Characterization of Polyethylene Pipe Properties Through Advanced Metrology Techniques

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Characterization of Polyethylene Pipe Properties Through Advanced Metrology Techniques

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Abstract. This study utilized advanced characterization techniques to evaluate the quality and performance of polyethylene (PE) pipes for water and gas applications. Three pipe types were examined: PE100 for water (blue and black) and PE80 for gas (yellow). Computed tomography quantified porosity, revealing 2.3 times higher void fraction in black PE100 vs yellow PE80 pipes. Surface roughness metrics showed black PE100 pipes had the smoothest internal surface (Ra 1.459 μm) attributed to its carbon black pigment. Friction coefficients indicated yellow PE80 pipes exhibited the highest resistance to fluid flow ($f = 0.0221$) among the three. These findings have significant implications on pipe quality control and selection for manufacturers and end users. The results demonstrate how factors like polymer composition and pigments influence critical performance metrics like porosity, surface roughness and friction.

Keywords: Polyethylene Pipes · Quality Assurance · Computed Tomography · Roughness · Porosity · Friction Coefficient · Geometrical Dimensions and Tolerances · Geometrical Product Specifications · Metrology

1 Introduction

Polyethylene (PE) pipes are flexible plastic pipes with various applications in water supply, gas supply, sewage, irrigation, fire protection and communications [1]. PE piping systems have been used successfully for decades and their performance is evaluated by standard extrapolation method based on internal pressure tests as described in EN ISO 9080 [2]. This method classifies PE pipes according to their minimum required strength (MRS) to ensure a service life of at least 50 years. Modern PE materials with classification PE 100 (MRS = 10 MPa) and above are available today [3]. However, the long-term failure behavior of these materials is a crucial factor for the lifetime and safety assessment of PE pipes. The main failure mechanisms of PE pipes are crack initiation and slow crack growth (SCG), which can be characterized by linear elastic fracture mechanics methods [1, 4]. The SCG mechanism causes small cracks in the porous structure to grow over

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time and eventually break the pipe. Therefore, it is important to examine and analyze the permeability properties of PE pipes at the microscopic level [4]. The aging behavior of PE materials should also be considered in long-term applications of PE pipe systems. This, in turn, can affect mechanical properties and resistance to crack initiation and SCG [5].

Computed tomography (CT) has proven its use in materials science over the past few decades to characterize internal microstructures non-destructively [6]. Although there are studies using CT-based models in the literature (the vast majority of them relate to medical applications), few have explored how these resource-demanding models can be used to derive reduced-order models more amenable to engineering analysis and design. The novelty of this work lies in understanding how advanced CT-based models can be used to construct continuity-based finite element models for use in large-scale numerical simulations of real structures [7].

Surface roughness measurement, porosity analysis, and friction coefficient calculation can be performed on the CT scan images to characterize the inner surface properties of the polyethylene pipes [8]. The high resolution of CT enables precise quantification of micro-scale surface roughness parameters like Ra, Rq, etc. [9]. The imaging contrast in CT scans allows segmentation of pores, from which porosity and pore size distribution can be obtained [10]. Friction coefficients can be estimated from surface roughness parameters based on established correlations [11].

Exemplarily, in one study JJ Klawitter et al. (1976) investigated bone growth in porous PE rods as a function of time and pore structure using quantitative techniques. The pore structures of the materials were evaluated by optical microscopy. They concluded that porous PE can promote bone growth in pores as small as 40 μm, the optimum rate of bone ingrowth was observed at pore sizes of about 100 to 135 μm, and no increase in bone in growth rate was observed in samples with larger pores [12].

Our aim in this article is to examine the microscopic structures and permeability characteristics of different types of polyethylene pipes using CT imaging. This examination will be carried out by segmenting and analyzing CT scan images of sample pipe sections. Factors such as the size, distribution and connectivity of the pores within the pipe samples will be evaluated. Surface roughness, porosity, and friction coefficients will also be quantified from the CT data. The findings of this study can contribute to the material selection and design process used in polyethylene pipe engineering.

2 Polyethylene Pipes

Polyethylene pipes, crucial for various industries, undergo a precise production process. This process begins with the careful selection and drying of high-quality PE granules, followed by extrusion, shaping in a die head, calibration, and cooling. Rigorous quality control is maintained throughout production, ensuring compliance with ISO standards like ISO 18553 for PE pipes. The resulting pipes are dependable conduits, meeting strict industry standards and guaranteeing reliability in their diverse applications [13].

A. *Production of Polyethylene Pipes*

While both PE100 and PE80 are produced based on polyethylene, they share common characteristics in the initial stages of their production processes. As seen in Fig. 1, PE100 and PE80 raw material granules are dried to remove moisture. Granules are then fed into the extruder hopper using a feeder. The pigments (yellow, blue, black) are mixed into the polyethylene material along with the plasticizer during the extrusion process at this stage. In the extruder barrel, granules are conveyed, compressed, melted, homogenized by the rotating screw and brought to processing temperature 200–220 °C for PE100 and 180–200 for PE80 Molten polymer from the barrel goes into the die head where the pipe geometry is formed using inner and outer rollers. The hot pipe is calibration cooled in a vacuum tank with water sprays. Guide pipe draws it along the line for cooling. The cooled and sized pipe is cut into lengths or coils as per customer requirements. Quality control is done. Pipes not meeting standards are granulated and recycled. The pipes are stocked for shipment. In addition, some stabilizer and reinforcing additives are added to PE100. PE80 is pure polyethylene and does not require additional additives. Therefore, PE80 goes through a relatively simple production process [13].

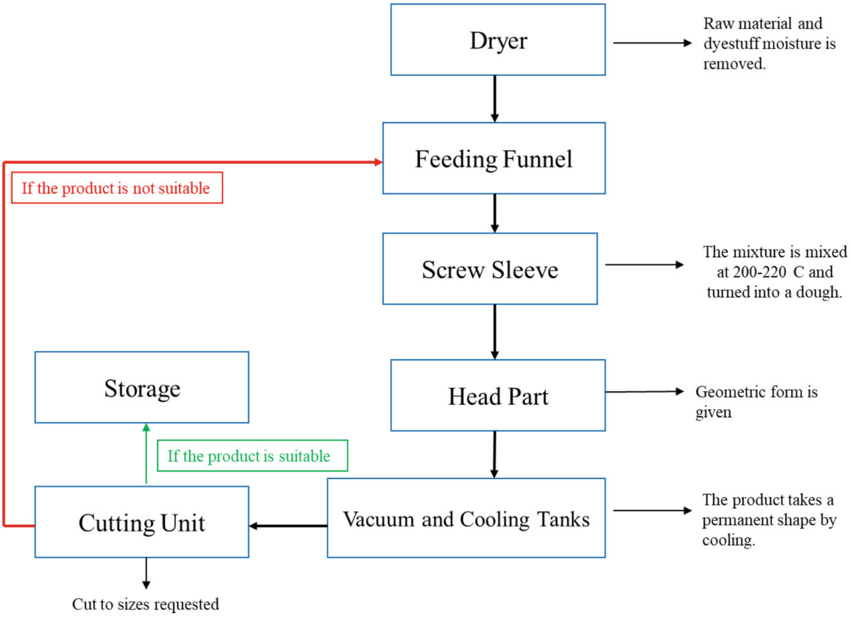


Fig. 1. Production of Polyethylene Pipes Flow Chart [13]

Polyethylene (PE) pipes are widely used for various applications due to their flexibility, durability and corrosion resistance. These pipes come in different types like PE80 and PE100 indicating minimum required strength. The blue PE100 pipe (shown in Fig. 2a) for water usage with 63mm outer diameter, 55mm inner diameter and 4mm wall thickness meeting SDR (Standard Dimension Ratio) 17 standard, contains 2% organic phthalocyanine blue pigment increasing density to 0.954 g/cm3. It has minimum strength of 12 MPa at 20 °C and minimum required endurance (MRS). This blue pipe exhibits high resistance to cracking, spreading and point loads. The yellow PE80 pipe (shown in Fig. 2b) for gas usage includes 2% inorganic lemon chrome yellow pigment increasing density to 0.989 g/cm3. It has minimum strength of 10 MPa at 20 °C, 63mm outer diameter and 55mm inner diameter meeting stringent gas standards. Finally, the black PE100 pipe (shown in Fig. 2c) for water usage includes 2.5% organic carbon black pigment increasing density to 0.962 g/cm3. It has properties similar to the blue PE100 pipe (Table 1). The key benefit of these PE pipes is easy installation and long service life due to their flexible, durable and corrosion resistant nature.

Table 1. Properties of PE [14].

Pipe color	Pipe Type	Usage for	Granulated Type	Pigment Type	Pigment Percentage	Granule Density (g/cm3)	Pigment Density (g/cm3)	Calculated Density (g/cm3)	Minimum Required Strength (MPa)	Outer Diameter (mm)	Inner Diameter (mm)
Blue	PE100	water	polyethylene	Organic Phthalocyanine Blue B.S	2.000%	0.940	1.650	0.954	12.000	63	55
Yellow	PE80	natural gas	polyethylene	inorganic Lemon Chrome Yellow	2.000%	0.930	3.900	0.989	10.000	63	55
Black	PE100	water	polyethylene	Organic Carbon Black	2.500%	0.940	1.800	0.962	12.000	63	55

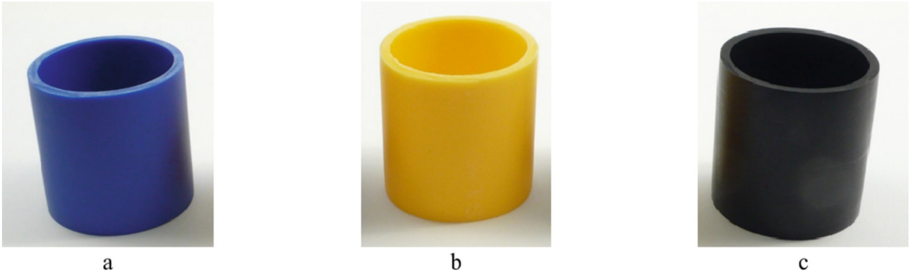


Fig. 2. Produced Polyethylene Pipes a) PE100 blue b) PE80 yellow c) PE100 black

B. *Usage Quality Standards in the Production of Polyethylene Pipes*

Several important ISO standards provide specifications and test methods for polyethylene pipes. Data on these standards are mentioned in Table 2. ISO 1183–1 in the table describes techniques such as gravimetric and volumetric density determination for measuring the density of PE pipe materials. The polymer density for PE80 is $\geq$ 0.930 at approximately 20 °C, while for PE100 it is $\geq$ 0.940. Density is an important parameter affecting mechanical properties. ISO 1133–1 outlines procedures for measuring melt mass flow rate (MFR) at 190 °C/5K to characterize the melt flow behavior and process ability of PE compounds. ISO 6964 provides a classification system for PE pipe types based on density, molecular structure (such as the amount of carbon black for PE100 black pipe) and minimum required strength. This standard classifies pipe qualities according to their properties. ISO 18553 provides guidance for selecting PE pipe materials and sizes based on desired properties such as strength, stiffness and temperature properties to meet system requirements. Carbon black distribution was determined as max 3 only for PE100 (Fig. 2). Together these ISO standards provide a framework for manufacturing, testing, classifying and selecting suitable PE pipe materials for applications such as water supply, gas distribution and sewage disposal. Adherence to ISO standards provides guidance on determining the material, geometric, mechanical and physical properties of pipes to be used in PE pipe systems. Enables appropriate PE pipe selection (Table 2) [13].

Table 2. Properties of PE Pipes According to ISO Standards [13].

Categories	Specifications	unit	Test Standard	PE80	PE100
Polymer Data	Density (at 20 °C)	g/cm^3	ISO 1183–1	≥ 0.930	≥ 0.940
	MFR (190 °C/5kg)	g/10min	ISO 1133–1	0.8–1.3	0.16–0.7
	Carbon Black Amount	%	ISO 6964	-	2 - 2.5
Other Features	Carbon Black Distribution	Nominal	ISO 18553	-	max 3

3 Geometrical Product Specifications and Physical Characteristics

This section examines properties of polyethylene pipes in detail such as form deviations, profile and surface roughness, porosity and friction coefficient. Form deviation quantifies deviations from the mathematical ideal shape of produced parts and is important for assessing manufacturing quality. Surface roughness parameters like Ra and Rq provide useful information about surface smoothness. Porosity represents the void fraction of the material and is critical for durability. Friction coefficient is used in fluid mechanics to calculate pressure drops. Measurement of these properties is essential for characterization of pipe materials.

A. *Form Deviations*

Form deviation refers to the difference between the actual measured points on a surface and its mathematically perfect form. To calculate form deviation, a geometric reference curve is fitted to the measured points first. Then the deviation of each point from this reference curve is quantified. Choosing the right reference curve is crucial for evaluating form deviation accurately, since techniques like least squares and minimum zone give different results [16]. Form deviation measures how closely a manufactured component's geometry matches the ideal design. Therefore, it is an important indicator of geometric accuracy and quality in precision engineering. To obtain the tightest possible tolerance, ISO standards recommend using the minimum zone reference for determining form deviation. This yields the most stringent assessment [13].

B. *Profile and Surface Roughness*

Surface roughness quantifies the texture and irregularities of a surface relative to its intended geometric form. It arises from production processes like machining or chemical treatment that cause vertical deviations from the ideal shape. High roughness values indicate an uneven, irregular surface, while low values denote a smooth surface. Since roughness varies between components, selecting an appropriate measurement technique is essential [14]. A commonly used roughness parameter is Ra - the arithmetic average of profile peak and valley heights over a sampling length. Ra provides useful information about overall surface roughness, which is vital for many engineering and manufacturing applications where smoothness and form accuracy are critical requirements. In summary, surface roughness measurement and analysis via parameters like Ra allows quantification of surface irregularities and quality control in precision manufacture [15, 16].

In this study, the surface roughness of the sample is determined using the Alicona Infinite Focus surface roughness tester, which employs an optical measurement technique known as focus variation. This method captures high-resolution images with a vertical resolution of up to 10 nm at 100 times magnification, utilizing a limited depth of field. The data from these images are then combined to create a comprehensive depth of field measurement [17].

C. *Porosity*

Porosity, also known as void fraction, serves as a critical metric for assessing the presence of empty spaces within a material. It offers valuable insights into the ratio of void volume to the total volume of the material. Porosity is typically expressed either as a decimal between 0 and 1 or as a percentage ranging from 0% to 100% [18]. The following formula is used to calculate porosity:

$$\text{Porosity}\o = \left(\frac{Vp}{Vt}\right)x100 \tag{1}$$

Here, ϕ, denoting the porosity percentage, V_p, representing the pore volume, which corresponds to the volume of empty spaces or voids within the material and V_t, indicating the total volume of the material [19].

D. *Friction Coefficient in Fluid Dynamics*

In fluid mechanics, the behavior of flow in a pipe can be influenced by the relative roughness (ε/D), which is a measure of the surface roughness of the pipe compared to its diameter. When the Reynolds number (Re) is sufficiently high, a condition known as the completely turbulent regime is reached, where the friction factor remains relatively constant. In this regime, the size of the roughness elements (represented by k) is significantly larger than the thickness of the viscous wall layer, rendering viscous effects relatively insignificant [20].

In this regime, the primary source of resistance to flow is the drag caused by the roughness elements that extend into the flowing fluid. However, as the relative roughness (ε/D) decreases and Reynolds number (Re) decreases, the friction factor starts to increase within the transition zone. Ultimately, it reaches a point where it matches that of a smooth pipe. This occurs because the roughness elements become submerged within the viscous wall layer, exerting minimal influence on the main flow [20, 21].

To calculate the friction factor (f) in this transitional zone, the Colebrook equation is commonly employed [22]:

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\frac{\varepsilon}{D}}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) \tag{2}$$

Here, ε represents the pipe roughness, and Re stands for the Reynolds number.

The effect of surface roughness is incorporated into the analysis by determining the relative roughness (ε/D) through Rp, Rsm, and Fp parameters. This physics-based modeling approach allows for the prediction of permeability based on the measured surface characteristics [23].

Reynolds number (Re) is calculated using the following:

$$Re = \frac{\rho VD}{\mu} \tag{3}$$

where ρ is the fluid density, V is the velocity, D is the pipe diameter, and μ is the dynamic viscosity of the fluid.

Finally, In engineering, the Moody chart or Moody diagram (also Stanton diagram) is a graph in non-dimensional form that relates the Darcy–Weisbach friction factor fD, Reynolds number Re, and surface roughness for fully developed flow in a circular pipe. It can be used to predict pressure drop or flow rate down such a pipe [24].

4 Metrology Technologies

This section explains advanced metrology techniques used for characterization of polyethylene pipes such as computed tomography, infinite focus microscope and surface roughness tester. Computed tomography is utilized to image the inner microstructure and porosity of the pipes. Infinite focus microscope provides 3D surface data at 10 nm resolution. Surface roughness tester measures parameters like Ra and Rz. These techniques enable precise measurement of pipe properties.

A. *Computed Tomography*

This device is an industrial computed tomography designed primarily for scanning products made of light metals (aluminum alloys) and plastic with the power of 225W. The basic system consists of an X-ray tube using a wolfram target to emit radiation. The X-ray beam is of conical shape and after the passage through a scanned object it falls onto the junction detector. Figure 3 represents the Metrotom 1500 device and its main components – an X-ray tube, a rotary table (in the middle), and a detector (on the right) [24].

Porosity quantification of various polyethylene pipe samples was carried out utilizing industrial computed tomography. The three-dimensional pore structure within polyethylene pipes of differing manufacturing parameters was comprehensively characterized via the non-destructive CT (Fig. 3). Technique.

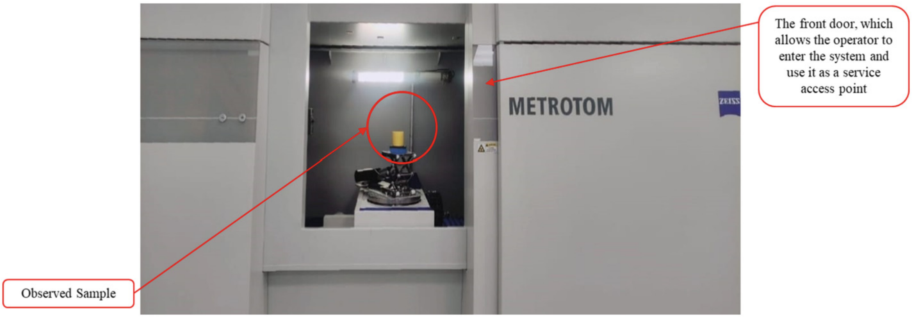


Fig. 3. PE pipe within Metrotom 1500 Computed Tomography at Preparatory Stage

B. *Infinite Focus Microscope*

The 3D optical measurement device Alicona Infinite Focus G5 microscope was utilized to measure the surface roughness of different milling methods. Both 2D (R) and 3D (S) roughness parameters were obtained. The 2D values were generally lower than the 3D counterparts. 3D visualization and histograms provided additional insights into the surface characteristics. The Alicona Infinite G5 incorporates a rigid Measurement Head housing to ensure stable optics alignment. The system uses a precision Z-Stage with high-resolution vertical drive for accurate surface profiling. The Rotary Optical Head enables continuous 360° sample rotation for comprehensive 3D inspection. Variable magnification Focal Objectives paired with coaxial or ring Illumination optimize contrast and detail. Precision crosstalk-free direct drives on the Motorized X-Y stage enable smooth sample positioning. Together, these sophisticated elements facilitate non-contact optical metrology of even highly complex geometries [25] (Fig. 4).

Fig. 4. 3D filtered surface of the components

The Alicona Infinite G5 was utilized in this study to characterize the roughness parameters of polyethylene pipe samples, providing more detailed 3D measurements compared to standard 2D roughness values.

C. *Perthomete*

The Perthometer M1 device (Fig. 5) was used to determine surface roughness, recording the mean surface roughness (Ra) values for each sample [26]. This instrument is designed to measure surface roughness parameters per standards including DIN EN ISO/AMSE/prEN 10049 and JIS. The Perthometer features a diamond-tipped probe, enabling measurement of parameters including Ra, Rz, Rmax, RPc, Rz, and Ra. It has automated identification of periodic/aperiodic profiles and phase-correct profile filtering per DIN EN ISO 11562. Traversing length, cutoff, and sampling length are user-configurable. The M1 allows blocking of settings to prevent unintentional changes. The measuring range is up to 150 µm with switchable µm/µin units. The set includes a built-in printer for results and profile output. Dynamic pick-up calibration provides reproducible measurements. As a portable instrument with automated functions conforming to key standards, the Perthometer M1 with its diamond-tipped probe facilitates efficient, standardized roughness measurements in lab and field applications. Overall, it is a versatile and robust tool for determining common surface roughness parameters [27]. In this study, the Perthometer M1 was utilized to measure polyethylene pipe roughness, allowing comparison to roughness values obtained via computed tomography.

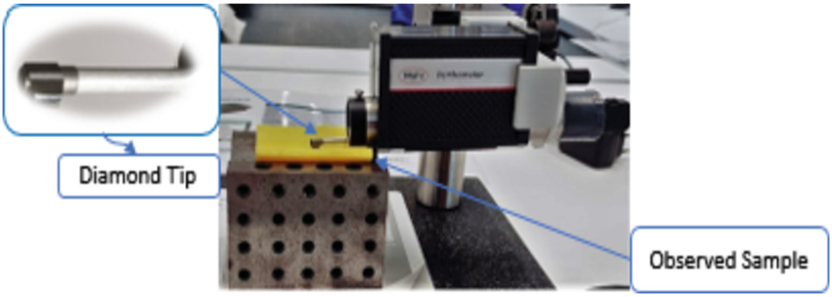


Fig. 5. Perthometer

In this study, the Perthometer M1 was utilized to measure polyethylene pipe roughness, allowing comparison to roughness values obtained via computed tomography.

5 Experimental Study and Results

In this section, we will delve into four crucial subtopics, where comprehensive evaluation processes were applied to polyethylene pipes from various angles. These four key subheadings constitute the primary focal points of the experimental study aimed at scrutinizing the performance and quality of polyethylene pipes.

A. *Evaluation of Profile and Surface Roughness of Polyethylene Pipes*

Gaining insights into the profile and surface roughness of polyethylene pipes is a crucial aspect of our analysis, allowing us to assess the dimensional accuracy and quality of these pipes.

This study provides a rigorous analysis of the physical properties of polyethylene pipes, explicitly sorted for water and natural gas applications. Through the use of advanced measurement techniques like Computed Tomography and precision scaling, various parameters, including total volume, defect volume, porosity, and density, were accurately quantified. The data reveals a nuanced situation but significant variations across different pipe types—PE100 for water and PE80 for natural gas—and colors, attributed to the various pigments and granule types used.

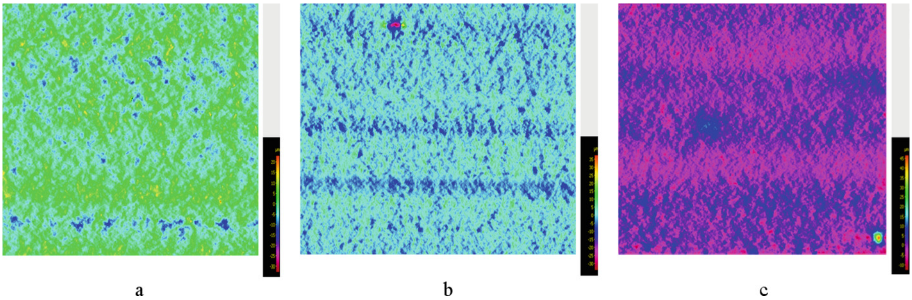


Fig. 6. Form Reduced Dataset 2D a) PE80 yellow pipe, b) PE100 blue pipe, c) PE100 black pipe

Surface topography of yellow, blue and black polyethylene pipes obtained with an Alicona Infinite Focus G5 device, respectively. While the yellow pipe (Fig. 6-a) exhibits distinct scratches and roughness, the blue pipe (Fig. 6-b) has a smoother surface structure. Comparatively, the black pipe (Fig. 6-c) has a more homogeneous and smooth surface. These images provide comparative information about the production quality and surface characteristics of each pipe.

The figures above show the 3D filtered surface of the components. In this case, the difference can be seen when values on the left tend to be positive. On the other hand, values from left to right (Fig. 6 a, b, c) tend to be negative.

In this comprehensive study seen in Table 3 and Fig. 7, surface roughness parameters of polyethylene pipes were rigorously evaluated. The data is presented on a logarithmic scale to better capture the variances across metrics and pipe types seen in Fig. 2. The pipes, categorized as Black PE100, Blue PE100, and Yellow PE80, were distinguished by their unique granule and pigment compositions. Specifically, Black PE100 pipes were comprised of 97.5% Polyethylene granules and 2.5% Organic - Carbon Black pigment. Conversely, both Blue PE100 and Yellow PE80 pipes had 98% Polyethylene granules but differed in their pigment types: Inorganic - Phthalocyanine Blue BS for Blue PE100 and Inorganic - Lemon Chrome Yellow for Yellow PE80 demonstrated in Table 1.

Initial measurements were conducted using Alicona Infinite Focus Microscope technology. The Black PE100 pipes exhibited the lowest Average Roughness (Ra) at 1.459 µm, followed by Yellow PE80 at 1.848 µm, and Blue PE100 at 2.110 µm. Additionally, Blue PE100 pipes showed the highest Peak-to-Valley Height (Rz) at 12.672 µm, compared to Yellow PE80 at 10.978 µm and Black PE100 at 9.077 µm. Root-Mean-Square Roughness (Rq) values correspondingly favored Black PE100 pipes with a value of 1.809 µm.

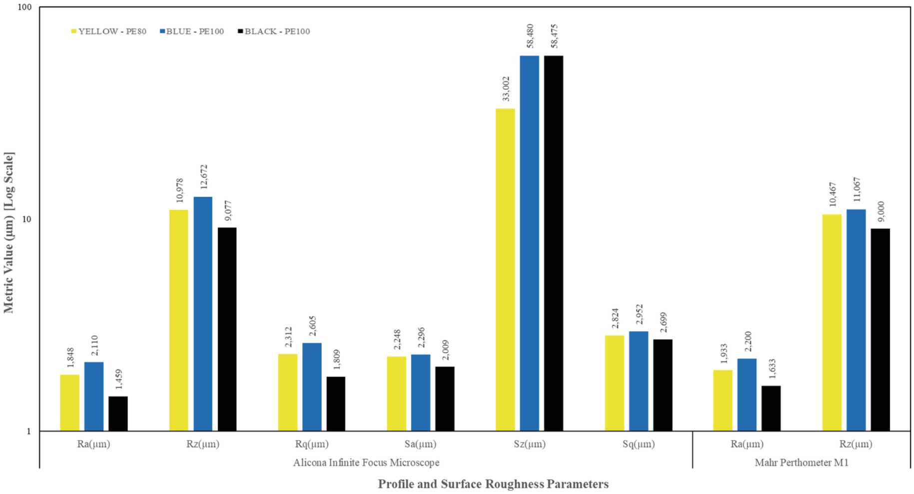


Fig. 7. Surface Roughness Metrics by Pipe Type (Logarithmic Scale)

Table 3. COMPARATIVE ANALYSIS OF SURFACE ROUGHNESS PARAMETERS FOR POLYETHYLENE PIPES USING ALICONA INFINITE FOCUS MICROSCOPE AND MAHR PERTHOMETER M1

Roughness Measurement Technology	Geometric Characteristics	Pipe Type								
		YELLOW - PE80			BLUE - PE100			BLACK - PE100		
Alicona Infinite Focus Microscope	Ra(µm)	1,848			2,110			1,459		
	Rz(µm)	10,978			12,672			9,077		
	Rq(µm)	2,312			2,605			1,809		
	Sa = ε (µm)	2,248			2,296			2,009		
	Sz(µm)	33,002			58,480			58,475		
	Sq(µm)	2,824			2,952			2,699		
Mahr Perthometer M1	**Measurement NR**	**one**	**2**	**3**	**one**	**2**	**3**	**one**	**2**	**3**
	Ra(µm)	2,100	1,800	1,900	2,300	2,100	2,200	1,700	1,600	1,600
	Rz(µm)	11,200	10,100	10,100	11,200	11,000	11,000	9,600	8,100	9,300
	Statistical Evaluation	**AVERAGE**	**STDEV**	**Per Error (%)**	**AVERAGE**	**STDEV**	**Per Error (%)**	**AVERAGE**	**STDEV**	**Per Error (%)**
	Ra(µm)	1,933	0.153	4,618	2,200	0.100	4,265	1,633	0.058	11,949
	Rz(µm)	10,467	0.635	4,658	11,067	0.115	12,668	9,000	0.794	0.848

To validate these results, additional measurements were carried out using the Mahr Perthometer M1. The average Ra and Rz values for Yellow PE80 were 1.933 µm and 10.467 µm, respectively, with a percentage error of about 4.6% compared to the Alicona measurements. Blue PE100 pipes showed an average Ra of 2.200 µm and Rz of 11.067 µm, with a notable percentage error of 12.668% for Rz. Black PE100 pipes had average Ra and Rz values of 1.633 µm and 9.000 µm, respectively, but with varying

Table 4. Properties of Gas and Water at 20 °C

Temperature (T): 20 °C	water	natural gas
Density (ρ)	998.23kg/m3	0.67kg/m3
Viscosity (μ)	0.0010 kg/m · s	1.83 × 10–5 kg/m · s,
Flow Rate (V)	2m/s	20m/s

percentage errors of 11.949% for Ra and 0.848% for Rz in Table 3. Additionally, in Table 4, the properties of water and natural gas at 20°C are shown respectively; density (998.23 kg/m3, 0.67 kg/m3), viscosity (0.0010 kg/m s, 1.83 × 10–5 kg/m s), flow rate (2 m/s, 20 m/s) shared including.

The experimental study expresses several key insights that have principal implications for both the manufacturing and engineering sectors. First and foremost, we observe that the type of pigment used in the polyethylene pipes, specifically Organic Carbon Black in Black PE100 pipes, has a significant influence on surface roughness metrics. These Black PE100 pipes consistently demonstrated smoother internal surfaces, as evidenced by their lower Ra and Rq values. Secondly, the low standard deviations across multiple measurements indicate a high degree of consistency in surface roughness, irrespective of the measurement position on the pipe. This not only confirms what has been found, but it also raises the reliability of these parameters in engineering contexts.

However, the percentage errors between the two measuring methods, which ranged from 0.488% to 12.668%, must be noticed. Such variations underscore the importance of employing consistent and accurate measurement techniques, especially when surface roughness metrics are critical to the pipe's application. For example, the smoother internal surfaces of Black PE100 pipes could be particularly beneficial in systems requiring reduced friction losses, such as in water supply infrastructures.

Furthermore, the presence of larger defects or irregularities, as indicated by higher Rz and Sz values, particularly in Blue PE100 and Black PE100 pipes, may necessitate additional examination for ensuring long-term material reliability. Even though the granule and pigment compositions are quite similar across the various types of pipes, the differences in surface roughness suggest that other elements, possibly related to the manufacturing process, could be influencing these metrics. Overall, the study provides a comprehensive and particular understanding that is invaluable for optimizing material properties and creates new paths for future research in this concern.

Another possible evaluation of the measured results is using a graphical comparison. It shows us the frequency of measured value, see Fig. 8 The value in the picture are close to the theoretical Gaussian distribution (Fig. 12).

Average roughness (Ra) was measured as 1.8 μm and maximum separation (Rz) was measured as 11.0 μm in yellow PE80 pipe. The blue PE100 pipe had Ra 2,110 μm and Rz 12,672 μm. Black PE100 pipe was obtained with Ra 1.5 μm and Rz 9.1 μm. For surface roughness profile measurements of these three different polyethylene pipes, the focusing method was used with the Alicona Infinite Focus G5 device. In this method, high-efficiency images of pipe processes are taken at different focal depths and combined with special software to obtain micro-precise 3D data. From the measurements, it appears

Fig. 8. Profile Form Measurements

that the black PE100 pipe has the lowest average roughness (Ra). However, Ra and Rz values are close to each other among the three pipe types. This shows whether there is performance in production. Rz values are useful for identifying possible surface defects.

B. *Evaluation of 3D Form Deviations of Polyethylene Pipes*

The assessment of 3D form deviations in polyethylene pipes represents a critical aspect of our study, shedding light on the dimensional accuracy and structural integrity of these piping systems.

The analysis of the 3D form deviations of the inner surfaces of pipes made from different materials offers significant insights into the quality and consistency of these materials. When visualizing the data using normal distribution curves, it's evident that two of the materials have similar distribution profiles. This similarity suggests comparable inner surface quality in terms of 3D deviation between them. On the other hand, the third material exhibits a more varied spread in its deviation measurements, indicating a broader range of inconsistencies in its inner surface. Analyzing the central tendencies, the mean values shed light on the average deviation for each material. A material with a mean value farther from zero might be consistently deviating from its desired form, whereas a mean closer to zero would indicate that the pipes, on average, align more closely with the intended shape. Furthermore, the variability of these deviations, as measured by the standard deviation, provides insights into the spread of measurements. A material with a low standard deviation would have measurements that are closely packed to its mean, suggesting consistency. In contrast, a high standard deviation would indicate a wider range of deviations, pointing to greater variability in the material's inner surface quality.

The 3D deviations for pipes made from different materials were statistically analyzed. For the Pe100 Black (Water), the mean value was approximately – 0.1458 mm. This suggests that, on average, the deviations are slightly in the negative direction for this material. Its standard deviation was measured at approximately 0.2143 mm, indicating a moderate dispersion of measurements around this mean value.

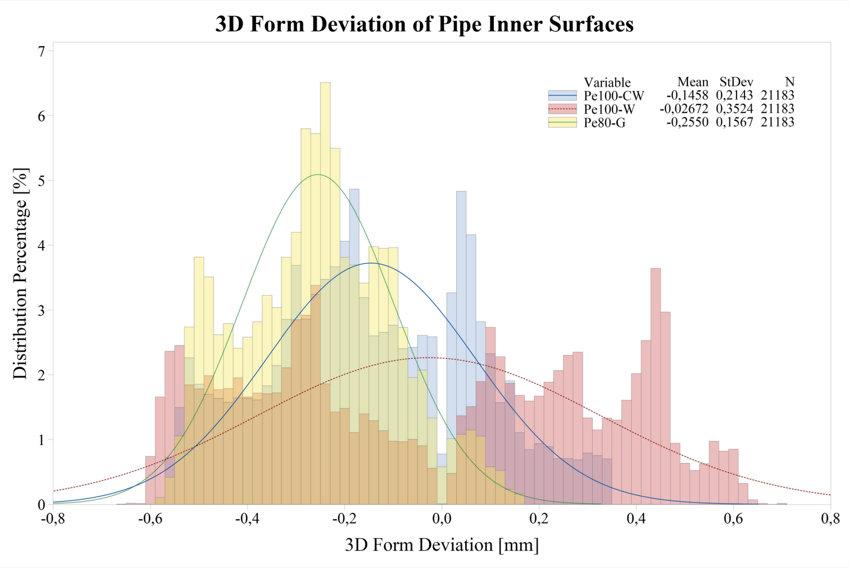


Fig. 9. 3D Form Deviation [mm]

On the other hand, the Pe100-Blue (Water) presented a mean value of approximately − 0.0267 mm, which is notably closer to zero in comparison to the other materials. This implies, on average, the deviations for this material are relatively minimal. However, its standard deviation, at approximately 0.3524 mm, was the highest among the three. This denotes a broader range of measurements around the mean, suggesting a higher variability in deviations. Lastly, the Pe80-Yellow (Gas) showed a mean value of approximately − 0.2550 mm, making it the most negative among the three materials. This indicates a more pronounced average deviation in the negative direction for this material. Its standard deviation stood at approximately 0.1567 mm, the lowest of the trio, signifying a more consistent set of measurements closely packed around the mean.

Drawing from these statistical results, the Pe100-Blue (Water) has a mean deviation value that is the closest to zero but also displays the highest variability among the measurements. In contrast, the Pe80-Yellow (Gas) demonstrates a more negative mean deviation but with a narrower dispersion around this average. The Pe100 Black (Water) positions itself as an intermediate between the two in both its mean deviation and its range of measurements (Fig. 9).

C. *Evaluation of Porosity of Polyethylene Pipes*

The examination of porosity in polyethylene pipes is a pivotal component of our research, as it provides valuable insights into the material's integrity and its potential impact on the pipes' performance.

The data presented in Table 5 provide a comprehensive evaluation of the physical properties of polyethylene pipes (Fig. 10) specifically designed for different applications. An important measurement of interest in pipes is porosity, PE100 for water (Black and Blue pipes) and PE80 for natural gas (Yellow pipe).

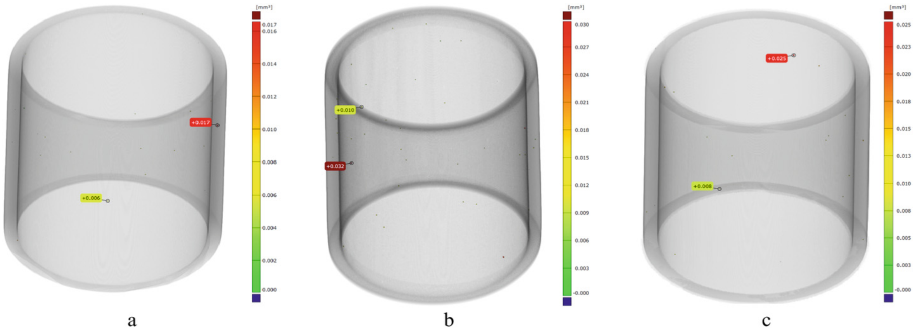


Fig. 10. Porosity Measurement of the Pipes on the GOM Software a) Blue PE100, b) Yellow PE80, c) Black PE100

(The yellow values in Fig. 10, captured using GOM software, denote average volume defects, whereas the red values represent maximum volume defects.)

Among the pipes examined, the Black pipe exhibited the highest porosity at 0.000798%; this numerical value is approximately 2.3 times higher than the porosity in the yellow pipe, which recorded the lowest porosity at 0.000256%. Although these values are quite low, indicating a high level of material reliability, these differences can have long-term effects in terms of durability and performance, especially when used in applications requiring high structural integrity.

Table 5. Quantitative Evaluation of Defects, Porosity, and Density in Polyethylene Pipes

Pipe Color	Pipe Type	Usage For	Total Volume [mm^3]	Volume Defects [mm^3]	Porosity	Average Volume Defects [mm^3]	Maximum Volume Defects [mm^3]	Measured Mass [g]	Measured Density [g/cm^3]
Yellow	PE80	natural gas	47601,051	0.122	0.000256%	0.006	0.017	44,660	0.938
Black	PE100	water	47479.707	0.379	0.000798%	0.010	0.032	45,360	0.955
Blue	PE100	water	48208,678	0.167	0.000346%	0.008	0.025	45,670	0.947

(Calculations were carried out using formula (1))

As for mass and density measurements, all pipes were found to have densities close to their theoretical value. The black pipe had the highest density with 0.955 g/cm3, followed by blue and yellow pipes with densities of 0.947 g/cm3 and 0.938 g/cm3, respectively. These slight variations in density can be attributed to the different pigments and granule types used in the tubes and require further investigation to understand their effects on the mechanical properties in Fig. 10.

The volume of defects in the pipes further complements the porosity findings. The Black pipe has the highest volume of defects at 0.379 mm^3, which is more than three times the volume of defects in the yellow pipe, which recorded the lowest at 0.122 mm^3. This trend is also reflected in the average and maximum volume defects, with the Black

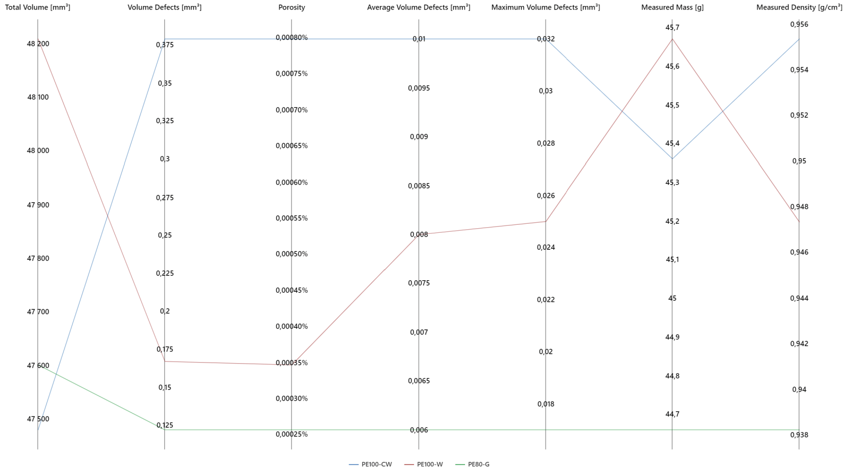


Fig. 11. Physical and Mechanical Characteristics of PE100 and PE80 Polyethylene Pipes

pipe registering at 0.010 mm^3 and 0.032 mm^3, respectively. These measurements provide a granular understanding of the material's overall quality and uniformity (Table 5).

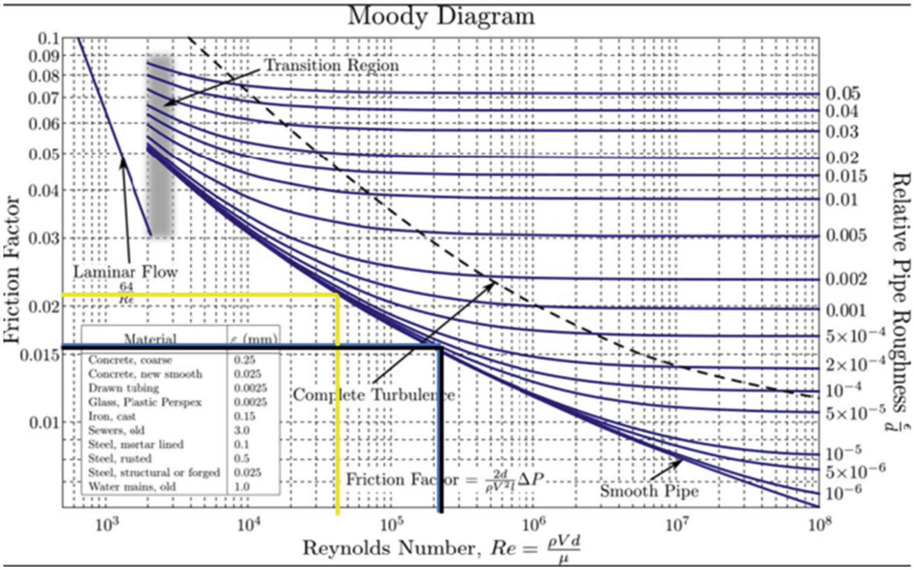
D. *Comparison of Friction Coefficient Factors of Polyethylene Pipes*

The roughness (ε) of the pipes is shown in Table 3 as Sa values for yellow PE80, blue and black PE100 pipes. As shown in Table 1, the pipe inner diameter (D) is 0.055 m. As a result, relative roughness (ε/D) was calculated separately for each pipe using the pipe roughness and inner diameter. Then in Table 1 and Table 4; Reynolds number (Re), fluid density (ρ), flow velocity (V), pipe diameter (D) and fluid viscosity (μ); The friction factor (f) was found for each pipe separately according to the Re and relative roughness values by substituting them in the formulas (1) and (2) in the 3rd section, and these values were shown on the Moody diagram. (Fig. 12).

Table 6. Friction of the Pipes

	PE100 blue pipe	PE80 yellow pipe	PE100 black pipe
Reynold Numbers of the Pipes	109805	40273	109805
Relative Pipe Roughness (ε/D)	$4,175 \times 10^{-5}$	$4,0874 \times 10^{-5}$	$3,065 \times 10^{-5}$
Friction of the Pipes	$F_{\text{blue}} = 0.0179$	$F_{\text{yellow}} = 0.0221$	$F_{\text{black}} = 0.0178$

Based on these values, it is evident that the Yellow PE80 pipe has the highest friction coefficient among the three types. This means that the Yellow PE80 pipe will exhibit higher resistance to the flow of fluid or gas passing through it compared to the other pipes. This increased friction can result in higher energy consumption or reduced flow rates, particularly in applications where fluid or gas flow efficiency is crucial.



Material	ε (mm)
Concrete, coarse	0.25
Concrete, new smooth	0.025
Drawn tubing	0.0025
Glass, Plastic Perspex	0.0025
Iron, cast	0.15
Sewers, old	3.0
Steel, mortar lined	0.1
Steel, rusted	0.5
Steel, structural or forged	0.025
Water mains, old	1.0

Fig. 12. Moody Diagram

On the other hand, the friction coefficients for PE100 Blue and PE100 Black pipes are quite close, with only a slight difference. Consequently, these two types of pipes are expected to have similar effects on flow resistance in practical applications (Table 6).

In conclusion, when selecting polyethylene pipes for specific applications, it is essential to consider factors such as the friction coefficient, as it can significantly impact the performance and efficiency of fluid or gas flow through the pipes.

6 Conclusions

This comprehensive experimental study analyzing the physical and mechanical characteristics of polyethylene pipes provides valuable insights for both manufacturers and users of these piping systems.

For manufacturers, the findings on 3D form deviations reveal that the PE100-Blue pipes displayed the highest variability in deviation measurements despite having the lowest average deviation. This indicates inconsistent quality control and manufacturing precision for this material. In contrast, the PE80-Yellow pipes showed the most consistent deviations with the lowest standard deviation of 0.1567 mm. Manufacturers should strive for tight consistency like the yellow pipes.

The porosity analysis showed the PE100-Black pipes had 2.3 times higher porosity than the PE80-Yellow at 0.000798% versus 0.000256%. This suggests inferior material integrity in the black pipes. Manufacturers should aim to achieve porosities at or below 0.000300% for robust performance.

Regarding surface roughness, the PE100-Black pipes demonstrated the lowest values with average Ra of 1.633 µm versus 1.933 µm for PE80-Yellow. This is likely due to the carbon black pigment composition. Manufacturers should consider using similar carbon black additives to achieve hydraulically smooth surfaces below 2 μm Ra.

For pipe users, the 50-year design life requires selecting materials with the highest quality and most consistent dimensions, lowest porosity, and smoothest surfaces. Based on the findings, PE80-Yellow pipes exhibited the most favorable characteristics, with the lowest and most consistent form deviations, lowest porosity, and surface roughness on par with the top performer. Users should opt for PE80-Yellow pipes where possible for optimal hydraulic performance and longevity.

In summary, this comprehensive metrological study of polyethylene pipe characteristics provides concrete data to guide quality improvements on the manufacturing side and informed material selection by users to maximize piping system performance over decades of service. Tighter dimensional tolerances, lower porosities, and hydraulically smooth surfaces are achievable through focused manufacturing improvements.

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