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Investigation into the Modes of Failure and the Causes of Failure of Water Pipeline Materials for Water Supply Schemes: Case of the Central Coastal Area of Namibia

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Abstract: ***The problem of aging waterpipes manifesting leaks and breaks provides extra burdens on the shoulders of the business and community in terms of high costs of repair, replacement and water loss. Proactive pipeline management may become a possible solution as it entails timely maintenance, repair, and renovation, thus increasing the service life of pipes. That is why a general knowledge of the properties and the state of deterioration of a water main network is needed to understand the mechanisms contributing to water pipe failure. There are various materials for piping infrastructure that are now available on the market. The old pre-stressed concrete pipes and asbestos-cement (AC) pipes employed at the coast of Namibia have reached the end of their useful life. These pipes are now being replaced by the Ductile Cast Iron (DCI) pipes, the Glass Fibre Reinforced Plastic (GRP) pipes, and High-Density Polyethylene (HDPE) pipes. This applied research will assess the performance of pipes made of different materials; establish the modes and the causes of failure of pipes.Research design will rely on descriptive analysis and physical analysis. Descriptive analysis will organise and summarise the inventory, condition, break data and break patterns for pipes and systems and physical analysis will use physical methods such as laboratory and field tests to summarise condition, break performance, break causes for pipes and systems. Research intends to model performance of pipes and predict the behaviour of pipes in the future thus helping the industry in developing rehabilitation or replacement strategy for existing pipe networks with a view for better management of the pipe assets.***

1. Background

The water supply situation of the Central Coastal Area of Namibia is becoming more desperate as the new and growing uranium mines' additional demand has outstripped the capacity of existing water supply schemes whose infrastructure is aged, unreliable and failing(NamWater, 2014).

The predicted water demand for mines and industries forErongo Coast was 5,426,346m^3 in 2014; 6,158,878 m^3 in 2015; 11,070,621 m^3 in 2016; 13,467,224 m^3 in 2017 and 13,657,274 m^3 in 2018(*SEIA*, 2015).

Considering the planned additional Uranium mines in the Region, the water demand was projected as 12.37, 43.49, 120.19, 241.35, and 408.41 Mm^3 for 2010, 2015, 2020, 2025 and 2030 respectively (Kgabi & Mashauri, 2014).

Most central coastal towns and mines in the Central Namib Area (CAN) have been historically supplied with water from the Omdeland Kuisebaquifers. The aquifers' volumes have been decreasing over the years. In 2014, the Omdel supplied 7.15Mm^3 of ground water to the CAN, but in 2015 it supplied 4.917 Mm^3 and it even exceeded the permit limit of 4.6 Mm$^{3/}$yr(NamWater, 2015a).

At present, there is one desalination plant, the largest of its kind in southern Africa, operating at Wlotzkasbaken, some 30 km from Swakopmund. It is owned by AREVA and operating since 2010, producing water at a rate of 55,000 m^3/day. The plant was constructed for the Trekkopje uranium mine, about 40 km away. It has the capacity to produce 20 Mm^3 of portable water per annum but it can be upgraded to produce 26 Mm^3 within the existing infrastructure. The Trekkopjie mine is expected to use around 12Mm^3 annually, with the surplus being made available for domestic and industrial users. The plant is currently connected to and supplies water to NamWater through a pipeline feeding from the Omdel aquifer that was completed in August 2013. In 2016 the plant was supplying to NamWater 5.04 Mm^3/yr, of which3 Mm^3/yr for Rössing mine and 2 Mm^3/yr for Husab mine.

The Omdel- Swakopmund water supply scheme supplies groundwater to Henties Bay and a mix of groundwater and desalinated water to Swakopmund and Arandis, as well as to three uranium mines Rössing Uranium, Husab and Langer Heinrich.

The 81.2 km long Omdel-Swakopmund Pipeline from the Omdel Collector Reservoir to the Swakopmund Base Station was previously of 700 mm diameter buried pre-stressed concrete pipe throughout. Due to the age of the pipeline 30-40 years old and adverse soil conditions, a number of sections deteriorated and were replaced with sections of 700 mm NB above-ground DCI pipe of 13.6 km in total.NamWater has registered a capital project, for completion in 2019, for the replacement of the old buried pipeline with a total length of 67.6 km.(NamWater, 2015b)

Currently, the new Wlotzkasbaken-Swakopmund Pipeline is being constructed of1200 mm NB DCI pipes above ground and buried Glass Reinforced Plastic (GRP) pipes, for a capacity of 30Mm^3/yr. It will replace a700 mm buried pre-stressed concrete pipes with a capacity of 10Mm^3/yr. Xing DCI pipes are being used, which are Chinese-manufactured by XingXing Pipes International Development Company (NamWater, 2015b).

Apparently, the cost of desalinated water is high. Rössing paid N$39 million in 2012 for aquifer water and N$129 million for desalinated water in 2014.RössingUranium mine currently purchases water through NamWater from the AREVA Desalination Plant for about US\$4.00/m^3(N\$56/m^3) and this constitutes a significant overhead cost for the mine.Also in the two months where Rössing Uranium experienced leach tank failure, the effective unit cost of water rose from US\$4.00/m^3 (N\$56.00) to approximately US\$9.00/m^3 (N\$126.00) (*SEIA*, 2015).

In January 2015, Rössing Uranium proposed to construct its own desalination plant, approximately 6 km north of Swakopmund at the existing Swakopmund Salt works, to supply the mine's needs.It is estimated that the cost of water from the new plant would decrease from the current average of US\$4.00/m^3 to less than US\$2.50/m^3 at point of supply, thus saving Rössing Uranium upwards of US\$3.5 Million per annum (approximately N\$50 million per annum). The plant would produce up to 10,000m^3 of portable water in every 24 hour cycle, which is consistent with their demand.

The clear water from the plant will be demineralised to meet potable water standards and pumped via an 850m long pipeline, which will be running into the existing NamWater pipeline (*SEIA*, 2015).

Steel, Ductile Cast Iron (DCI) and Glass Reinforced Plastic (GRP) piping materials were considered for a new 400mm diameter pipeline which will intersect with the existing 700mm diameter NamWater pipeline (*SEIA*, 2015).

Construction of the proposedRössing Uranium desalination plant was planned in 2015 and the investment cost for the plant was estimated to be between N\$220 million and N\$275 million. The cost did not include constructing a new pipeline from the plant to the mine.

For 3 million m^3/yr of water from the proposed desalination plant Rössing was expecting to save between N\$40 million to N\$60 million per year. It anticipates recovering the cost of constructing the plant within four years.

In April 2016 the government released its new Harambee Prosperity Plan (HPP). The plan includes water as a priority under infrastructure development. To meet the increased demand for water at the coast as a result of uranium mining activities, the government sets a goal to construct a 25 Mm^3/yr seawater desalination plant at Mile 6, North of Swakopmund municipal area,by February 2019 (*HPP*, 2016).

In 2015, AREVA announced its intent to sell its Erongo Desalination Plant and after a year of negotiations with the Government,AREVA put a price of N\$ 3 billion (US\$216 million) on its desalination plant. The government declined the offer, and said it would proceed with building of a new plant in a public-private partnership("Namwater desalination plant a "National Project," 2015).

In the light of the above, it is clear that desalinated water is only option available to mines operations in Erongo region.The Namibian Government and uranium mines are prepared to invest millions of dollars for construction of new desalination plants with the water carrying infrastructure in order to sustain the mining industry and the economy of Namibia.

The choice of material for piping systems for transportation of desalinated water is very important at the initial planning stage of any project, especially for highly aggressive environment at the coast. There are various materials for piping infrastructure that are now available on the market. The old pre-stressed concrete pipes and asbestos-cement(AC) pipes (30-40 years old) have reached the end of their useful life. These pipes are now being replaced by the Ductile Cast Irons (DCI) pipes of different classes C25, C30 (ISO);the Glass Fiber Reinforced Plastic (GRP) pipes andHigh-Density Polyethylene (HDPE) pipes.

2. Problem Statement

NamWater Corporation reported that during the financial year ending March 2015, a total of 433 pipe breaks throughout the country were repaired by the Corporation at a cost of N\$2,513,706.01.

Pipe breaks and leakages cause losses of water and customers pay for these losses. In Swakopmund, there is a special tariff for water leakage, which is equal to N\$14.20/m^3 (US\$1) in 2017, while households usually pay N\$4.20/m^3("Swakopmund Municipality tariffs," 2016).

In Windhoek, the lowest tariff the customers pay for portable water is N\$17,77/m^3 if they use not more than 6 m^3 per month, N\$26.47/m^3 (6-40 m^3 p.m.), N\$48,82/m^3 (40-50 m^3p.m.) and N\$112,50 (above 50/m^3 p.m.). Semi-purified water costs less N\$4,79/m^3("Windhoek Municipality tariffs," 2016).

Water is a very expensive commodity in Namibia and water losses must be minimized.

In January of 2017, the Namibian government has partnered with the French government on a project to curb water wastage due to pipeline leakages. Experts from the French engineering firm G2C Ingeniere intended to inspect three underground pipelines the Von Bach-Windhoek pipeline, Omatako-Von Bach pipeline and the Naute-Keetmanshoop pipeline (Ngatjiheue, 2017).

NamWater's pipeline network covers over 4000 kilometers across the country.

In the NamWater Annual report for 2015, the company identified the following problematic areas that need urgent attention in the CNA:

- There is a need for more reliable Wlotzkabasken-Swakopmund pipeline, 38 km long,that carries water from AREVA desalination plant. A section of this pipeline was replaced at an estimated cost of N\$450 million.
- Kuiseb-Schwarzekuppe-Swakopmund pipeline has reached the end of its economic life and needs to be replaced.
- Construction of the new water supply scheme consisting of a 600mm diameter pipeline and four pump stations,

from the Swakopmund Base reservoirs to the Husab Uranium mine needs to be completed.

Deterioration of water pipes at the coastal area is a big challenge faced by NamWater along with the lack of adequate funds to install, repair and replace the aged water supply infrastructure(*NamWater Annual report*, 2015).
The failure of materials due to corrosion is not uncommon,itcan be attributed to the use of improper materials for water pipes. Some of the engineering industry investigations on causes of failure showed that 38 % of failures are due to improper material selection (Brooks & Choudhury, 2002). Namibia water utility is faced with a dilemma on what materials are most suitable for transporting water at the coast.

3. Research Objectives

The main objective of this applied research is *to investigate the failure modes and the causes of failure of pipe materials used for water supply schemes in the Central Namibia Coastal area.*

To achieve the main objective the following objectives were identified:

1. Investigate the modes of failure of different pipe materials.
2. Establish the failure rates of different pipe materials.
3. Establish the causes of failure for different pipe materials.

In order to arrive at the objectives listed above, the following research questions are raised:

1. What are the modes of failure of different classes of pipes?
2. What are the rates of failure of different pipe materials?
3. What are the causes of the failure of water pipes?

4. Preliminary Literature Review

Water scarcity is already a problem in Namibia and in many parts of the world due to increasing populations, greater emands for water, and diminishing fresh water resources. In 1996, the Department of Water Affairs in the Ministry of Agriculture, Water and Rural Development of the Republic of Namibia conducted a feasibility study on the water supply to the Central Namib Area of Namibia. A variety of alternative water supply sources were investigated to assess their potential as a supplement to the utilized groundwater sources:

- Antarctic iceberg harvesting
- Solar distillation
- Utilization of coastal fog
- Tankering of water from Congo river
- Wastewater reclamation
- Saltwater desalination

The study concluded that seawater desalination was the most favourable option for the supplementing of the future water supply of the CAN (Ministry of Agriculture, Water and Rural Development., 1996).

An absolute necessity for the desalination process to work is to use corrosion-resistant materials in the construction of the plant and piping. Materials election and design criteria are affected by the specific operating conditions the material will be exposed to during its lifetime. Sea water contains approximately 3.5% salt (predominantly sodium chloride), as well as some minerals and organic matter. Seawater is generally more corrosive than fresh water, frequently producing pitting and crevice corrosion. Sea water materials in desalination plants are subject to uniform attack, galvanic corrosion, crevice-corrosion, pitting, and erosion-corrosion (Callister & Rethwisch, 2010).

DuctileIron has been a great material in water carrying pipes, heavy duty parts of farm equipment and other heavy applications. Oke and Ukoba (2013) looked into the corrosion rate of ductileiron in different environments of usage and storage for a period of six (6) months. The environments were outside air, air conditioned (A/C) environment, brackish (salty) and alkaline environments. The results showed that as the period of exposure increased the corrosion rate decreased. There was a sharp corrosion rate at the first few months for all the environments but as the month increased the corrosion slowed down. Brackish (NaCl) environment had the highest weight loss (Oke & Ukoba, 2013).

Steels and cast irons are composed of iron alloyed with relatively small percentage by weight of carbon. However, cast irons differ from standard steels by having significantly higher carbon (C) and silicon (Si) contents. Steels typically has 1.2% by weight carbon and little or no silicon, whereas the carbon content in cast irons typically ranges from 2.5 to 4.5% by weight C and from 1% to 3% by weight Si. Cast irons also often have higher sulphur (S) and Phosphorus (P) contents, and Manganese is an important additive in both metals.The basic material of cast iron consists of metal and graphite flakes. The size and the shape of the graphite flakes and the exact type of metal depend on the manufacturing process.

The creation of graphite flakes as cast iron cools is unavoidable, but it is also detrimental to the strength of a pipe. Flat flakes act as natural crack former, which means that gray cast iron tends to produce brittle fractures that travel along the flakes. Modifying the shape or size of these flakes can improve the material’s mechanical properties. In ductile iron the addition of small amounts of magnesium causes the graphite to form spheres rather than a continuous network of flakes. As a result ductile iron is stronger than gray iron (Makar & Rajani, 2000).

A detailed examination of the pipe failure records for the City of Winnipeg, Canada, was performed. The failures were examined by age, type of failure, and degree of spatial and temporal clustering for each of the four most common failure types: namely, joint, circular crack, longitudinal split, and hole. A detailed examination of joint failure showed universal joints in castironpipes to be the most common type of joint failure. It was found that failures in general were more common in pipes 11–30 years old (Gowlter & Kazemi, 1989).

A failure investigation was conducted on a 30.5-cm diameter graycastiron water main that failed in Anchorage, Alaska, due to a longitudinal fracture. Mechanical testing and microanalysis were performed on the pipe material. The cause of the failure was determined to be brittle fracture which initiated at a subcritical corrosion fatigue (CF) crack approximately 40.6 cm in length(Cullin, Petersen, & Paris, 2015).

A study on the long-term corrosion behaviour of castironpipes in the absence of historical data was carried out by Mohebbi& Li (2011). The corrosion behaviour of three ex-servicepipes was thoroughly examined in three simulated service environments. It has been found that localised corrosion was the primary form of corrosion of castironwaterpipes. It has also been found that the microstructure of cast irons was a key factor that affects the corrosion behaviour of castironpipes. It concluded that long-term tests on corrosion behaviour of castironpipes could help develop models for corrosion-induced deterioration of the pipes for use in predicting the remaining service life of the pipes.

Deteriorated water distribution system in the Canadian city of Torontoloses 25% of all drinking water due to leaks and water main breaks. On average, it encounters 0.02 breaks per kilometre per year. For comparison, the New York City's average break rate is approximately 0.05 breaks per kilometre per year. Most of the pipes in the Toronto system range between 102 mm and 305 mm in diameter and were made of gray cast iron. A study was conducted to establish mechanical properties of exhumed water pipes. Some of the factors that contributed to pipe failure were corrosion and mechanical properties of pipes. Corrosion pits could affect the strength of the pipe material by acting as stress concentrators and crack initiators. Strength could also be influenced by manufacturing defects such as presence of air inclusions (Seika & Packer, 2004).

In the study of Moreno (2003), the Geographic Information System (GIS) was used to identify the areas with a high potential risk of failure. It was found that the major causes of leakage in water distribution systems are deteriorated pipes, defective joints and sealing, and faulty service connections. The major causes of pipe failure are corrosion, erosion of the pipe bedding support, excessive loads, and temperature stresses. It was determined that previous failures increased the likelihood of future failures in its immediate vicinity. Corrosion appeared to be the most detrimental factor in the pipe failures.

Fiberglass pipe was first used in 1948 and was originally used primarily in the oil and chemical process industries. In the 1960s, fiberglass became more common in the water and sewage markets.Resistance to corrosive soils, water and wastewater is one of the advantages of fibreglass pipe. No protective coatings and linings are necessary. Fibreglass pipe has not been in use for long enough to definitely determine a useful life, but field research would indicate a life expectancy greater than 100 years (Beieler, 2014).

Glass-fiber reinforced polymer (GRP) pipes are used extensively in petrochemical, desalination and power industries for the last two decades in many engineering structures that need high strength-to-weight ratio and corrosion resistance. GRP is made of glass fibers with epoxy polymer matrix. For the use in low temperatures and low-pressure applications, GRP would offer an attractive alternative to steel in pipe manufacturing. The presence of various defects, such as voids, pits, inclusions, corrosion, disbands, improper cure and delaminations is almost common during manufacturing, handling, and under servicing conditions of GRP pipes. Among various defects, severe pits or wall loss defects can be internally produced after a certain period of time due to media corrosion, stress corrosion cracking, materials deterioration, and cavitation erosion. These defects finally lead to accidents in most of the industries due to leakage of pipes(Vijayaraghavan & Sundaravalli, 2011).

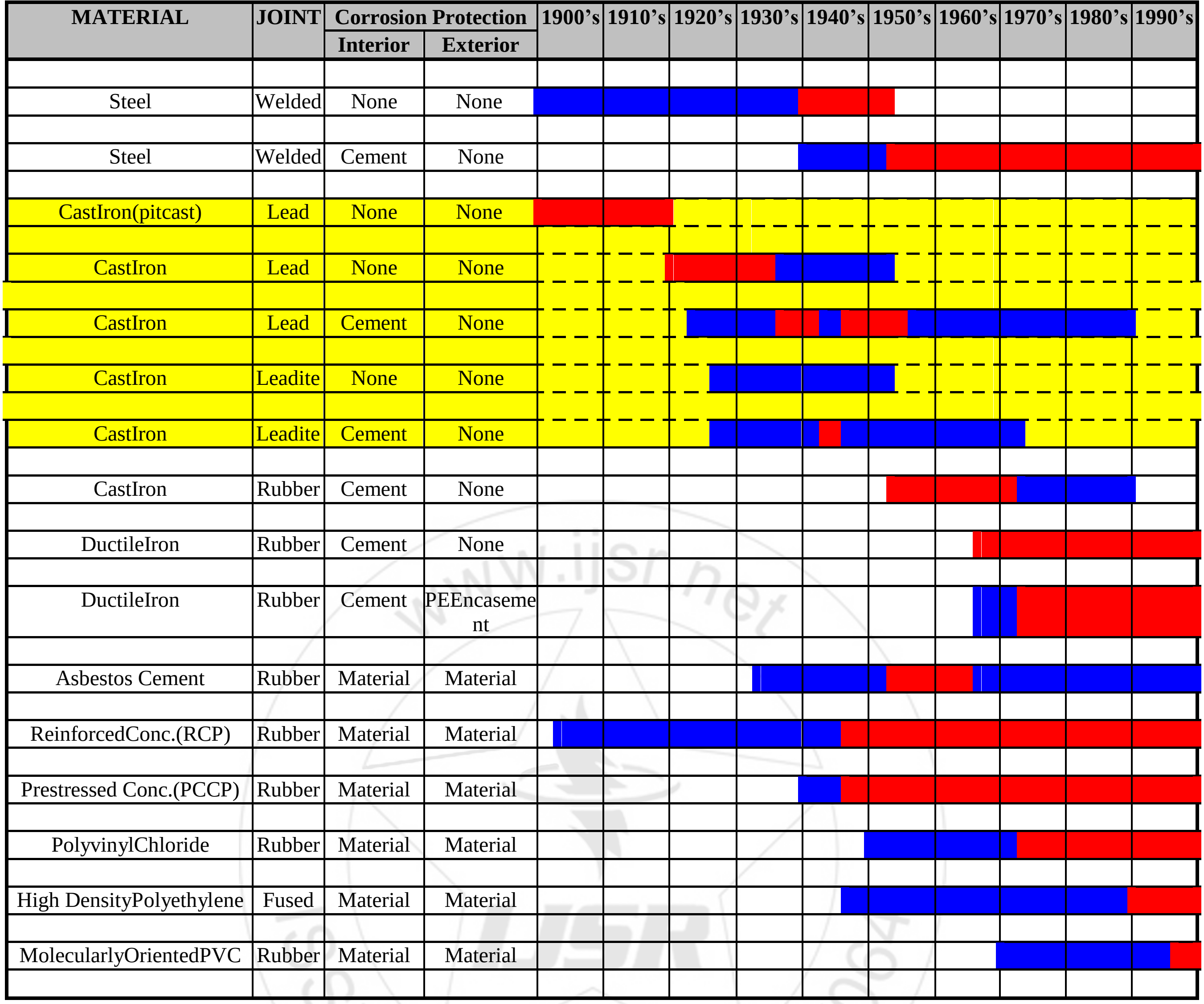
GRP pipes are frequently subjected to humid conditions and these materials absorb moisture from the environment. The strength of bonding at the fibre matrix interface decreases in the presence of high temperatures and moisture uptake(Guedes & Alcides, 2010).

High Density Polyethylene (HDPE) pipes are corrosion resistant and do not require protective coatings. If appropriate stabilisers are not added to the polyethylene, ultraviolet (UV) light can cause degradation to the product by long-term exposure. The most common stabiliser is carbon black. HDPE pipe has a relatively high coefficient of expansion (2.2×10^{-4} m/m/^{0}C). Thermal expansion and contraction effects must be considered in the design of pipes that will experience significant temperature changes. The useful life of a polyethylene pipe system is dependent on proper installation, stress applied to the pipe, maintenance and the environment. Experience has shown that such pipes in service for more than 40 years have not suffered any significant problems. Research indicates that the useful life is in excess of 100 years (Beieler, 2014).

The first Polyvinyl chloride (PVC) pipes were made in the 1930s. During the 1950s, they were used to replace corroded metal pipes. The predicted lifetime of plastic piping systems exceeds 100 years.

The use of both polyvinylchloride (PVC) and high- density polyethylene (HDPE)in USA began to emerge in the1970's and 1990's respectively. Although these pipes did not have the strength of ductile iron, the irresistance to corrosion is unsurpassed (American Water Works, 2002).

Table 1: Timeline of Pipe Technology in the U.S. in the 20thCentury(American Water Works, 2002)



MATERIAL	JOINT	Corrosion Protection		1900's	1910's	1920's	1930's	1940's	1950's	1960's	1970's	1980's	1990's
		Interior	Exterior										
Steel	Welded	None	None	🟦	🟦	🟦	🟦	🟥	🟥				
Steel	Welded	Cement	None					🟦	🟦🟥	🟥	🟥	🟥	🟥
CastIron(pitcast)	Lead	None	None	🟥	🟥								
CastIron	Lead	None	None			🟥	🟥🟦	🟦	🟦				
CastIron	Lead	Cement	None			🟦	🟦🟥	🟥🟦🟥	🟥🟦	🟦	🟦	🟦	
CastIron	Leadite	None	None			🟦	🟦	🟦	🟦				
CastIron	Leadite	Cement	None			🟦	🟦	🟦🟥🟦	🟦	🟦	🟦		
CastIron	Rubber	Cement	None						🟥	🟥	🟥🟦	🟦	
DuctileIron	Rubber	Cement	None							🟥	🟥	🟥	🟥
DuctileIron	Rubber	Cement	PEEncasement							🟦	🟦🟥	🟥	🟥
Asbestos Cement	Rubber	Material	Material				🟦	🟦	🟦🟥	🟥🟦	🟦	🟦	🟦
ReinforcedConc.(RCP)	Rubber	Material	Material	🟦	🟦	🟦	🟦	🟦🟥	🟥	🟥	🟥	🟥	🟥
Prestressed Conc.(PCCP)	Rubber	Material	Material					🟦🟥	🟥	🟥	🟥	🟥	🟥
PolyvinylChloride	Rubber	Material	Material						🟦	🟦	🟦🟥	🟥	🟥
High DensityPolyethylene	Fused	Material	Material					🟦	🟦	🟦	🟦	🟦	🟥
MolecularlyOrientedPVC	Rubber	Material	Material								🟦	🟦	🟦🟥

Commercially Available	🟦	Predominantly In Use	🟥

Table 2: Comparison of Distribution Size Pipe Materials-Material Properties(American Water Works, 2002)

MaterialProperty	DCI	PVC	HDPE
Tensile strength	414 MPa	48 MPa	22MPa
Compressivestrength	331 MPa	62 MPa	110 MPa
Yieldstrength	290 MPa	100 MPa	34 MPa
Ring bending stress	331 MPa	none specified	none specified
Impact strength	934 J/m	40 J/m	187 J/m
Density	7064 kg/m^3	1419 kg/m^3	955 kg/m^3
Modulus ofelasticity	165GPa	3GPa	1GPa
Temperaturerange	<65,56^0 C	< 60^{0}C	-45,56^{0}C to 60^{0}C under press.
Thermal expansion	4,8 x 10^{-6} m/m/^{0}C	22,5 x 10^{-6} m/m/^{0}C	68,2 x 10^{-6} m/m/^{0}C
Corrosion resistance(int)	Good-w/cement lining	Excellent	Excellent
Corrosion resistance (ext)	Good- w/polywrap	Excellent	Excellent
UV resistance	Excellent	Gradual strength decline	Yes-w/carbon black
Abrasion resistance	Excellent	Good	Good
Cyclic resistance	Excellent	Fair	Good
Permeationresistance	Yes	No -solvents& petroleum	No -solvents& petroleum
Scale &growthresistance	Good	Excellent	Excellent

The primary difference between the three materials is that DCI is much stronger than PVC or HDPE. However, DCI is susceptible to corrosion which is not an issue with the other two materials. PVC pipe is very similar to DCI pipe interms of installation, repair, and tapping, and thus it was easy for water utilities, which had historically used cast iron pipe, to transition to PVC pipe. HDPE is flexible and less brittle than PVC pipe, and has been popular in applications such as directional drilling, slip lining, and pipe bursting. 70% of all new pipe installed in the United Kingdom was HDPE, and it has successfully been utilized in that country for over 50 years. Both PVC and HDPE pipes experienced a reduction in strength over time (American Water Works, 2002).

5. Significance of the Study

The availability of water remains a key factor to Namibia's economic development. Decisions on the need form a intenance or replacement of pipes should be based solely on how the pipe performs. Similar types of pipes in different operating conditions perform differently.

Water pipes are subject to uniform attack, galvanic corrosion, crevice-corrosion, pitting, and erosion-corrosion. The findings of this research will provide knowledge and understanding of how different pipes perform. This appliedresearch will address a problem of fast deteriorating pipes faced by water utilities at the coastal area of Namibia. Research intends to model performance of pipes and predict the behaviour of pipes in the future thus helping the industry in developing rehabilitation or replacement strategy for existing pipe networks with a view for better management of the pipe assets.

6. Research Methodology

Research design will rely on descriptive analysis and physical analysis. Descriptive analysis will organise and summarise the inventory, condition, break data and break patterns for pipes and systems and physical analysis will use physical methods such as laboratory and field tests to summarise condition, break performance, break causes for pipes and systems.

The main objective of this research is *to investigate the failure modes and the causes of failure of pipe materials used for water supply schemes in the Central Namibia Coastal area.*

In order to achieve the main objective and answer the research questions the researcher will:

- Conduct a survey and collect information on pipe materials, their classes and properties
- Collect information on the size, diameter, coatings, thickness, chemical composition of pipes, age.
- Collect historical pipe breakage records
- Examinethe mill fabrication certificates from manufacturers
- Examine operating conditions of pipelines employed
- Conductinterviews with engineers, maintenance workersand management
- Conduct visual examination of pipelines during field visits
- Visual inspections of failure modes and fractures
- Take photographs of failure modes and fractures
- Examine corrosiontypes
- Examine the fracture surfaces to establish the mechanisms of fracture.
- Examine maintenance reports
- Examine the failure reports and calculate ofthe unit of intensity failures, which is the number of failures per 1 km per year (failures/km year)
- Calculate the corrosion parameter or the rate of material removal as a consequence of the chemical action. This is expressed as the corrosion penetration rate (crp), or the thickness of material per unit time. The researcher intends to use the formula to calculate the corrosion rate for old pipes:

$CPR = \frac{KW}{\rho At}$, where W is the weight loss in milligrams, after exposure time t (hours); ρ- density (g/cm^3), A-area (cm^2), K is a constant equals to 87.6 for CPR in mm/yr. For most applications a corrosion rate of 0.05 mm/yr is acceptable.

- Carry out the geometrical evaluation to characterise the general state of the pipes.
- Use of scanning electron microscopy for fracture analysis
- Investigate the microstructure of dci pipes of different classes
- Preparesamples for microscopicexamination in accordance with iso standards. Specimens (10mmx10mmx10mm) from different ex-service dci pipes will be cleaned, cut, polished, etched and examined using a scanning electron microscope (sem), ssm-it 300.
- Conductmicroscopic examination and analysis of metallographic specimens.
- Determine the chemical composition of the samples using x-ray spectroscopy (edx).imaging with back-scattered electrons (bse) and secondary electrons (se) will provide information about the distribution of different elements in the samples, graphite flakes types and sizes and percentages of the phases present in the microstructure (graphite, pearlite, ferrite and cementite)
- Use spss to record and analyse collected data
- Carry out regression analysis to model the performance of pipes

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