Glass Reinforced Epoxy (GRE) as an alternative pipeline for onsite surface installations: A structural integrity and financial feasibility study

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ABSTRACT

In this modern era when every single operation is being optimised for specific improvement, this study focuses on the sustainable alternative pipeline i.e. Glass Reinforced Epoxy (GRE) composite for onsite surface transportation of oil products. To provide a better solution to large maintenance and durability issues and to deliver durable alternative pipeline with lower operation expenditures (OPEX) The significance of the GRE pipeline in contrast to conventional carbon steel (CS) pipeline provides better resistivity to erosion, corrosion and chemical degradation. The 202.5 m GRE pipeline of varying diameters (8”,6”& 4”) in layout network has been analysed for pipeline qualification in which the structural integrity analysis on CAESER-II has been performed. All the analysis performed are in conformance to guidelines of ISO-14692, a standard for composite pipe installations. The life cycle cost analysis and financial feasibility of GRE pipeline is analysed for the designed system in contrast to equivalent CS pipeline. The capital budgeting ratios are calculated to determine the alternative selection. In the analysis the procurement and installation cost, Net Present Value (NPV), Payback (PB) period and Profitability Index (PI) has been comparatively analysed. From the analysis GRE pipeline is concluded to be structurally stable for the designed layout with an extended life time and lower OPEX for transportation, with more NPV and PI along with quick Payback period GRE conforms to be a reliable alternative for installation and provides you enough saving cost to be readily invested on some other projects or to carry out routine maintenance operations.

Keywords: sustainable alternate pipeline, CS & GRE pipeline comparison, Life cycle cost analysis, alternative composite pipeline, Advantages of composite pipeline, Durable pipeline, Structural integrity of GRE pipeline, corrosion resistant pipeline, Alternative oil & gas pipeline

1 Introduction

In this era of modernization where every organisation is in pursuit to optimize and cut short the energy expenses to increase the yield and to become more efficient. In the oil and gas industry a lot of improvement in systems can be seen from drilling to refining to distribution. Every step has been innovated to decrease the energy expenses and optimise the system in the perfect manner possible. Following this chain, it can be observed that alternate materials implementation can be seen in the recent years in place of conventional carbon steel pipelines to increase the durability of the system and on the other side to reduce the energy operating expenses.

In the operation expenditures (OPEX) for oil and gas transportation pipeline acquire a major chunk. We can see that in oil fields, pipelines are expanded more than 1000km. Therefore, the operative conditions also present to major challenge mainly related to steel pipes because they are susceptible to internal and external corrosion. Catering all these problem glass fibre reinforced polymers (GFRP) presents a unique alternative. As they are outnumbered with advantages like enhanced mechanical properties and corrosion resistant. Being perfectly low weight with inner wall smoothness enhance its market value and GRE provides an efficient hydraulic performance due to low coefficient of friction. The installation procedure is relatively easy since the thread connections and low weight offers quick installation in contrast to conventional carbon steel pipelines [1].

Considering glass reinforced epoxy (GRE) as a potential alternative for carbon steel pipelines, there is a need for a comparative analysis of GRE with conventional carbon steel pipelines in terms of mechanical properties and longevity. The operating pressure ranges from atmospheric to 40 MPa. Considering the fact that GRE pipes can operate without any discrepancy at temperature of about 100°C give them an absolute advantage since when considering composite pipelines operating temperatures put the constraint. And they can be implemented as an on-ground transportation medium effectively due to higher temperature operating range. The fundamental advantage that is acquired using composite materials in contrast to carbon steel is the reduction of mass for primary and secondary constructions, they have better chemical properties like inertness and mechanical properties like more buckling strength. The longer span of life since after 25 years in service carbon fibres loses only 2-10% of its initial strength, easy to install and are quite safe to work with. [2]

The brief analysis of the GRE pipeline in contrast to carbon steel pipeline which includes the mechanical

Table 1-1 CS and GRE pros and cons

Carbon Steel (CS) Pipes	**Glass Reinforced Epoxy (GRE) Composite Pipe**
Advantages of Composites	
Internal corrosion	No internal corrosion
External Corrosion	No external corrosion
Lower Strength to weight ratio	Higher Strength to weight ratio
Lower toughness	Higher Toughness
Lower Tensile Strength	Higher Tensile Strength
Brittle Fracture Failure when corroded	Brittle Fracture Failure: The composites have the better ability to absorb shocks because the failure is not sudden as even after the failure of the fibre the matrix remains intact.
Higher Conductivity	Lower Conductivity (No Electrostatic charge accumulation)
Lower Breaking length	Higher Breaking length
Heavier in weight (6 times than GRE)	Lighter in weight
Higher Life cycle cost	Lower life cycle cost
Higher Thermal expansion coefficients	Lower thermal expansion Coefficients
Higher Residual thermal relaxation	Lower residual thermal relaxation (lower strain)
Joining techniques are quite specific	Have different joining techniques (Time and cost saving)
Heavy defects due to welding	No defects as no welding is being done
Higher Machining cost	Lower machining cost
Higher maintenance cost	Lower/Minimal maintenance cost
Higher coefficient of friction	Lower coefficient of friction
Disadvantages of composites	
Skilful personnel are available in Pakistan market.	Skilful personnel are required because of limited application in industry
Higher hardness	Lower Hardness
No such careful handling during loading, unloading and installation is required.	Require stringent criteria for handling.
No Strain due to moisture absorption	Strain due to moisture absorption (within safe limit in specific humidity level) up to max 0.2%
Higher impact values	Lower impact values
Raw material is less expensive	Raw material is expensive than Steel pipelines
Lower Installation cost	Higher installation cost

advantages/disadvantages along with erosion and corrosion issues[3]-[4]-[5]-[6]-[7]-[8] is mentioned in Table *1-1*.

Internal corrosion is occurring because of the presence of the H2S and CO2 in the pipeline which results in further sweet corrosion and sour corrosion (where Pressure of H2S > 0.05 psi). Note that corrosion rate is enhanced because of the presence of oxygen and organic acid as they dissolve the iron carbonate scale but when we consider the chemical composition of GRE it adds benefit in such a way that it remains resistant in high alkali and acidic conditions. By using GRE pipeline, we would likely to avoid the different types of corrosions like uniform corrosion, pitting corrosion, wormhole attack, galvanic ringworm corrosion, heat-affected corrosion, mesa attack, raindrop corrosion, erosion corrosion & Corrosion fatigue.

External Corrosion can be avoided in GRE pipes as they possess the excellent insulator properties so it would avoid whereas in carbon steel pipelines there is differential cell corrosion, galvanic cell erosion, stress corrosion cracking and microorganism influenced corrosion (MIC).[9]-[10]-[11].
Every industry encounters a shocking corrosion impact on the business. As estimated by NACE that each year about $300 billion is used in different operations at US. From the report of Ross [12] it can be seen that almost about $150 billion can be saved if the corrosion issues in industrial sector could be sorted out. And an estimate says that only in the tubular corrosions, industries are facing loss of billions of dollars each year. Therefore, it is imperative to mitigate corrosion related issues through implementation of alternate material selection, a chemical treatment process or providing an altogether different environment. Among them the FRC development to choose right material has seemed to be most viable option [13].
Considering these factors, the basic foundation can be laid that GRE pipes are the most suited alternative currently present to be applied to ensure sustainability of pipelines in terms of durability and longevity. Therefore, there is a need to analyse the quantitative corrosion rates of carbon steel pipelines to asses and compare it with GRE pipelines erosion rates so that the financial feasibility of GRE pipelines can be determined like Net Present value (NPV), Payback period & relative installation costs. Since FRP are being implemented for years and considering all the advantages that they are providing, the scope has not been widened as it is suggested to be because of absence of integrity evaluation methods and less knowledge about failure and degradation mechanisms [1].

Therefore, this study will include the quantitative analysis on integrity evaluation of GRE pipeline by doing hydro analysis, operating pressure analysis at average and higher temperatures. Furthermore, the buckling analysis, pipe thickness calculations, allowable stress for failure, external pressure to collapse & stresses due to thermal expansion will also be analysed quantitatively as per the designed pipeline network scenario. The financial feasibility of GRE has been determined considering installation & operating cost, NPV analysis, Profitability Index and Payback periods in contrast to CS pipeline.

2 Methodology & setup

This research study has been carried out in the infrastructure department of Pakistan State Oil (PSO), Head office Karachi Pakistan, to analyse the potentiality of GRE pipes in contrast to conventional carbon steel pipelines with regard to structural integrity for the designed systems and financial feasibility as sustainable alternative. The pipeline system is being validated for on-surface installations of Pakistan State Oil (PSO) - Kemari Terminal A, Port of Karachi, Karachi City, Sindh, Pakistan which serves as decant and receipt of gasoline product to and from the reservoir. The pipeline network system has been designed for maximum pressure which is being used to transport the oils through the pipelines at the terminal. The layout of GRE pipeline consists of diameters of 8 inches, 6 inches & 4 inches with subsequent necessary accessory equipment for pipe fitting which are enclosed in the Table *2-1*.

Table 2-1 GRE pipeline designed layout specifics

Parameters	**Quantity**			**Total**
Pipe Diameters (inches)	**8**	**6**	**4**	
laying length of pipe (m)	105	77.5	20	202.5
Bolts	17	17	13	47
No. of valves (Placement of valves)	5	7	4	16
Check valves	2	3	-	5
Gate valves	3	4	4	11
Elbows	4	4	2	10
Flanges	17	13	13	43

Blind Flanges	5	3	-	8
Tees	4	3	-	7
Strainer	2	-	1	3
reducer (6" to 4")	-	-	5	5
Pumps	2		-	2
Ball valves	-	-	4	4
Adhesives	100 kg			

The designed pressure for the system is considered to be 41 psi (282.68 kPa) corresponding to delivery pressure generally retained at the terminal site. The flowrate is maintained at 37.8 L/s in the receipt and decant lines. The temperature values for the pipeline network is analysed at increased operating temperature of 40 °C and designed temperature of 50 °C corresponding to temperatures in Karachi [14]. The major reason for not being used in oil & gas sector is that after being tested at 80 °C along with relative humidity of 90% sustained at 60 days, it was concluded by Almeida et al, [15] that the reduction in shear strength and modulus was 30% and 38% respectively. And it was because a reversible plasticization of the matrix induced such stresses. Furthermore, Mohamed Elarbi and Wu [16] concluded that epoxy samples are susceptible to more degradation under combined conditions of moisture and elevated temperature as compared to only exposed moisture conditions. However, the under-consideration layout is being implemented and designed for safe environmental conditions. There can be a reduction in the mechanical properties because of the ingression of moisture levels which react with the polymer material in the composites as the impose internal stresses. Manalo et al. [17] experimental study revealed that the flexural strength of Glass Fibre Reinforced Polymer having phenolic core could reduce by 20% when being tested at 80°C. That is why the designed conditions are selected such that to avoid any complexity as stated.

2.1 Thickness calculation for GRE pipeline

The carbon steel (CS) pipelines which follows the schedule system that corresponds to specific pressure values and suggest the pipeline thickness, API 5L a guideline for pipeline specification [18] whereas in GRE pipelines the aim of required pipe thickness is to ensure that GRP piping systems are capable of transporting the specified fluid at the specified rate, pressure and temperature throughout their intended service life as given in (2-1).2-1 The selection of nominal pipe diameter depends on the internal diameter required to attain the necessary fluid flow consistent with the fluid and hydraulic characteristics of the system. The required thickness is calculated from the hoop stresses specific to the material which would give the proper size and dimension of the GRE pipeline being used as recommended practise in ISO-14692 [19] using following formula

$$\max thickness\ (mm) = \frac{Pi.d.1000}{((n.h - sa) - Pi)} \quad \text{2-1}$$

where Pi = max internal pressure (5MPa); n = safety factor; h-sa = allowable hoop stress; pipe internal diameter

2.2 Allowable stress in GRE pipelines

As per the recommendation of ISO-14692, which is the characteristic standard to evaluate the integrity tests and to validate pipe compliance to the system in which is implemented, suggests that allowable stress for the composite pipeline which is equal to the sum of hoop stress caused due to internal pressure (σ_{hp}) and hoop stresses caused due to hoop directional load (σ_{hu}) (2-2, 2-6, 2-4) considering glass rupture. This stress gives you a quantitative measure of the stress that is being applied for a GRE pipeline transporting fluid at certain pressure.

$$\sigma_{h,sum} = \sigma_{hp} + \sigma_{hu} \quad (2\text{-}2)$$

$$\sigma_{hp} = \frac{P.D_{r.min}}{2.t_{r.min}} \quad (2\text{-}3)$$

$$\sigma_{hu} = r_c . D_f . E_{hb} . \frac{\Delta y}{D_{r.min}} \frac{t_{t.min}}{D_{t.min}} \quad (2\text{-}4)$$

Where P Internal pressure (MPa); $t_{r.min}$ minimum reinforced pipe wall thickness, expressed in millimetres; $D_{r.min}$ mean diameter of the minimum reinforced pipe wall, expressed in millimetres; r_c Rerounding coefficient, equal to 1 – P /3; Df Shape factor, see AWWA Manual M45 Second Edition.
The calculated stresses are compared with the 2-5, 2-6 equation to satisfy the results:

$$\sigma_{ha,sum} \leq f_2 A_1 A_2 A_3 \, \sigma_{qs} \quad (2\text{-}5)$$

$$\sigma_{a,sum} \leq f_2 A_1 A_2 A_3 \left[\left(\frac{\sigma_{qs}}{2} - \sigma_{al(0:1)} \right) \frac{\sigma_{h,sum}}{\sigma_{qs}} + \sigma_{al(0:1)} \right] \quad (2\text{-}6)$$

Where $f_2 A_1 A_2 A_3$ are the characteristics constant of the material i.e. GRE as per the standard i.e. ISO-14692

2.3 External Pressure to collapse

The maximum external pressure that can be applied form the fundamental factor to be considered for composite pipelines since in accordance to ISO-14692, pipes and fittings shall have sufficient stiffness to resist vacuum and/or external pressure loads (2-7). The minimum stiffness shall be sufficient to resist a short-term vacuum (e.g. by the operation of an upstream valve) with a safety factor Fe of 1.5. Piping susceptible to long-term vacuum and/or external pressure loads shall have a stiffness sufficient to resist the induced load with a safety factor Fe of 3.0. The external collapse pressure (Pe), in megapascals, for our designed model of GRE pipeline which caters hoop bending modulus, specific to GRE material, and minimum pipe thickness and diameter factor, since the system is analyzed for the maximum external pressure conditions is calculated.

$$P_e = 2.\frac{1}{F_e}.E_{hb} \cdot \left(\frac{t_{t.min}}{D_{t.min}} \right)^3 \quad (2\text{-}7)$$

Where Fe safety factor; E_{hb} hoop bending modulus, expressed in MPa

2.4 Load calculation due to thermal expansion:

In pipelines due to of the thermal gradients thermal expansion occurs and strain is induced which leads to load due to thermal expansion (2-8). And this load would be compressive in nature as the pipe is anchored at both the ends so the risk of buckling must be analysed succeeding to the loads due to thermal expansion. The thermal expansion coefficients for conventional carbon steel [20] and GRE were taken from study by [21] and analysed comparatively to determine the advantage that GRE pipeline offers i.e. more buckling strength. The loads are calculated using the thermal loads formula which is dependent upon thermal gradients and axial elastic modulus corresponding to GRE and carbon steel [22].

$$F_t = tc \, . \Delta T \, . E - a . A \quad (2\text{-}8)$$

Where F_t thermal load at ends in (N), A is cross sectional area, E-a Elastic modulus, ΔT Temperature gradient, tc thermal expansion coefficient

2.5 Buckling Analysis

It can be defined as the elastic deformation of the material under the application of the load and the buckling must be avoided In the pipe networking because the pipes are restrained at both ends and they are limited by the allowed vertical deflections according to as per the recommendation of ISO 14692 otherwise the elastic bending however for a short instance may be would lead to the stress concentrations at the supports that might result In the failure of the pipeline at the supports. A safety factor of 4.0 has been applied to make sure any anomaly in future operations in this regard. The axial load has been calculated from where the respective buckling strength is calculated (2-9) and compared with unsupported compressive stress for GRE pipeline.

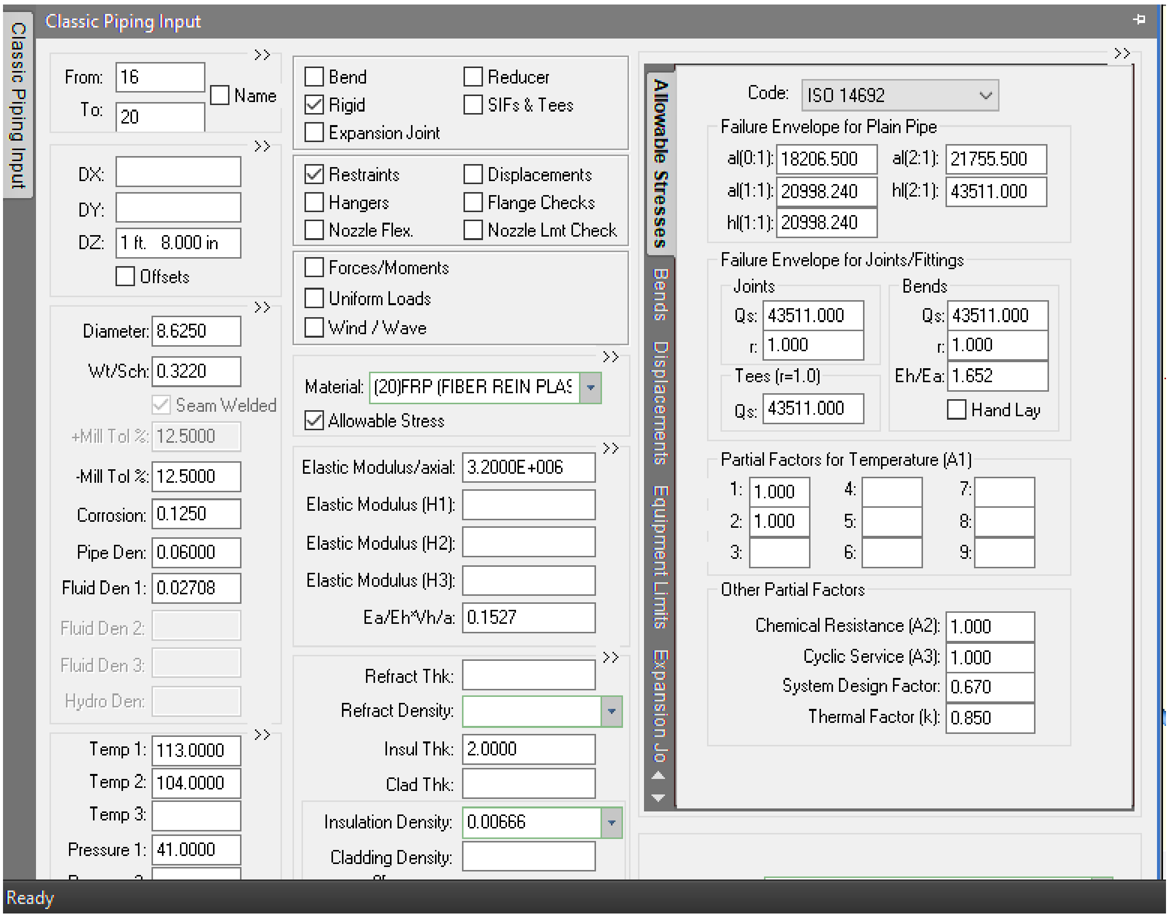
$$F_{a.max} = \frac{\pi^2 I_r}{L^2} . E_a x10^6 \qquad (2\text{-}9)$$

Where Ir minimum reinforced pipe wall moment of inertia, expressed in mm4; L length of unsupported pipe, expressed in metres; Ea axial tensile modulus, expressed in MPa.

2.6 GRE structural integrity analysis for designed layout

Considering the fact that when you a GRE pipeline then it is required to determine certain stresses that must assured the integrity of the pipeline as recommended in ISO-14692, in this study the stress analysis is performed on pipe network stress analysis software CAESER-II, the software settings for the analysis are shown in Figure 2-1, the pipeline network layout diagram is shown in Figure 2-2, , in which the hydro-testing, Operating stress analysis and Designed stress analysis is performed at 1.5 times of operating pressure as recommended by quick guideline and updates to ISO-14692 [23], considering the 41 psi pressure

Figure 2-1 CAESER-II GRE pipe network input for structural analysis



in the pipeline, in each pipe section a pressure of 41 psi is considered to make the criteria stringent for qualification, neglecting major and minor losses. And also assumed that all valves (gate & check) are

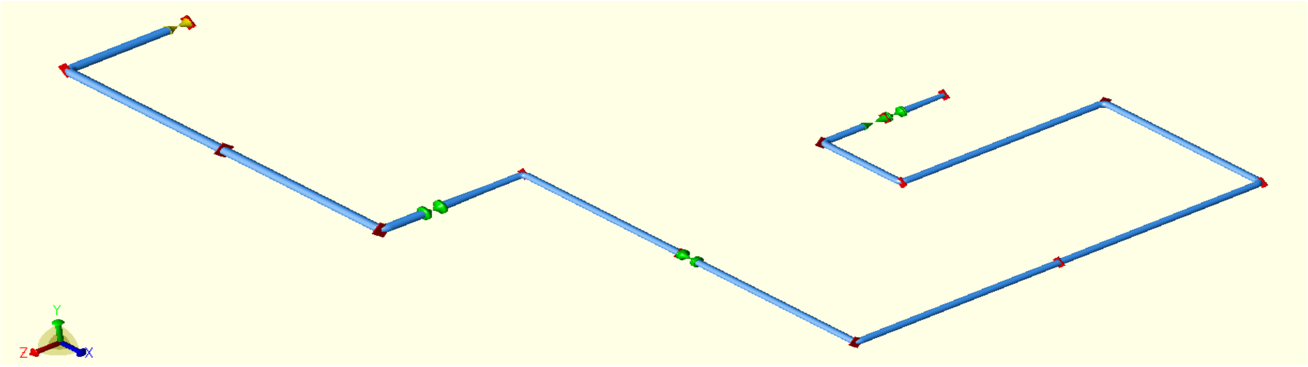


Figure 2-2 Schematic diagram of pipe layout sketched in CAESER-II

anchored independently leading no stresses on the system as per guidelines of the standard being followed (ISO-14692).

2.7 Erosion, Corrosion rates & Life time of CS & GRE

Since carbon steel is susceptible to erosion and corrosion rates much faster than a composite fibre pipeline, (citation required), therefore to analyse quantitatively for (GRE & CS) the designed system an erosion analysis as per the guide lines of **DNV RP 0501** [24]**,** as in equation (2-10) is presented**,** Furthermore, the erosion rates in elbows are also calculated to evaluate to check the systems for any integrity compromises (2-11), the presence of water and aromatics in the oil transportation pipelines do interact with the inner wall. [1] and from the literature [25]-[26] it interacts with matrix and fibre resulting in internal erosion similarly for carbon steel pipeline considering the internal (Corrosion due to Sulphide reducing bacteria, corrosion due to CO_2) and external corrosion, are taken from corrosion studies. The erosion and corrosion rates are summed up for the pipelines of GRE & CS to determine the life time.

$$E_l = \frac{m_p.K.U_p^n.F(\alpha)}{p_t.A_t} C_{unit} \tag{2-10}$$

Where E_l is the erosion rate [mm/yr], K-numerical constant 2x10^-9 for CS, 3x10^-10 for GRE, n-dimensional constant 2.6 for CS & 3.0 for GRE, F (α) is fluidity constant 0.9 for CS; 0.7 for GRE, Up is the impact velocity in m/s, pt density of target material, A-t Area exposed to erosion, C_{unit} 3.15x10^15.
For erosion in the elbows the formula is as follows as given in DNV-RP 0501.

$$E_t = \frac{m_p.K.F(\alpha).\sin(\beta).U_p^n.G.C1}{p_t.A_t}.C_{unit} \tag{2-11}$$

Where E_t is the erosion rate [mm/yr] in elbow, β is the impact angle 60˚, G is the size correction 0.067, C1 is elbow constant 2.5, the critical parameters values are taken from[27] corresponding to our design requirements. The impact angle parameter is taken from [28]**.** The corrosion rates are cited from different sources for the generic pipeline behaviour of carbon steel in corrosive environments as per the designed layout system.

2.8 Life Cycle Cost Analysis or Financial feasibility analysis of GRE pipeline in contrast to conventional carbon steel pipeline

The financial feasibility is generally based on fundamental parameters of Net Present Value (NPV), installation cost & payback period 2-21 of the alternatives being considered. Therefore, the procurement & installation cost has been calculated for both CS & GRE pipeline. The horsepower requirements are calculated (2-14) for GRE & CS (newly installed & badly corroded) to evaluate the constant increased cost incurred for operating CS pipeline. The erosion rates for GRE pipelines being minimal in-contrast to corrosion, erosion rates of CS pipeline have been neglected. Since GRE pipelines having lower coefficient of friction values as compared to CS pipelines bear lesser head loss, which forms the fundamentals of operating expense difference between the two. The major and minor losses (2-12, 2-13) are calculated for the respective layout design as described in Table *2-1*. Using the following formulas from mathematics of pumping water [29]. The cost of operation is calculated by (2-15)

$$Major\ Head\ loss\ (m) = \frac{f.l.v^2}{2.D.g} \quad 2\text{-}12$$

$$Minor\ Head\ loss\ (m) = \frac{K_L.v^2}{2g} \quad 2\text{-}13$$

Where f is the friction factor, D is the internal diameter, v is the flow velocity, K_L is minor loss coefficient.

$$HP = \frac{Q.SG.TH}{3960} \quad 2\text{-}14$$

Where Q is the flowrate in US GPM, SG is specific gravity of fuel 0.75, TH is the total head required in ft
The cost of operation is calculated in PKR using following formula

$$C.Op = \frac{CO.HP.OH.T-days}{\mu} \quad 2\text{-}15$$

Where C. Op is operating cost in PKR, CO is the cost of operation (per kWhr) i.e. 8, OH is the operating hours i.e. 14, T-days 365, μ is the pump efficiency 80%.

To analyse the NPV 2-19 of the alternatives the annual operating cost has been calculated and the annuity cost are converted to present value using the formula P/A (2-16). The increment rate/year in cost are assumed to be at 3% (2-17) considering the electric supply cost increments. The similar NPV analysis has been performed for duplex stainless steel in contrast to other pipeline alternatives [LCC] The future expenditures of CS installation for second life are approximated by (2-18)

$$P = A.\left[\frac{i(1+i)^n}{(1+i)^n-1}\right]^{-1} \quad 2\text{-}16$$

$$P = G\left[\frac{(1+i)^n - in - 1}{i^2(1+i)^n}\right] \quad 2\text{-}17$$

$$P = F\left(\frac{1}{1+i}\right)^n \quad 2\text{-}18$$

Where P is the present value, A is the annuity, G is the Gradient, i is the increment rate, n is the number of years, F is the future value.
The operating cost for the two useful life time of CS has been calculated and from the expenses saved from the CS pipeline are summed up to calculate the payback period for GRE pipeline. The surface roughness values for CS (newly and badly corroded) [30] & GRE [31] are taken from international operational acceptable thickness standards for respective pipelines.

$$NPV = P(A) + P(G) + P(F) \quad 2\text{-}19$$

Where NPV is the net present value

$$PB = \sum_{i=1}^{14} SV + Inst.Cost = Inst.Cost\ of\ GRE \quad 2\text{-}20$$

Where PB is the payback period, SV is the saved expense, Inst. Cost is installation cost of CS
The profitability index (PI) is calculated using following formula

$$PI = 1 + \frac{NPV}{Initial\ Investment} \quad 2\text{-}21$$

All the capital budgeting formulas are taken from developing new pipeline project [32].

3 Results and Discussion

From the thickness calculation the following results are obtained Table *3-1* which states that as the diameter is reduced lesser thickness value is required for the same pressure to sustain generally due to more compactness or the reduced impact area of applied pressure by fluid. The minimum thickness and thickness values for diameter < 100 mm is provided by ISO-14692. The thickness results obtained are in conformance to results obtained by Anyang Flying Eagle Group Co. Ltd following ASTM 2992-96 [33].

Table 3-1 Thickness Calculation for GRE pipes

Pipe diameters in inches	**8**	**6**	**4**
Hoop strength (Pa)	1.09E+08	1.09E+08	1.09E+08
Internal Diameter (m)	0.2032	0.1524	0.1016
Internal pressure (max) (Pa)	5.00E+06	5.00E+06	5.00E+06
safety factor	0.5	0.5	0.5
Allowable hoop stresses (Pa)	5.45E+07	5.45E+07	5.45E+07
Max. Thickness (mm)	**9.77E+00**	**7.33E+00**	**4.88E+00**
Min. thickness (mm)	**3**	**3**	**3**
Thickness: dia <100mm	**Diameter*0.025mm**		

The total allowable stress before the pipeline network is structurally compromised is calculated in Table *3-2*, which states that the results are in the safe operating range also from the allowable stress analysis study [34] the same analysis has been done for 6 inches pipe which conforms to the allowable stress criteria.

Table 3-2 Allowable stress to failure in GRE pipes

Pipe diameters in inches	**8**	**6**	**4**
Rounding factor	1	2	2
Shape factor	1	1	1
Vertical deflection	0.03	0.03	0.03
Hoop modulus (Pa)	3E+10	3E+10	3E+10
Calculated hoop stress σ_{hu} (Pa)	6.02E+07	6.49E+07	4.33E+07
Calculated hoop stress σ_{hp} (Pa)	280580	157826	70145
Sum of hoop stress applied $\sigma_{h,sum}$ (Pa)	6.05E+07	6.51E+07	4.33E+07
Axial stress (0:1) $\sigma_{al(0:1)}$ (Pa)	110995	62341.4	27707.3
Biaxial ratio	0.79	0.79	0.79
Allowable stress σ_{qs} (Pa)	1.4E+08	1.4E+08	1.4E+08
Long term axial stress (Pa)	5.5E+07	5.5E+07	5.5E+07
Sum of allowable hoop stress $\sigma_{ha,sum}$ (Pa)	1E+08	1E+08	1E+08
Sum of allowable axial stress $\sigma_{a,sum}$ (Pa)	4.56E+07	4.59E+07	4.43E+07

The external pressure that can be applied to GRE pipeline is calculated in Table *3-3* External pressure to

Collapse in GRE pipeline to show that for point loads which forms a concentrated pressure region in the GRE pipeline are assessed, the layout external pressure to collapse is calculated for all pipe's diameters in designed network.

Table 3-3 External pressure to Collapse in GRE pipeline

Pipe diameters in inches	**8**	**6**	**4**
Factor of safety	2	2	2
Hoop modulus (Pa)	3E+10	3E+10	3E+10
Max. Thickness (mm)	9.77E+00	7.33E+00	4.88E+00
External pressure for collapse (Pa)	**3.33E+06**	**3.33E+06**	**3.33E+06**

From the results it can be observed that external pressure is the characteristic of the pipeline material and is independent of pipe diameters. And as GRE can bear 3.33 MPa of external pressure therefore they structurally conform to on-surface installation for the designed setup as also calculated in stress analysis study in [34] for external pressure structural integrity.

The pipeline network is exposed to thermal gradients round the year therefore corresponding to the thermal expansion coefficients for GRE & CS the compressive thermal loads are calculated in **Error! Reference source not found.** which shows that for GRE due to low thermal expansions the compressive loads are quite lesser due to which the pipe is susceptible to be damaged due to buckling or compressive failures. The thermal end load is compared with buckling load in Table *3-5* and it can be observed that for GRE, the thermal loads are just 0.81% of the buckling load and thus pipeline is structurally stable. Whereas for CS pipeline due to higher thermal expansion coefficients the compressive thermal loads are quite higher. As the analysis done in thermal post buckling analysis [35] also shows the thermal loads for the corresponding temperature gradients to buckling for hinged-clamped pipelines of composites, which showed that GRE pipeline would buckle in a failure mode.

Table 3-4 Load calculation due to thermal expansion

For GRE			
Thermal expansion coefficients m/m ˚C	0.000013		
Max. Temperature grad. (˚C)	22		
Axial elastic modulus (Pa)	1.20E+10		
Cross sectional Area (m^2)	0.032423161	0.01823803	0.008106
Thermal end load (N)	1.11E+05	6.26E+04	2.78E+04
For CS			
Thermal expansion coefficients m/m ˚C	0.000018		
Max. Temperature grad. (˚C)	22		
Axial elastic modulus (Pa)	2.05E+11		
Cross sectional Area (m^2)	0.032423161	0.01823803	0.008106
Thermal end load (N)	2.63E+06	1.48E+06	6.58E+05

To ensure the flexural rigidity of GRE pipeline, the buckling analysis is performed and the results are shown in Table *3-5*.

Table 3-5 Euler Buckling Stress for GRE

Pipe diameters (inches)	**8**	**6**	**4**
Pipe wall moment of inertia (mm^4)	5.53E-04	1.75E-04	3.46E-05
Unsupported length (m)	4	3.5	3.1
Axial tensile modulus (Pa)	1.00E+10	1E+10	1E+10
Axial Load (buckle) (N)	1.36E+07	5.64E+06	1.42E+06

Wall cross section area (m^2)	3.19E-01	1.80E-01	7.98E-02
Euler Buckling stress (Pa)	**4.27E+07**	**3.14E+07**	**1.78E+07**
Compressive strength (Pa)	2.10E+08	2.10E+08	2.10E+08
Conclusion	**Pipe would buckle**		
Unsupported stress (Pa)	1.07E+07	7.85E+06	4.45E+06

From the table the pipe would buckle before it yields to fracture however, the results showed that the compressive strength of GRE is 10 times greater than Euler buckling stresses, therefore the designed network at the specific pressure and flow conditions would sustain without being buckle. The buckling analysis results are compared with ASTM D2924 [36] which is "Standard Test Method for External Pressure Resistance of Fiberglass Reinforced Thermosetting pipe resin" as compared in Buckling analysis [37] in which the 6 inches pipe of similar thickness has been analysed and the corresponding buckling pressure is noted to be 323 kPa for clamped support pipeline.

The operating pressure analysis at increased temperature, hydro testing, designed pressure analysis at increased temperature is performed as shown in Table *3-6*, Table *3-7*, Table *3-8* respectively on CAESER-II for fundamental stresses of axial, bending, hoop and torsion, to ensure the integrity of the pipeline system, the results here are showing the maximum stress conditions on the specific node. The hydro tests performed are cross checked to comply with ASTM D1599, Standard test method [38] for resistance to short-time hydraulic failure pressure of plastic pipe, tubing, and fittings.

Table 3-6 Operating pressure at 40 ˚C testing results on GRE pipeline

CAESAR II 2014 Ver.7.00.00.2800, (Build 140416) Date: JUL 28, 2019 Time: 14:54
Job Name: DELIVERY-PASSED
Licensed To: SPLM: Pakistan State Oil (PSO)
STRESSES REPORT: Stresses on Elements
CASE 3 (OPE) W+T2+P1 (Load includes: weight+Temperature:40 deg.C + Op. Pressure)
Piping Code: ISO 14692 = ISO 14692 (2005) GRE pipeline
CODE STRESS CHECK PASSED: LOADCASE 3 (OPE) W+T2+P1
Highest Stresses: (KPa)
Ratio (%): 35.2 @Node 90
OPE Stress: 43861.1 Allowable Stress: 124518.6
Axial Stress: 2933.8 @Node 28
Bending Stress: 40651.8 @Node 90
Torsion Stress: 2926.0 @Node 120
Hoop Stress: 46323.7 @Node 90

Table 3-7 Hydro testing of GRE pipeline

CAESAR II 2014 Ver.7.00.00.2800, (Build 140416) Date: JUL 28, 2019 Time: 14:54
Job Name: DELIVERY-PASSED
Licensed To: SPLM: Pakistan State Oil (PSO)
STRESSES REPORT: Stresses on Elements
CASE 1 (HYD) WW+HP (Hydrostatic Analysis)
Piping Code: ISO 14692 = ISO 14692 (2005) GRE pipeline
CODE STRESS CHECK PASSED: LOADCASE 1 (HYD) WW+HP
Highest Stresses: (kPa)

Ratio (%):	8.8 @Node 90
Code Stress:	11819.4 Allowable Stress: 133664.0
Axial Stress:	4293.3 @Node 28
Bending Stress:	6278.9 @Node 90
Torsion Stress:	2780.8 @Node 90
Hoop Stress:	14579.3 @Node 90

Table 3-8 Designed pressure at temperature of 50 ˚C of GRE pipeline

CAESAR II 2014 Ver.7.00.00.2800, (Build 140416) Date: JUL 28, 2019 Time: 14:54	
Job Name: DELIVERY-PASSED	
Licensed To: SPLM: Pakistan State Oil (PSO)	
STRESSES REPORT: Stresses on Elements	
CASE 2 (OPE) W+T1+P1 (Load includes: weight+Temperature:50 deg. C+Des.Pressure:61psi)	
Piping Code: ISO 14692 = ISO 14692 (2005) GRE pipeline	
CODE STRESS CHECK PASSED: LOADCASE 2 (OPE) W+T1+P1	
Highest Stresses: (KPa)	
Ratio (%):	42.9 @Node 90
OPE Stress:	53425.8 Allowable Stress: 124518.6
Axial Stress:	2933.8 @Node 28
Bending Stress:	50283.8 @Node 90
Torsion Stress:	2926.0 @Node 120
Hoop Stress:	55955.7 @Node 90
Max Stress Intensity:	53488.7 @Node 90

From the tabulated data obtained it can be clearly noted that the GRE pipeline successfully passed all the three necessary tests for the stress analysis, from the Table *3-8* it can be seen that at the maximum pressure and temperature conditions that is at the designed conditions the ratio is about 42.9%.

The erosion analysis for GRE & CS are performed using analytical formulas as mentioned for a pipeline and also through the elbows which is illustrated in Table *3-9* Erosion rates for pipeline & for elbows for GRE are 67% lesser as compared to CS for the same flow conditions. The erosion rates are analysed for GRE in [39] erosion testing rig, which were found out to be 0.003mm/year for 30% fibre loaded resins for range of impact velocities. The erosion rates of CS are determined by E.H. Coker (erosion rates CS) using a numerical model for a 6 inches diameter pipe due to sand to be 0.0027 mm/year which for the similar flow conditions and sand particle size.

Table 3-9 Erosion rates for pipeline & for elbows

General erosion rates (Due to sand)		
Parameters	**For CS**	**For GRE**
Diameter (inches)	6	6
mass flow of sand particle	0.001131732	0.001131732
mass flow of fluid	28.2933	28.2933
ppmW of sand	0.00004	0.00004
Area exposed to erosion	0.021061863	0.021061863
Erosion Rate (mm/year)	**0.002596263**	**0.001756602**

Erosion rates for elbows: 90˚ (Due to sand)		
Radius of curvature (m)	0.229	0.229
Density of particle (kg/m^3)	1442	1442
viscosity of the fluid (Pa-s)	0.0006	0.0006
Critical particle diameter (m)	0.029344986	0.029344986
Particle diameter (m)	0.0003	0.0003
Diameter relation	0.001968504	0.001968504
Area exposed to erosion (m^2)	0.022001773	0.022001773
Fluid density correction factor	0.365514069	0.365514069
Erosion rate (mm/year)	**0.004214334**	**0.003666049**

Table 3-10 Life time corresponding to Erosion & Corrosion rates

Pipe material	CS	GRE
Corrosion rate mean value due to CO_2 (internal corrosion) (mm/year)	0.09	--
Corrosion rate mean value due to sulphide reducing bacteria (mm/year)	0.023086364	--
Corrosion rate Industrial (external) (mm/year)	0.1	--
Total corrosion (mm/year)	0.215682626	
Corrosion allowance (mm)	3	
Life time (years)	**13.90932618**	**50**

From Table *3-10* the erosion & corrosion rates give a life time for CS pipelines of about 14 years when no cathodic protection or inhibitors are used, the corrosion rates due to CO_2 are taken from [10]- [40] Prediction-Of-Corroding-Pipeline-Remaining-Life-Time-Using-Semi-Probabilistic-Approach following DNV RP-F10 & Corrosion Rate of Carbon Steel For Flowline[41], the internal corrosion due to sulphide reducing bacteria is taken from [42] Determination of Corrosion rates and remaining life of piping using API and ASME standards in oil and gas industries. The external corrosion rates were taken from Parametric Study on the Factors of External Corrosion of Offshore Pipelines in Malaysia [9] and in contrast GRE pipeline has a life time of 50years [43] due to the fact there is no external & internal corrosion in GRE, and is only susceptible to erosion due to sand which is also lesser in rates due to pipe internal smooth surface as stated in [13] Failure analysis of GFRP. Furthermore, the results of creep, stress analysis and failure evaluation are extrapolated to 50 years which conforms to international acceptable standards for GRE operation [44] as stated in Simulation of the long-term hydrostatic tests on Glass Fibre Reinforced Plastic pipes. Also, from the Arrhenius model, it has been concluded that particulate filled epoxy polymers even after service of 100 years at an average temperature of 30 °C could retain above 70% of mechanical properties [17].

The Procurement & installation cost is calculated for the network designed in Table *2-1*, after obtaining quotes from different suppliers like *Future Pipe Industries (FPI)* and other local suppliers. From the Figure *3-1* it can be seen that being a new technology and owing to expensive raw material, installing GRE would cost you 1.5 times more than corresponding Carbon Steel pipeline, the installation cost are analogous to cost ratios as mentioned in [7] which states that GRE pipeline is 1.5 to 1.75 times costly than CS for a 100 m pipeline model of same configuration.

For life cycle cost analysis, the operation expenditure for both CS & GRE is calculated as shown in Figure *3-3*, which states that every year a certain amount of cost i.e. PKR 12,351 is being incurred for a 202.5 m long pipeline using CS due to corrosion leading to more head losses as in Figure 3-2 under the designed flow conditions for gasoline (S.G: 0.75), and the operating cost for GRE is PKR 906,946 which is 1.24

times lesser than operating CS pipeline under same parameters as shown in Figure *3-3* as stated in [45] cost effective use of fibre that composite materials have lesser head losses and lower operating cost in contrast to carbon steel.

Figure 3-1Procurement & Installation cost of GRE & CS for designed layout

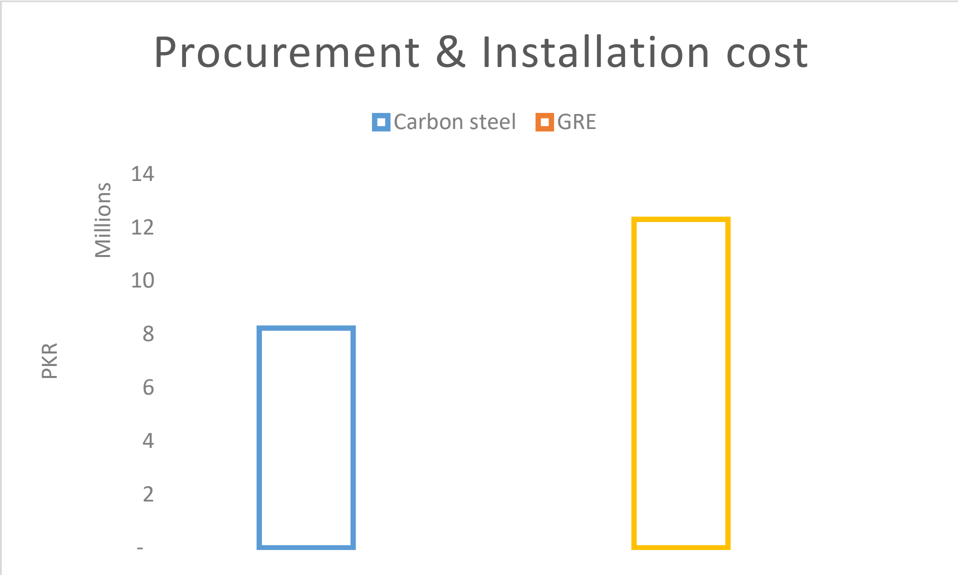
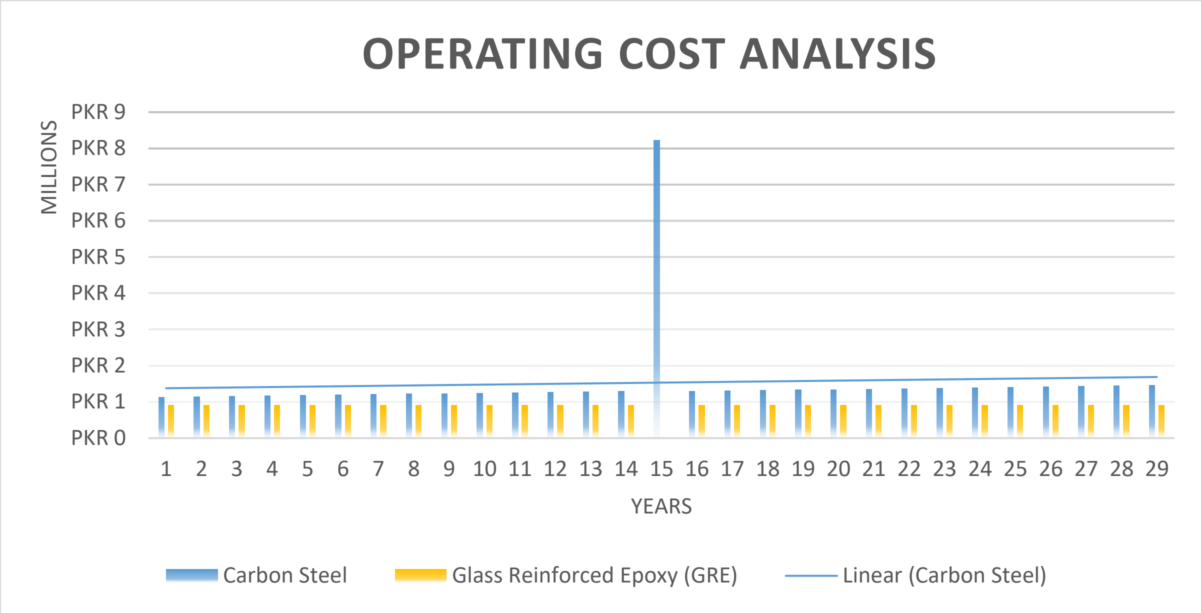


Figure 3-2 Head loss calculation of CS (new & old) and GRE

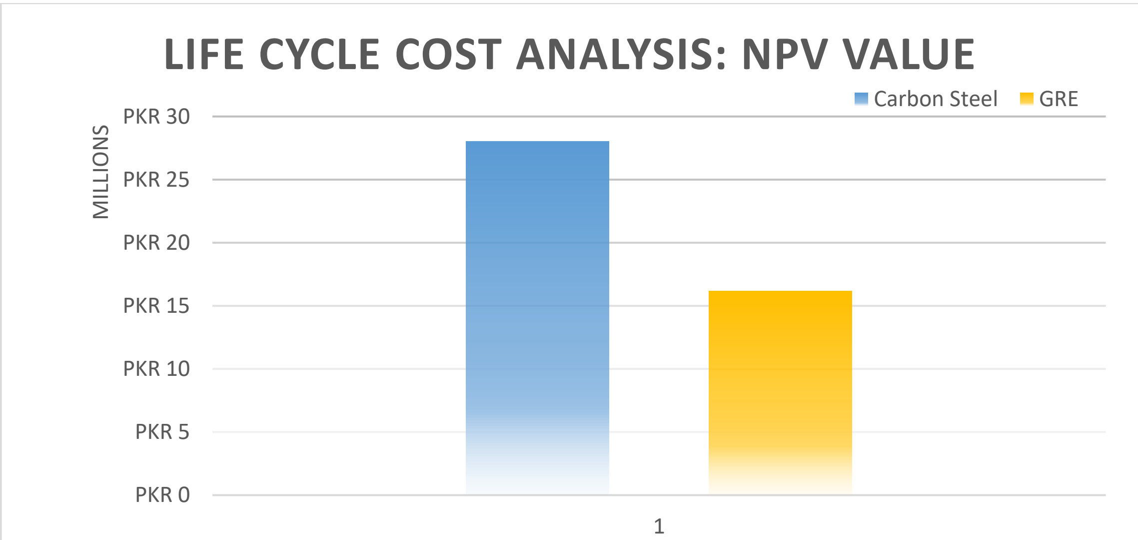
	CS (new)			GRE			CS (Badly corroded)		
Parameters (SI Units)	**8''**	**6''**	**4''**	**8''**	**6''**	**4''**	**8''**	**6''**	**4''**
Diameter (m)	0.2032	0.1524	0.1016	0.2032	0.1525	0.1016	0.2032	0.1524	0.1016
Flow rate (m^3/2)	0.0378	0.0378	0.0378	0.0378	0.0378	0.0378	0.0378	0.0378	0.0378
Velocity (m/s)	1.16583	2.07259	4.66333	1.165833	2.06988	4.663333109	1.165833277	2.072592493	4.66333311
surface roughness (m)	0.0019	0.0019	0.0019	0.000006	6E-06	0.000006	0.0050	0.0050	0.0050
Viscosity of fluid (Ns)	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006
Re	2.96E+05	3.94E+05	5.91E+05	2.96E+05	3.94E+05	5.91E+05	2.96E+05	3.94E+05	5.91E+05
friction prime	5.17573	4.93236	4.58487	8.266941	8.43733	8.61281647	4.345207255	4.097737108	3.74739588
friction factor	0.03733	0.0411	0.04757	0.014632	0.01405	0.013480612	0.052963784	0.05955412	0.07120998
Pressure (Pa)	2.83E+05	2.83E+05	2.83E+05	2.83E+05	2.83E+05	2.83E+05	2.83E+05	2.83E+05	2.83E+05
Pressure head (available) (m)	38.4983	38.4983	38.4983	38.49834	38.4983	38.49833544	38.49833544	38.49833544	38.4983354
length of pipe (m)	105	77.5	20	105	77.5	20	105	77.5	20
Maj. Head loss (m)	1.33764	4.5812	10.3901	0.524315	1.56046	2.944304401	1.897848003	6.637435601	15.5529919
Cumulative Maj. Head loss (m)	16.30893493			5.029084871			24.08827547		
No. of valves (Placement of valves)	5	7	4	5	7	4	5	7	4
Loss coefficient valves	0.75	1.05	0.6	0.75	1.05	0.6	0.75	1.05	0.6
No.of Elbows	4	4	2	4	4	2	4	4	2
Loss coefficient elbows	1.2	1.2	0.6	1.2	1.2	0.6	1.2	1.2	0.6
No. of Tees	4	3	0	4	3	0	4	3	0
Loss coefficient tees	4	3	0	4	3	0	4	3	0
No. of reducer (6'' to 4'')	0	0	5	0	0	5	0	0	5
Loss coefficient reducer	0	0	1	0	0	1	0	0	1
Min.Head loss (m)	0.4126	1.15062	2.44095	0.412604	1.1476	2.440953393	0.412604338	1.150617761	2.44095339
Cumulative Min. Head loss (m)	4.004175492			4.001160445			4.004175492		
Total head loss (m)	**20.31311042**			**9.030245317**			**28.09245096**		

Figure 3-3 Operating cost analysis of GRE & CS



Since all the expenses are cash out flows therefore the NPV results shown in Figure *3-4* are negative in nature states that from the two alternatives the GRE has lesser negative value concluding a more reliable options with regard to investment point of view. Quantitatively NPV of GRE is 1.75 times greater than corresponding CS pipeline and there are cases in international practise when economic effect was $45 million via using composite pipes [46].

Figure 3-4 Life Cycle Cost analysis: NPV analysis of CS & GRE pipeline



For the payback since the carbon steel pipeline is never going to payback along with increased maintenance costs being incurred, whereas for the GRE pipeline the saved operating cost in contrast to CS pipeline & the installation cost being incurred for CS pipeline after one useful life summed up to meet the payback period of the GRE pipeline as indicated in Figure *3-4*. Thus after 14 years the investment of GRE installation pipeline will be a payback summing up to PKR 12 million.

Figure 3-4 Payback analysis of GRE pipeline

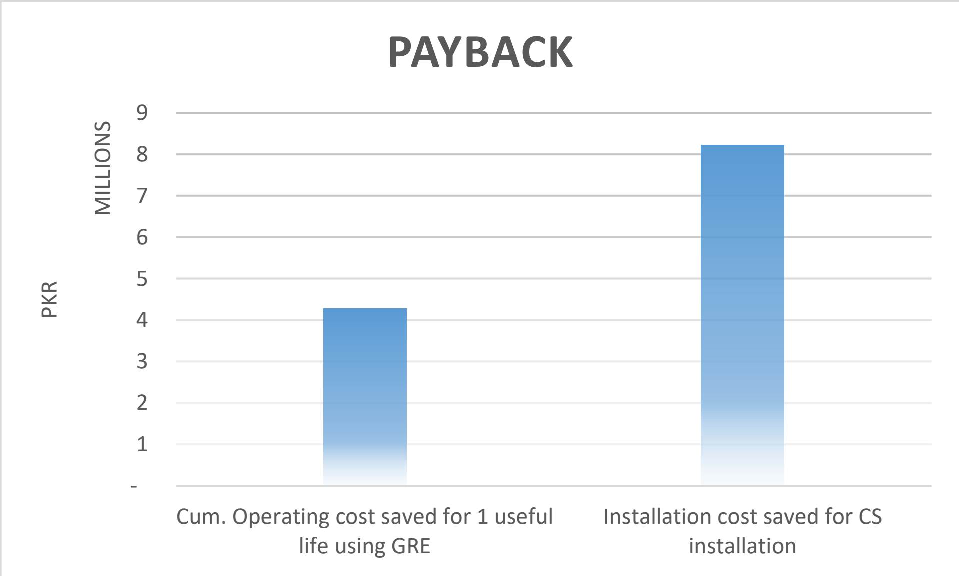
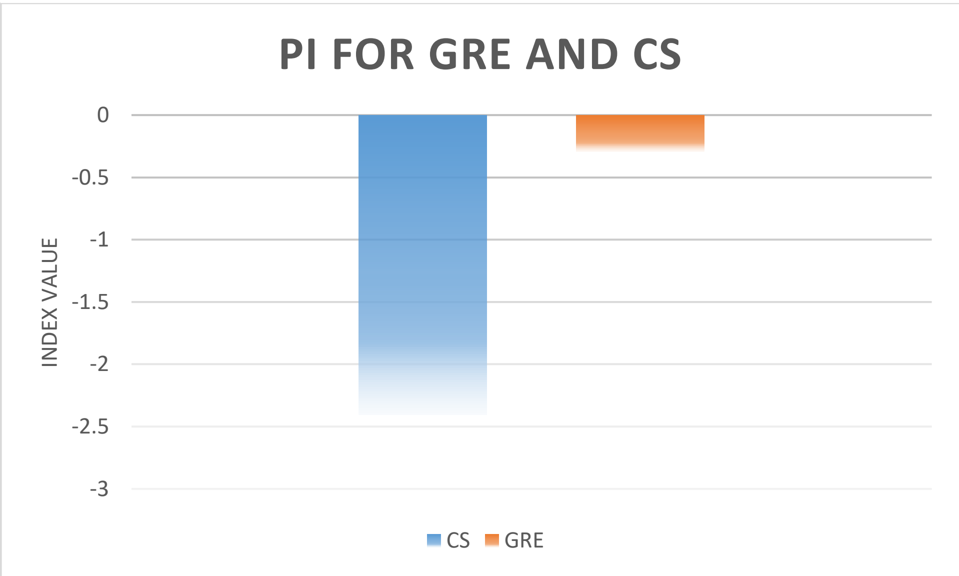


Figure 3-5 Profitability Index of CS and GRE



Being solely an investment and expense project, the PI is negative for both alternatives, GRE has more profitability index in contrast to CS as also mentioned in [46] that composite pipelines are highly profitable to use yielding 34% more profitability than conventional materials.

From the analysis it can be concluded that GRE being the most suitable alternative and being highly financially feasible with lower life cycle cost and more durable as also suggested from similar capital budgeting analysis for pipelines [32].

4 Conclusion

This study has quantitatively analysed the structural integrity of GRE pipeline system and its financial feasibility in contrast to conventional carbon steel pipeline. The analysis performed are in conformance to International standards for composite pipeline. The study highlights the advantages and sustainability that can be availed by exploiting GRE composite pipeline for onsite surface installation. The life cycle cost analysis performed depicts that GRE pipeline is an effective alternative available to Oil and Gas industry at present. This study thus provides a model for pipeline qualification before its installation, the necessary analysis to be performed and also the financial feasibility analysis required before implementing an alternative. GRE is concluded to be an effective alternate material for onsite surface installation evaluated at maintained pressure and flow conditions. The research performed is among very few studies conducted on the financial feasibility and life cycle costing of GRE composite on comparative basis with CS pipeline. And from the results it can be concluded that GRE provides you with an extended lifetime & lower OPEX in contrast to CS pipeline. With more NPV and PI, owing to these edges GRE pipeline has quick Payback and provides you enough saving cost to be readily invested on some other projects or to carry out routine maintenance operations.

The study is performed for onsite surface installation therefore it is recommended to analyse the pipeline for offshore installations using model presented in this study pipelines are susceptible to induced stresses due to elevated temperature and higher moisture rates. The GRE pipeline should be tested and analysed at such condition and then correspondingly manipulated or articulated with more resistant material during manufacturing or as an additional coating before installation at such sites.

5 Declarations

5.1 Study Limitations

none

5.2 Funding source

none

5.3 Competing Interests

The authors whose names are listed certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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