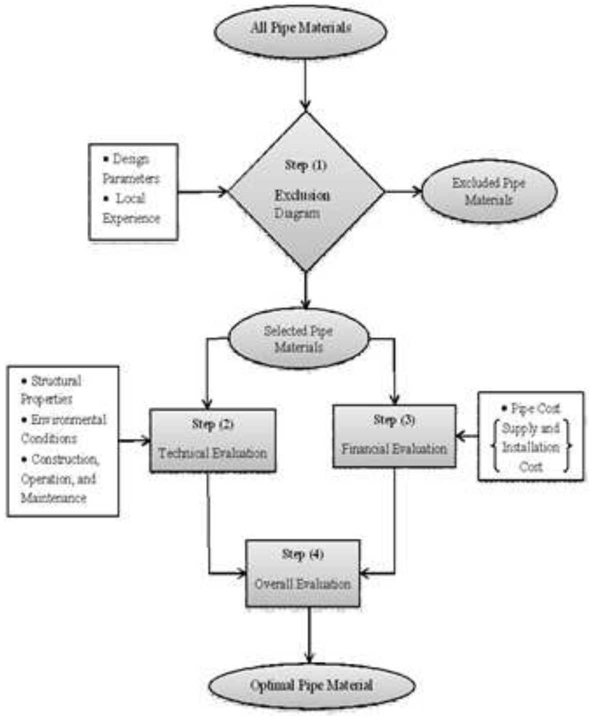

Fig. (1) - Pipe Selection Flow Chart

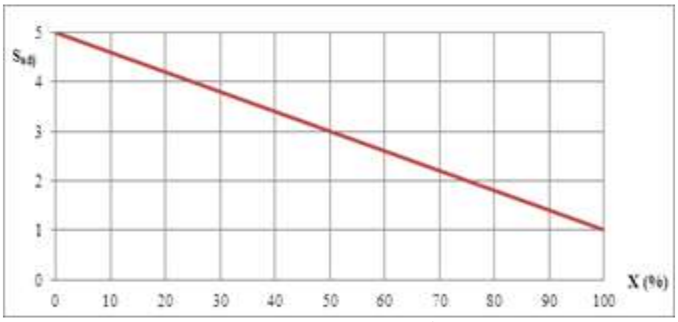

Fig. (2) – Relation between S_{adj} and X for Pipe Materials

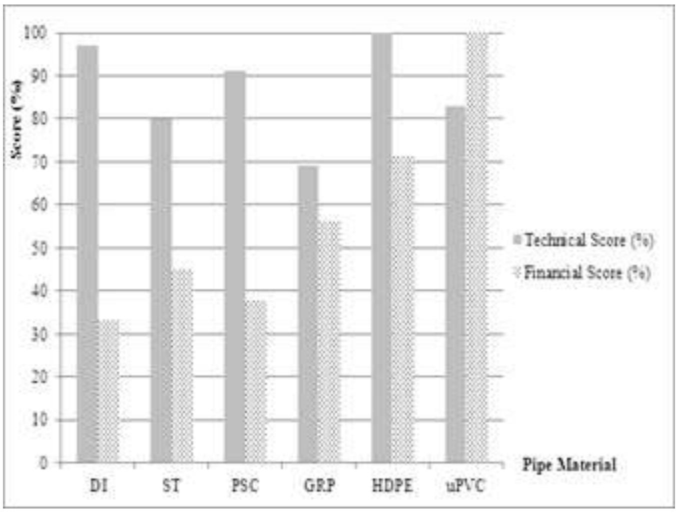

Fig. (3) - Technical and Financial Comparison among Pipe Materials

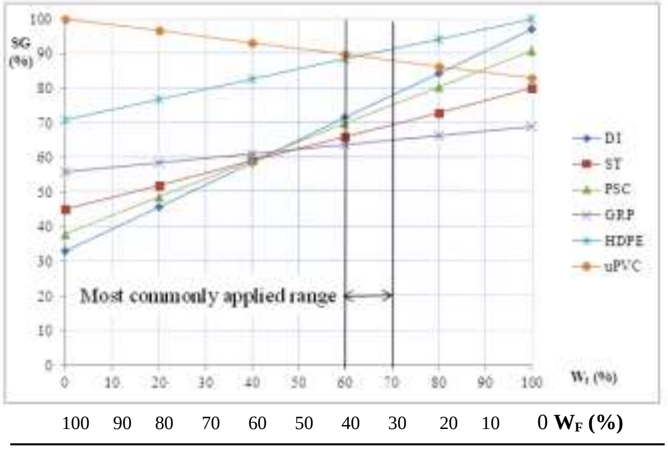

Fig. (4) - Pipe Material General Score at Different Merging Ratios

Criteria	All Pipe Materials	Exclusion
Diameter (mm)	600 1000	uPVC, HDPE
Pressure (bar)	16 30	uPVC, HDPE
Local Experience	All pipes are accepted	None
	DI, ST, PSC, GRP	

Fig. (5) – Exclusion Diagram for Case Study

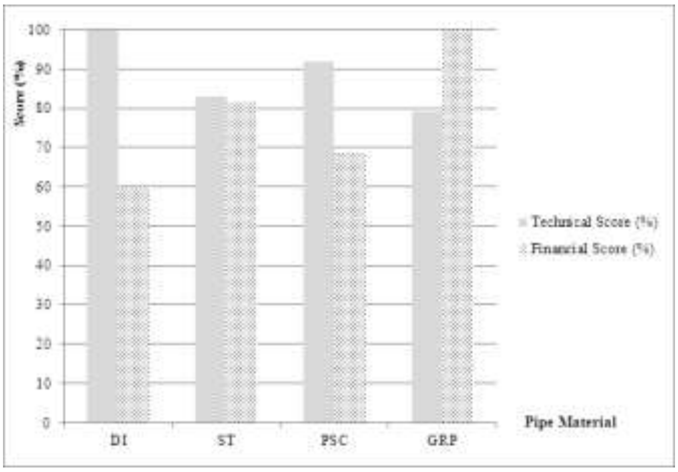

Fig. (6) -Technical and Financial Comparison among Pipe Materials

Table (5) presents the results of Method (1) application. It is noted that for the most commonly applied range of W_T = 62 to 82% and W_F = 38 to 18%, HDPE is the optimal pipe material, followed by uPVC, DI, PSC, ST, and GRP pipes.

Method (2) - Using Adjusted Financial Score

The financial score is adjusted by dividing its value by the technical score, as presented in Table (6).

Table (1) - Exclusion Diagram Parameters

Parameter	Range			Causes for Exclusion
Diameter (mm)	< 600	600 - 1000	> 1000	Pipes are not available with these diameters in Egypt.
	Exclude PSC	Exclude HDPE, uPVC	Exclude DI, HDPE, uPVC	
Pressure (bar)	< 16	16 - 30	> 30	Pipes cannot withstand these pressures.
	None	Exclude HDPE, uPVC	Exclude DI, HDPE, uPVC, GRP,PSC	
Local Experience				Frequent failure and difficulty of installation and maintenance. Unskilled labors.

Table (2) - Technical Evaluation Scoring System

Description	Score
Best	5
Good	4
Medium	3
Bad	2
Worst	1

Table (6) presents the results of Method (2) application. It is noted that Method (2) gives higher priority to financial score than technical score. Therefore, uPVC is the optimal pipe material, followed by HDPE, GRP, ST, PSC, and DI pipes.

Comparison between Method (1) and Method (2)

It is noted that pipe materials ranking varies between Method (1) and Method (2) and at different merging ratios of Method (1). Therefore, the overall evaluation criteria should be clearly stated in the project documents. It is generally recommended to follow Method (1) with higher weight for technical evaluation.

Table (3) General Technical Evaluation Parameters of Pipe Materials

Technical Evaluation Parameters	Pipe Score													
	Weight (%)	DI		ST		PSC		GRP		HDPE		uPVC	
		S	S_{adj}	S	S_{adj}	S	S_{adj}	S	S_{adj}	S	S_{adj}	S	S_{adj}
Structural Properties (40%)													
Lifetime	**10**	5	10.0	3	6.0	4	8.0	2	4.0	3	6.0	1	2.0
Resistance to internal pressures	**10**	4	8.0	5	10.0	3	6.0	3	6.0	2	4.0	1	2.0
Resistance to external pressures	**10**	4	8.0	3	6.0	5	10.0	1	2.0	2	4.0	1	2.0
Resistance to shock loads	**10**	5	10.0	5	10.0	5	10.0	1	2.0	3	6.0	1	2.0
Sub-Total (%)	**40**		**36.0**		**32.0**		**34.0**		**14.0**		**20.0**		**8.0**
Environmental Conditions (30%)													
Resistance to soil corrosion	**10**	2	4.0	1	2.0	3	6.0	5	10.0	5	10.0	5	10.0
Resistance to ground water corrosion	**10**	2	4.0	1	2.0	3	6.0	1	2.0	5	10.0	5	10.0
Resistance to internal corrosion	**5**	3	3.0	1	1.0	3	3.0	5	5.0	5	5.0	5	5.0
Resistance to stray currents corrosion	**5**	2	2.0	1	1.0	3	3.0	5	5.0	5	5.0	5	5.0
Sub-Total (%)	**30**		**13.0**		**6.0**		**18.0**		**22.0**		**30.0**		**30.0**
Construction, O & M (30%)													
Route width	**5**	3	3.0	3	3.0	1	1.0	2	2.0	4	4.0	5	5.0
Need for specific bedding	**5**	5	5.0	3	3.0	5	5.0	1	1.0	4	4.0	3	3.0
Need for thrust blocks	**4**	1	0.8	5	4.0	1	0.8	1	0.8	5	4.0	1	0.8
Ease of jointing	**4**	4	3.2	1	0.8	3	2.4	3	2.4	2	1.6	5	4.0
Ease of leakage detection	**4**	5	4.0	5	4.0	3	2.4	1	0.8	1	0.8	1	0.8
Ease of repair	**4**	4	3.2	3	2.4	1	0.8	4	3.2	4	3.2	5	4.0
Weight	**4**	2	1.6	3	2.4	1	0.8	4	3.2	5	4.0	5	4.0
Sub-Total (%)	**30**		**20.8**		**19.6**		**13.2**		**13.4**		**21.6**		**21.6**
Total (%)	**100**	**69.8**		**57.6**		**65.2**		**49.4**		**71.6**		**59.6**	
Tech. Score, S_T (%) = T / T_{max}	**100**	**97.0**		**80.0**		**91.0**		**69.0**		**100.0**		**83.0**	
Rank		**2**		**5**		**3**		**6**		**1**		**4**	

Where, Sw = (S/5) * W = Weighted Score

III. Case Study

A case study of transmission pipeline with diameter 1000 mm and internal pressure 20 bars is conducted to illustrate the process of selection with the design parameters as shown in Table (7). HDPE and uPVC pipes are excluded because these pipes are not available with this diameter and cannot withstand the pressure.

It is noted from Fig. (5) that DI, ST, PSC, and GRP pipes can be used while HDPE and uPVC pipes are excluded.

Step (1) - Exclusion Diagram

Exclusion Diagram described in Fig. (5).

Step (2) - Technical Evaluation

It is noted from Table (8) that DI pipe is the best pipe material from the technical point of view followed by PSC, ST and then GRP pipes.

Step (3) - Financial Evaluation

It is noted from Table (9) that GRP pipe is the cheapest followed by ST, PSC pipes, and then DI pipe.

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Fig. (6) shows the technical and financial scores for the selected pipes.

Step (4) - Overall Evaluation

Method (1) - Using a Specific Merging Ratio

Table (10) presents the results of Method (1) application. It is noted that for the most commonly applied range of W_T = (70) % and W_F = (30) % DI is the optimal pipe material.

Table (4) - Financial Evaluation Scoring System

Pipe Material	DI	ST	PSC	GRP	HDPE	uPVC
Relative Cost (F)	3.0 Y	2.2 Y	2.6 Y	1.8 Y	1.4 Y	1.0 Y
S_F (%)= F_{min} / F	33.0	45.0	38.0	56.0	71.0	100.0

Table (5) - Application of Method (1)

W_T (%)	W_F (%)	Rank					
		DI	ST	PSC	GRP	HDPE	uPVC
(0-40)	(100-60)	6	4	5	3	2	1
(40-45)	(60-55)	5	6	4	3	2	1
(45-52)	(55-48)	3	6	4	5	2	1
(52-62)	(48-38)	3	5	4	6	2	1
(62-82)*	**(38-18)***	**3**	**5**	**4**	**6**	**1**	**2**
(82-88)	(18-12)	2	5	4	6	1	3
(88-100)	(12-0)	2	5	3	6	1	4

*With most commonly applied range

Method (2), Using Adjusted Financial Score

Table (11) presents Method (2) application. It is noted that GRP is the optimal pipe material.

Comparison between Method (1) and Method (2)

The ranking is completely different between Method (1) and Method (2). Method (2) gives higher priority to financial evaluation. It is recommended to apply Method (1), which gives higher priority to technical evaluation.

Table (6) - Application of Method (2)

Pipes	DI	ST	PSC	GRP	HDPE	uPVC
S_T (%)	97.0	80.0	91.0	69.0	100.0	83.0
F	3.0 Y	2.2 Y	2.6 Y	1.8 Y	1.4 Y	1.0 Y
F_{adj}= F / S_T	3.10 Y	2.75 Y	2.86 Y	2.61 Y	1.40 Y	1.20 Y
S_G (%)	38.7	43.6	42.0	46.0	85.7	100.0
Rank	6	4	5	3	2	1

Table (7) - Input Data for the Case Study

Parameter	Value
Diameter (mm)	1000
Internal pressure (bar)	20
Project lifetime (year)	50
Local Experience	All pipes are accepted
No. of fittings / km	2
Percent of route with insufficient pipe trench (%)	80 %
Percent of route under heavy traffic load (%)	80 %
Percent of route exposed to shocks (%)	30 %
Percent of route with groundwater above pipe (%)	70 %
Percent of route with aggressive soil (%)	50 %
Percent of route exposed to stray currents (%)	80 %

Table (8) - Technical Evaluation of Pipe Materials

Technical Evaluation Parameters	Weight (%)	Pipe Score							
		DI		ST		PSC		GRP	
		S_{adj}	S_w	S_{adj}	S_w	S_{adj}	S_w	S_{adj}	S_w
Structural Properties (40%)									
Lifetime	**10**	5	10.0	3	6.0	4	8.0	2	4.0
Resistance to internal pressures	**10**	4.3	8.6	5	10.0	3.4	6.8	3.4	6.8
Resistance to external pressures	**10**	4.2	8.4	3.4	6.8	5	10.0	1.8	3.6
Resistance to shock loads	**10**	5	10.0	5	10.0	5	10.0	3.8	7.6
Sub-Total (%)	**40**		**37.0**		**32.8**		**34.8**		**22.0**
Environmental Conditions (30%)									
Resistance to soil corrosion	**10**	3.5	7.0	3	6.0	4	8.0	5	10.0
Resistance to groundwater corrosion	**10**	2.9	5.8	2.2	4.4	3.6	7.2	2.2	4.4
Resistance to internal corrosion	**5**	3	3.0	1	1.0	3	3.0	5	5.0
Resistance to stray currents corrosion	**5**	2.6	2.6	1.8	1.8	3.4	3.4	5	5.0
Sub-Total (%)	**30**		**18.4**		**13.2**		**21.6**		**24.4**
Construction, O & M (30%)									
Route width	**5**	3.4	3.4	3.4	3.4	1.8	1.8	2	2.6
Need for specific bedding	**5**	5	5.0	3	3.0	5	5.0	1	1.0
Need for thrust blocks	**4**	4.6	3.7	5	4.0	4.6	3.7	4.6	3.7
Ease of jointing	**4**	4	3.2	1	0.8	3	2.4	3	2.4
Ease of leakage detection	**4**	5	4.0	5	4.0	3	2.4	1	0.8
Ease of repair	**4**	4	3.2	3	2.4	1	0.8	4	3.2
Weight	**4**	2	1.6	3	2.4	1	0.8	4	3.2
Sub-Total (%)	**30**		**24.1**		**20.0**		**16.9**		**16.9**
Total (%)	**100**	**79.5**		**66.0**		**73.3**		**63.3**	
Tech. Score, S_T (%) = T / T_{max}	**100**	**100**		**83.0**		**92.0**		**79.0**	
Rank		**1**		**3**		**2**		**4**	

Table (9) - Financial Evaluation for Pipe Material

Pipe	DI	ST	PSC	GRP
Relative Cost (F)	**3.0 Y**	**2.2 Y**	**2.6 Y**	**1.8 Y**
SF (%)= Fmin/F	**60.0**	**82.0**	**69.0**	**100.0**
Rank	**4**	**2**	**3**	**1**

Table (10) - Application of Method (1) for Case Study at (70, 30)

Pipes	DI	ST	PSC	GRP
ST (%)	**100.0**	**83.0**	**92.0**	**79.0**
SF (%)	**60.0**	**82.0**	**69.0**	**100.0**
SG (%)	**88.0**	**82.7**	**85.1**	**85.3**
Rank	**1**	**4**	**3**	**2**

Table (11) - Application of Method (2) for Case Study

Pipes	**DI**	**ST**	**PSC**	**GRP**
S_T (%)	100.0	83.0	92.0	79.0
F	3.0 Y	2.2 Y	2.6 Y	1.8 Y
$F_{adj} = F / S_T$	3.00 Y	2.65 Y	2.83 Y	2.28 Y
76.0	86.0	80.6		100.0
Rank	4	2	3	1

IV. CONCLUSION

An algorithm is proposed for the selection of the most optimal pipe material in certain application of water supply projects. The process is carried out in four steps as presented below:

1. Exclusion Diagram is developed to select the acceptable pipe materials that can be used for a certain application, taking into consideration design parameters (diameter and pressure), and local experience.
2. Technical Evaluation is conducted among the selected pipe materials that can be used for specific application, taking into consideration structural properties, environmental conditions, construction, operation, and maintenance.
3. Financial Evaluation is conducted among selected pipe materials. In the current study, the financial evaluation is introduced as a relative score, taking into consideration the cost of supply and installation.
4. Overall Evaluation, Technical and financial evaluations are merged for the final selection of the appropriate pipe material for a certain application. Two methods are presented for merging technical and financial evaluations. Method (1) - using a specific merging ratio and Method (2) - using adjusted financial score.

The process is applied for a case study of transmission pipeline with diameter 1000 mm and internal pressure 20 bars. HDPE and uPVC pipes are excluded because these pipes are not available with this diameter and cannot withstand the pressure.

Method (1) showed that DI is the optimal pipe material and Method (2) showed that GRP is the optimal pipe material; the ranking is completely different between Method (1) and Method (2). Method (2) gives higher priority to financial evaluation. It is recommended to apply Method (1), which gives higher priority to technical evaluation.

REFERENCES

[1] Trew J. E., Tarbet N. K., De Rosa P. J., Morris J. D., Cant J., and Olliff J. L. “Pipe Materials Selection Manual Water Supply” 2nd edition, UK Water Industry Reseach, June 1995.

[2] Alferink F., Janson L.E and Olliff J.L "Design of thermoplastics pipes": Prediction of pipe deflection versus field measured values", Plastics Pipes X Göteborgh, Sweden, 1998.

[3] Rajani, B. B. and Kleiner, Y. “Comprehensive Review of Structural Deterioration of Water Mains: Physically Based Models,” Urban Water, Vol. 3, 151–164, October 2001.

[4] El Khadem, S. “Effects of Pipe Stiffness and Installation Methods on performance of GRP pipes”. The 6th International Water Technology Conference, Alex. 23-25, March 2001.

[5] Drew L. Wilson, Jim Craig, PE, Chris C. Greggs, Polyethylene Plays Vital Role in Conservation, American Water Works Association, 2002.

[6] Abdel-Razik, M.H. “Deflection of GRP Pipes”, Journal of Architectural and Civil Engineering, Ain Shams University , Vol. 39, No. 2, pp. 291-305, June 2004.

[7] Merah N., Khan Z., and Bazoune A. “Temperature and Loading Frequency Effects on Fatigue crack Growth in HDPE Pipe Material”. Arabian journal for science and engineering, volume 31, number 2C, 2006.

[8] Gargari, M. T. “Selection of Pipe for a Drinking Water Project; a Case Study”, Proceedings of the 2006 IJME-INTERTECH Conference.

[9] Farshad, M. “Plastic Pipe Systems: Failure Investigation and Diagnosis,” Elsevier, Maryland Heights, Mo. 2006.

[10] Wols B.A., Daal K. van, van Thienen P. “Effects of climate change on drinking water distribution network integrity: predicting pipe failure resulting from differential soil settlement”, Procedia Engineering, Volume70, Pages 1726-1734, 2014.