

# **PVC PIPES FOR LIFE – MODERN DEVELOPMENTS AND DESIGN CRITERIA : PVC-U, PVC-M AND PVC-O**

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## **ABSTRACT**

Pipe materials technology and market needs have combined to advance developments in material savings while enhancing pipe properties. Increasing PVC pipe material design stresses from 10 to 32 MPa and the corresponding reduction in wall thicknesses and safety factors is described and includes a consideration of the concepts of strength and toughness as applied to design criteria for PVC-U, PVC-M and PVC-O pressure pipes. Starting with the stringent requirements of modified pipes for the mining industry, these developments clearly demonstrate the versatility and durability of PVC.

## **INTRODUCTION**

High value thermoplastic pipes such as polyvinyl chloride (PVC-U) and polyethylene have been used for almost 60 years; their properties and design criteria are well understood. Interestingly, perhaps surprisingly, it is only in recent years that significant steps have been taken to improve the competitive position of PVC pipes via material savings. The impetus has mainly been in developing countries, given the critical requirement for potable water and the incentive for water authorities and engineers to accept new pipe technologies. Pipe standards were virtually being written even as pipelines were being commissioned! The acceptance of more cost effective pipe systems is motivated by the fact that no single measure can do more to reduce poverty and disease and to save lives, than the provision of safe water and adequate sanitation.

In this paper we consider the development of modified PVC (PVC-M) and relevant pipe design criteria. This necessitates a review of the development and use of impact modified PVC pipes in the mining industry in South Africa which clearly demonstrates the durability and versatility of PVC in the harshest of environments.

The move to higher design stress, thinner wall pipes would probably have slowed were it not for the advances made in perfecting the in-line production process for oriented PVC (PVC-O) pipes (1,2). PVC-O pipes made using this process have an exceptional combination of strength and toughness properties enabling much higher design stresses and material savings.

## **PVC PIPES IN MINING**

South Africa is blessed with an abundance of minerals, especially gold and coal. However, a problem with gold is that it is mined at very deep levels underground, today approaching 5000m. Working conditions are extremely onerous with ambient temperatures approaching 50°C and, for health and productivity reasons, cooling and fresh air ventilation is necessary. Cooling underground is effected by pumping water at 5°C many kilometers down vertical shafts, along haulage

ways and to gold bearing rock faces. Ventilation air is conveyed underground, then cooled to reduce ambient temperatures and improve working conditions, while compressed air is necessary for operation of rock drills and other mining equipment. The chilled water, having done its job, must be pumped back up to the surface for reuse. Steel pipes are the preferred carrier notwithstanding the high humidities underground and corrosive acidic conditions.

Under these conditions the safety of miners is paramount and all aspects of underground mining are subject to the most stringent safety rules; obviously pipe failures cannot be tolerated. In the mid-1970's it was decided to enter this market with PVC pipes.

### **PVC Mining Water Pressure Pipes – Some Design Considerations**

It became obvious that toughness was an essential requirement if PVC pipes were to penetrate the market held almost 100% by steel. Development work involved:

- The properties and consistency of the PVC polymer, in particular: K-value, apparent density, CPA (cold plasticisor absorption or porosity) and thermal stability.
- Various impact modifiers, taking into account pipe storage and outdoor weathering.
- The level of addition of these modifiers.
- Extrusion conditions to optimise processing and pipe toughness.
- The development of a suitable pipe joint.
- Testing procedures to verify quality in terms of pipe strength, toughness and consistency.
- A pipe standard for mining which had to be devised and accepted by the industry.

Chlorinated polyethylene (CPE) impact modifiers were selected as giving the best balance of properties and ease of processing. The first PVC pressure pipes supplied for chilled water contained 12 phr of modifier which was subsequently reduced to 10 phr in order to increase long-term strength and was later reduced still further, whilst maintaining acceptable toughness and a 50-year failure stress of 25 MPa.

A special 'pipe grade' polymer was developed and close tolerances set for pertinent polymer properties. Higher extrusion temperatures and shear are necessary to achieve correct levels of gellation and develop optimum toughness properties; this lead to improvements in the heat stability of the polymer. Polymer developments undertaken at that time and which have continued over the years, resulted in a material whose critical properties were essential to the later development of higher design stress, PVC-M pipes.

Mine pipes are suspended along haulage ways using metal S hooks and chains as shown in Figure 1.



**Figure 1.** Chilled water pipe installation in a mine haulage way.

As seen in Figure 1, the pipes are suspended and a pipe coupling resistant to end thrust was developed to handle the 16 bar and higher pressures used in mining. The coupling is compatible with steel pipes and uses standard fittings. The factory fitted Victaulic steel joint has serrated teeth on the inner surface which bonds to the pipe ends via mechanical interference, providing a watertight joint. Standard rubber seals and clamps are used to couple the pipes, as shown in Figure 2.



**Figure 2.** PVC mine pipe coupling system.

Standard impact tests are inadequate for determining toughness properties of these pipes and a high-speed (20m/second) impact test had to be developed so as to characterise pipe toughness properties and for process control purposes. The test involves dropping steel strikers having masses up to 30kg on pipes from a height of 20m; impact energies are 600-5000J, depending on pipe size (3). Ductile ‘failure’ is the requirement on this test. These special toughness properties are essential to prevent (brittle) failures of the pipes, in particular at the rigid steel ends, resulting from stress concentration effects.

The impact test equipment and a typical ductile pipe failure are shown in Figures 3(a) and (b).



**Figure 3a.** High-speed impact test.



**Figure 3b.** Results of the impact test on mine pipe test sample.



PVC mine pipes offer superior thermal insulating properties vs. steel pipes. This translates into energy savings, as less power is consumed in re-cooling the return water to 5°C.

The modified PVC product with Victaulic steel ends has also been preferred for many years now by the Johannesburg City Council for 12 and 16 bar municipal water supply.

### **PVC Mine Pipes for Compressed Air**

Pipes conveying compressed air at 7 bar must be ‘fail-safe’ under all conditions, especially considering stored energy effects and possible impact failure. A modified PVC pipe has been developed to meet this critical requirement.

In early development testing pipes were burst using nitrogen at approximately 50 bar. In another test for ductility, the failure of the pipe containing 7 bar air pressure was initiated by an explosive detonator attached to the pipe wall.

Given the critical application and the mining environment, a long-term safety factor of 3 is used for pipe design.

### **PVC Pipes in Mining – Some Conclusions**

Modified PVC pipes have been used successfully in extremely harsh mining environments for 25 years. The material's versatility lends itself to formulations covering a variety of demanding applications. Sustainability of the product is demonstrated in several mines where PVC pipes are later removed for reuse; this is not generally the case with steel pipes because of deterioration through corrosion.

The design stress for modified PVC mine pipes has been raised to 12,5 MPa based on a long-term safety factor of 2, accepted by the industry (3).

Most importantly, the experience gained with PVC polymers and modified formulations, pipe extrusion and gellation, the material properties of strength *and* toughness and especially the proven durability of modified PVC mine pipes over many years, all contributed to the development of a product that was to have far reaching consequences in pressure pipe markets. This product, now known as PVC-M (or PVC-A) was to prove itself the most cost effective pressure pipe for potable water reticulation and agriculture.

Before examining the design criteria for PVC-M, it is worthwhile considering the history and developments of PVC-U pressure pipes.

### **A BRIEF HISTORY OF DEVELOPMENTS WITH UNPLASTICISED POLYVINYL CHLORIDE (PVC-U) PRESSURE PIPES**

PVC-U pressure pipes have been in use at least since the early 1950's. Correctly processed, the material with its high modulus and excellent retention of long-term strength, has proven itself the most successful plastic pressure pipe worldwide (4). Only in recent years with the development of HDPE in grades PE80 and PE100, and the attacks on chlorine and PVC in certain countries, has the growth rate slowed in comparison with that of HDPE (5,6).

Unfortunately, failures of PVC-U pressure pipes manufactured in the 1960/70's in the UK led to setbacks for the product which are apparently being experienced to this day. By most accounts, the major cause of these pipeline failures was extrusion processing problems associated with pipeline installation and operational conditions (7). It is to the credit of the industry in that country and elsewhere, that the extensive work undertaken effected solutions to these problems. Hitch, Benjamin, Marshall and others were at the forefront of these developments (8,9,10,11). This led not only to a realisation of the importance of processing and gellation with respect to slow crack growth, fracture toughness and stress concentration effects but also to procedures for controlling the properties and quality of PVC-U pipes. These involved improvements to the polymer, a better understanding of formulations, a closer involvement of extruder manufacturers and improvements in processing, as well as pipe testing and quality control procedures.

A positive outcome to the improvements in the quality of PVC-U pipes was a decrease in the factor of safety from 2,5 to 2,0, accepted by most countries in Europe and elsewhere (12,13).

Nevertheless, the properties of PVC-U remain essentially the same, hence the requirement for the relatively high safety factor.

## **HIGH DESIGN STRESS, MODIFIED PVC (PVC-M) PRESSURE PIPES**

How to satisfy the critical need for the distribution of potable water in developing countries, allied to the lack of, and competing capital resources, was the motivation for developments which (at that time) resulted in the greatest design change in the history of thermoplastic pipes for large scale water reticulation.

The raw material component makes up about 60-70% of the ex-factory cost of plastic pipes. Notwithstanding this, most cost saving efforts over the past 50 years have been directed at the manufacturing process in terms of productivity and control systems.

Why have developments involving material savings not received more attention? Some possible reasons:

- Pricing structures vs. traditional materials.
- Concern by pipe manufacturers that lighter pipes would lead to a reduction in overall tons converted.
- Energy expended on manufacturing productivity improvements.
- The conservative nature of the industry, as evidenced by relatively high pipe design safety factors and resistance to change.
- Opposition and a negative response by less innovative competitors.
- Excessive time involved in finalising new pipe standards.

Against this background, several years were spent developing a more cost effective piping system which would meet international quality requirements, including the minimum 50 year design life.

Some basic design principles that are well known to manufacturers and pipeline design engineers are dealt with below to assist with an understanding of PVC-M pipe technology. (These are aimed at readers who are perhaps not well versed with these issues).

### **Pipe Design Principles – Material Strength**

Standards for plastic pipes have, until fairly recently, dealt almost exclusively with the *strength* properties of materials (12,14). Pipe standards do include requirements for impact but these are usually of the qualitative, pass/fail variety and essentially process related. Few standards specify definitive requirements for *toughness* and only in recent years has a test for fracture toughness been introduced (12, 13).

### **Creep Rupture Regression**

This is the primary *strength* requirement contained in plastic pipe standards (12,13,14). The creep property relates to the dimensional stability or gradual deformation under load. It is the essential factor when evaluating working pressure and the expected life of the pipe.

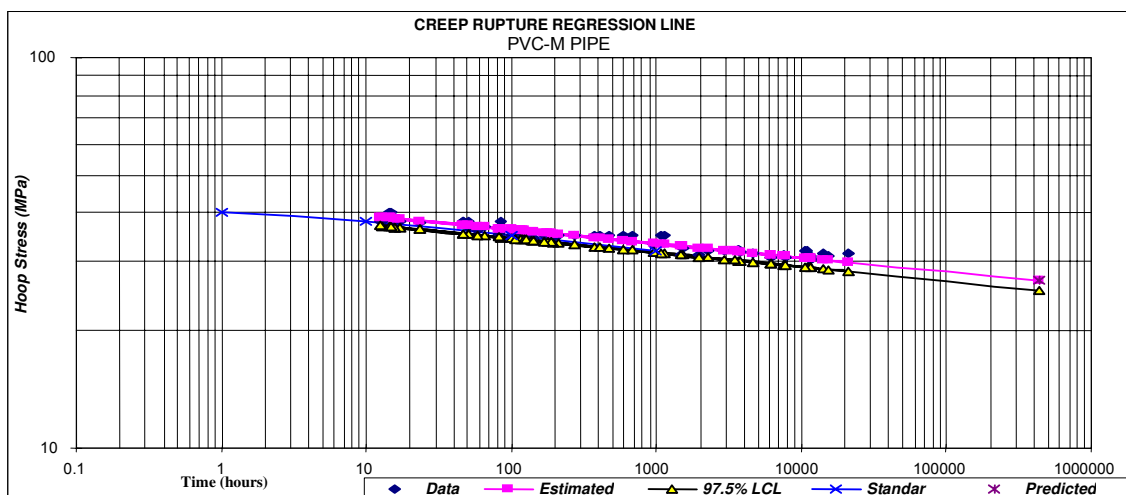
The stress on the material at any given pressure is calculated from Barlow's formula :

$$\sigma = \frac{p(d_e - e)}{2e} \quad [1]$$

where  $\sigma$  = hoop stress in the pipe wall (MPa)  
 $p$  = internal pressure (MPa)  
 $d_e$  = mean external diameter (mm)  
 $e$  = min. wall thickness (mm)

The rate of creep in response to stress gradually decreases with the passage of time, but it is necessary to study the creep rupture strength of plastics for a period of time. From the creep tests on a plastic pipe, a creep rupture or stress regression curve is developed which takes the form of a plot of the logarithm of the hoop stress against the logarithm of the time to failure, at constant temperature (e.g. 20 or 60°C). Creep rupture analysis lends itself to extrapolation using well established mathematical procedures as described in ISO/TR9080 (15).

Long-term pressure testing of PVC-M has been carried out for many years now – the creep rupture regression curve for PVC-M takes the form of a straight line and is shown in Figure 4.



**Figure 4.** Creep rupture regression line for PVC-M

Application of the method described in ISO/TR 9080 gives the 97,5% lower confidence limit of the long-term hydrostatic strength and from this the minimum required strength (MRS) at 50 years is determined. The MRS for PVC-M is 25 MPa (16).

### Material Toughness

In many cases strong materials can be quite brittle which may be a problem with materials having small defects or notches and then subjected to impact or external stresses; high stresses developed at the tip of the notch can lead to unpredictable crack growth and eventual failure. Therefore, higher safety factors are accepted as a requirement for materials having greater strength but subject to brittle failure in certain circumstances. Such failures are due to the inability of the pipe wall to absorb and distribute the stresses through the matrix of the material and under these circumstances premature failure can occur at stresses well below the ductile or failure yield line and the mode of failure will inevitably be brittle (17,18,19).

**Toughness** must be considered equivalent in importance to strength as it is this property that increases the resistance of the material to the propagation of cracks. Brittle failure would not occur with tough materials having predictable failure properties; therefore the material's toughness bears a direct relationship with the long-term safety factor.

### **Design Stress and the Safety Factor**

With the development of PVC-M advantage was taken of the many years of work on the technology of alloys and blends and experience gained with modified PVC pressure pipes in the mining environment. The excellent long-term strength properties of PVC-U have been retained while the toughness of the material has been enhanced to the extent that ductile failure modes are achieved in the high-speed impact test, C-ring fracture toughness, tensile-impact and other tests (16).

Toughness properties are optimised in the extrusion process through the development of an entangled molecular network by subjecting the PVC powder particles and additive mixture to the appropriate amount of heat and mechanical shear; gellation is the key to the development of these properties.

A design stress of 18MPa is used for the calculation of wall thickness; this results from the MRS of 25 MPa and the application of a 50 year safety factor of 1,4 (16).

### **PVC-M - Other Properties**

PVC-M pressure pipes have been used for potable water reticulation and agriculture throughout Southern Africa; over 25 000 km of these pipes in the size range 50-500mm and pressure classes PN 6 to 25 have been successfully installed over the past ten years - proof of a durable and very competitive pressure pipe

The wall thickness and mass of PVC-M pressure pipes are approximately 30% less than the equivalent PVC-U pipes, with obvious advantages in hydraulic capacity, transport, handling and installation. The thinner walls and slightly lower modulus of elasticity results in lower water hammer wave celerities than PVC-U pipes.

Creep in tension tests over six years indicate a maximum strain value of 1,5% at 50 years. The Poisson ratio determined on pipe subjected to working pressure for six years was found to reduce to 0,33 over this period; these properties show joint integrity well over 50 years.

### **BIAXIALLY ORIENTED (PVC-O) PRESSURE PIPE**

PVC-O pressure pipes have been used for almost 30 years but it is only with the advent of the in-line production process that the product has become competitive against pipes such as PVC-M, for the following main reasons:

- The greatly improved production output rates and reduced manufacturing costs.
- The remarkable combination of strength and toughness properties which allows for higher design stresses and material savings, especially in the higher pressure classes.

### **Strength and Toughness Properties**

PVC-O pipes are manufactured by a patented process which orientates the long chain molecules of feed stock PVC-U pipe produced by conventional methods of extrusion. Increasing the

diameter of the pipe during the process orientates the molecules in the hoop direction and leads to substantial improvements in the physical properties, both ***strength and toughness***. The molecular orientation greatly increases the short and long-term strength of the material.

Given the outstanding strength and toughness properties, 50 year safety factors of 1,6 or 1,4 can be applied for MRS 45 and MRS 50 PVC-O materials (20). Design stresses of 28 and 32 MPa are used for these PVC-O pipes resulting in material savings of over 50% and 30% against the equivalent PVC-U and PVC-M products, respectively.

The process of molecular orientation produces a laminar or layered structure which is the key to the toughness and performance of PVC-O pipes. If cracks do form, for example, due to defects or point loads, their passage through the material is hindered by the layered structure and propagation is effectively arrested by a reduction in stress concentration as the crack passes through each layer (1,2).

Other advantages of PVC-O pipes resulting from the higher design stress are increased hydraulic capacity and improved handling and installation characteristics.

### **Special Properties of PVC-O Pipes - Surge and Fatigue**

Fatigue of plastics pipes is not usually associated with well-designed and operated pipelines and failures due to fatigue are extremely rare. PVC-O pipes have extremely good resistance to fatigue failure and can be specified in those installations where some pressure cycling is anticipated and providing design engineers with greater confidence. PVC-O pipes also have excellent resistance to surge pressures and water hammer and are quite capable of withstanding pressure transients over twice their rated working pressure (21). To further illustrate this property, the tensile-impact strength of PVC-O pipes determined on test specimens cut in the hoop direction of the pipe is 1 000 kJ/m<sup>2</sup> (over twice that of PVC-M pipes) at an impact velocity of 4m/sec.

### **Applications for PVC-O pipes**

Applications include pumped water reticulation systems and rising sewer mains and installations where greater safety is required with respect to pressure surges, water hammer or pressure cycling.

Figure 5 is a practical field example illustrating the excellent toughness and handling properties of PVC-O pipes.



**Figure 5.** A construction site illustration of the toughness properties of PVC-O pipes.



PVC-O pipes fitted with steel Victaulic joints are suitable in the mining environment. Having less than half the mass of modified PVC mine pipes provides advantages in handling and installations underground and in the higher pressure classes (16-25 bar) the product is competitive against traditional steel pipes.

The products good performance in rapid crack propagation tests (2) implies potential for conveyance of compressed air.

## **QUO VADIS : PVC THE FUTURE**

Despite the advances made by other thermoplastics and some environmental concerns, PVC is still the preferred material for pipes (4,5). It makes the best possible use of valuable resources and uses minimal energy during production compared to other pipe materials.

What of the polymer? It seems unlikely that a stronger molecule can be made. Rather, greater emphasis will be placed on the material's consistency, improvements in thermal stability and processing properties.

The new 36D twin screw extruders provide the latest in extrusion technology with high production rates and significant improvements in processing and gellation and overall pipe quality.

Given its remarkable versatility, outstanding durability and cost effectiveness there is no reason why PVC should not continue into the future as the material of choice for pipes. The material's attributes are well illustrated in this paper, from traditional PVC-U to competitive PVC-M and PVC-O, produced by the in-line process, destined to become increasingly used for higher pressures and more demanding applications. The trend to larger diameters will continue at the expense of traditional pipe materials. Safety factors down to 1,25 for PVC-O pipes should soon be accepted in the industry.

Indeed a success story for the pipe industry!

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