OVERVIEW OF THE INTER-LABORATORY COMPARISON SCHEME FOR UPVC PIPE TESTING

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Abstract

This study presents the results of an Inter-Laboratory Comparison (ILC) program conducted across 10 laboratories to evaluate the consistency and accuracy of testing unplasticized polyvinyl chloride (uPVC) pipes as per IS 4985. Focusing on five critical parameters—sulphated ash content, density, wall thickness, Vicat softening point, and opacity—the program revealed strong consistency in density and opacity measurements but identified significant variability in sulphated ash content and thermal softening tests. Statistical tools such as Z-score analysis and graphical distribution plots were used to assess inter-laboratory performance. The findings underscore the need for harmonized testing methodologies, regular equipment calibration, and structured training of laboratory personnel. This ILC program serves as a key initiative to enhance the reliability of testing practices, support regulatory compliance, and improve product quality assurance in the uPVC pipe industry.

Keywords: uPVC Pipes, Inter-Laboratory Comparison, IS 4985, Quality Assessment, Testing Methodologies

1. Introduction

Unplasticized polyvinyl chloride (uPVC) pipes have emerged as a critical component in modern infrastructure, particularly in water supply and drainage systems. The development of uPVC pipes can be traced back to the mid-20th century, when the need for durable, corrosion-resistant, and cost-effective piping materials became increasingly apparent. This introduction provides a comprehensive overview of the history of uPVC pipe development globally, highlighting significant research and advancements in the field.

The origins of uPVC can be traced back to the early 1930s when German chemist Friedrich Heinrich August Klatte first synthesized polyvinyl chloride (PVC) through the polymerization of vinyl chloride monomer (VCM). Initially, PVC was used in various applications, but its rigidity limited its use in plumbing and piping systems. The introduction of plasticizers allowed for the development of flexible PVC, which became widely used in various applications, including electrical insulation and flooring (Baker, 2010).

However, the need for a more rigid and durable material for plumbing applications led to the development of unplasticized PVC (uPVC) in the 1950s. The first uPVC pipes were produced in Germany, where they quickly gained popularity due to their excellent resistance to corrosion, chemical attack, and UV degradation (Kumar et al., 2017). By the 1960s, uPVC pipes began to be adopted in various countries, including the United States and the United Kingdom, for water supply and drainage systems.

The global adoption of uPVC pipes was facilitated by the establishment of various standards and regulations. In the United States, the American Society for Testing and Materials (ASTM) developed standards for uPVC pipes, including ASTM D1784, which specifies the requirements for rigid PVC compounds used in the manufacture of pipes (ASTM International, 2019). Similarly, in Europe, the European Committee for Standardization (CEN) established standards for uPVC pipes, ensuring their quality and performance in various applications (CEN, 2018).

In India, the Bureau of Indian Standards (BIS) introduced IS 4985 in 2000, which outlines the specifications for uPVC pipes used in potable water supply systems. This standard has played a crucial role in ensuring the quality and safety of uPVC pipes in the Indian market (Bureau of Indian Standards, 2000).

Research on uPVC pipes has evolved significantly over the years, focusing on various aspects such as material properties, manufacturing processes, and performance in real-world applications. Numerous studies have been conducted to evaluate the mechanical properties of uPVC pipes, including tensile strength, impact resistance, and thermal stability.

For instance, a study by Al-Mansoori et al. (2015) investigated the mechanical properties of uPVC pipes under different environmental conditions. The researchers found that exposure to high temperatures and UV radiation significantly affected the mechanical properties of uPVC, leading to a decrease in tensile strength and impact resistance. This research highlighted the importance of considering environmental factors when assessing the performance of uPVC pipes.

Another significant area of research has been the evaluation of the long-term performance of uPVC pipes in various applications. A study by Khatri et al. (2018) examined the durability of uPVC pipes used in water supply systems over a 20-year period. The researchers found that uPVC pipes exhibited excellent resistance to corrosion and degradation, making them a reliable choice for long-term applications.

Recent advancements in uPVC pipe technology have focused on improving the material's properties and expanding its applications. Innovations such as the incorporation of nanomaterials and additives have been explored to enhance the mechanical and thermal properties of uPVC pipes. For example, a study by Zhang et al. (2020) demonstrated that the addition of graphene oxide to uPVC significantly improved its tensile strength and thermal stability, paving the way for the development of high-performance uPVC pipes.

Moreover, the growing emphasis on sustainability has led to research on the recyclability of uPVC pipes. Studies have shown that uPVC can be recycled multiple times without significant loss of properties, making it an environmentally friendly choice for piping applications (Kumar et al., 2017). This aspect is particularly important in the context of increasing environmental regulations and the push for sustainable construction practices.

As the demand for uPVC pipes continues to grow, ongoing research is focused on addressing challenges related to performance, sustainability, and environmental impact. The development of bio-based uPVC and the exploration of alternative materials are areas of active research, aiming to reduce the carbon footprint associated with traditional uPVC production (Baker, 2010).

Furthermore, the integration of smart technologies in uPVC pipe systems is gaining traction. Smart sensors embedded in pipes can monitor flow rates, pressure, and potential leaks, providing real-time data for better management of water supply systems (Zhang et al., 2020). This trend aligns with the broader movement towards smart cities and sustainable urban development.

A study by Patnaik et al. (2021) evaluated the effect of soil properties on the performance of uPVC pipes buried underground. The authors found that variations in soil type and composition can significantly impact the mechanical properties and durability of buried pipes. Another study by Rahaman et al. (2021) investigated the potential of recycled uPVC as a sustainable alternative to conventional PVC in the manufacturing of pipes. The results showed that recycled uPVC exhibited comparable properties to virgin PVC, highlighting its potential as a sustainable material for uPVC pipe production. These studies and others contribute to the ongoing research efforts aimed at enhancing the performance and sustainability of uPVC pipes.

Liu et al. (2020) investigated the flexural behavior of large-diameter uPVC pipes. The study used both experimental testing and numerical simulations to understand the mechanical performance of the pipes. Results showed that the nonlinear stress-strain curves of the pipes were heavily influenced by the geometrical properties of the pipes, such as the diameter and thickness of the pipe's wall. Furthermore, the numerical simulations were able to predict the failure modes of the pipes accurately. The study indicates that further research is necessary to better understand and optimize the design and construction of large-diameter uPVC pipes.

Wang et al. (2019) evaluated the mechanical properties of uPVC pipes through full-scale testing and numerical modeling. The study examined the effects of pipe diameter and wall thickness on the axial and circumferential strength, stiffness, and ultimate strain of the pipes. The results showed that the strength and stiffness of the pipes increased with larger diameters and wall thickness. The study also found that numerical simulations could predict the mechanical behavior of the pipes with reasonable accuracy. The study underscores the importance of comprehensive testing and modeling for the design and selection of uPVC pipes.

Xi et al. (2017) examined the creep behavior of uPVC pipes with nano-material fillers added to the polymer matrix. The study aimed to improve the long-term performance of uPVC pipes under static loads and elevated temperatures. The addition of nano-materials was found to reduce the creep deformation of the pipes over time compared to pipes without added fillers. The study suggests that the incorporation of nano-material fillers could lead to longer-lasting and more reliable uPVC pipes.

Yang et al. (2016) studied the effect of temperature and strain rate on the mechanical properties of uPVC pipes. The study used tensile and compression tests to measure the strength, stiffness, and ductility of the pipes under different conditions. The results showed that high temperatures and strain rates reduced the strength and stiffness of the pipes while increasing their ductility and deformation. The study emphasizes the importance of understanding the temperature and loading conditions of the pipes in order to optimize their performance.

Gong et al. (2015) investigated the mechanical properties of uPVC pipes under water hammer conditions. Water hammer is a phenomenon that can occur in pipelines, in which sudden pressure changes can cause stress on the pipes. The study examined the pressure transients and stresses on uPVC pipes under different water hammer conditions. Results showed that uPVC pipes were able to withstand the stresses and pressure changes caused by water hammer without significant deformation or failure. The study suggests that uPVC pipes are a reliable and durable option for water transport systems.

Wahab et al. (2014) evaluated the hydrostatic design basis for uPVC pipes. The hydrostatic design basis is a measure of the pipe's ability to withstand water pressure without rupturing. The study examined the factors that affected the hydrostatic design basis of uPVC pipes, including the material properties, diameter, and wall thickness of the pipes. Results showed that larger diameter and thicker wall pipes had higher hydrostatic design basis values. The study provides important insights for designing uPVC pipe systems that can withstand high water pressures.

Paven et al. (2012) analyzed the fracture behavior of uPVC pipes with different molecular weights. The study aimed to understand the relationship between the molecular weight of the polymer and the fracture properties of the pipes. Results showed that the fracture strength and toughness of the pipes increased with higher molecular weight. The study suggests that selecting uPVC pipes with higher molecular weights could lead to improved fracture resistance and longer service life.

The development of uPVC pipes has come a long way since their inception in the mid-20th century. With a rich history of research and innovation, uPVC pipes have established themselves as a reliable and durable choice for water supply and drainage systems worldwide. As the industry continues to evolve, ongoing research and advancements will play a crucial role in enhancing the performance and sustainability of uPVC pipes, ensuring their continued relevance in modern infrastructure.

Inter-Laboratory Comparison (ILC) programs serve as a valuable tool for assessing the consistency and reliability of laboratory testing methods. By comparing results from multiple laboratories, ILCs help identify discrepancies and promote standardization in testing procedures. This study aims to evaluate the results of an ILC conducted on uPVC pipes, focusing on the aforementioned parameters and their implications for the uPVC pipe industry. The quality of uPVC pipes is critical for their long-term performance and reliability. Parameters such as sulphated ash content, density, wall thickness, Vicat softening point, and opacity are essential indicators of the material's properties and suitability for various applications. Variability in testing results across different laboratories can lead to discrepancies in product quality, potentially affecting the safety and efficiency of water supply systems.

1.1 Importance of Inter-Laboratory Comparison (ILC) in uPVC Pipe Testing: As the demand for uPVC pipes continues to grow, ensuring the quality and reliability of these products becomes paramount. Inter-Laboratory Comparison (ILC) programs serve as a vital tool in this regard, providing a systematic approach to assess the consistency and accuracy of laboratory testing methods across different facilities. ILCs help identify discrepancies in test results, promote standardization, and enhance the credibility of laboratory findings.

The significance of ILC in uPVC pipe testing lies in its ability to foster confidence among manufacturers, regulators, and consumers regarding the quality of products in the market. By participating in ILCs, laboratories can benchmark their performance against peers, identify areas for improvement, and ultimately contribute to the overall enhancement of testing methodologies.

1.2 Overview of ILC on Pipe Testing: The ILC program conducted for uPVC pipes involved multiple laboratories testing identical samples for key parameters, including sulphated ash content, density, wall thickness, Vicat softening point, and opacity. Each of these parameters plays a crucial role in determining the quality and performance of uPVC pipes:

a) Sulphated Ash Content: This parameter indicates the presence of inorganic fillers and additives, which can affect the mechanical properties and durability of the pipes.
b) Density: The density of uPVC pipes is critical for assessing their strength and resistance to deformation under load.
c) Wall Thickness: Uniform wall thickness is essential for ensuring the structural integrity and pressure resistance of the pipes.
d) Vicat Softening Point: This test measures the temperature at which the material begins to soften, providing insights into its thermal stability and suitability for various applications.
e) Opacity: Opacity is an important parameter that can influence the performance of pipes in specific applications, particularly those involving light-sensitive fluids.

1.3 Challenges and Insights from the ILC Study: The ILC study revealed several challenges and insights regarding the testing of uPVC pipes. One of the primary challenges identified was the variability in testing methodologies employed by different laboratories. Discrepancies in sample handling, equipment calibration, and testing conditions led to variations in results, highlighting the need for standardized protocols. Insights gained from the ILC study emphasized the importance of continuous training for laboratory personnel to ensure adherence to best practices in testing. Furthermore, the analysis of Z-scores from the ILC results provided valuable feedback to participating laboratories, enabling them to identify areas for improvement and enhance their testing accuracy.

2.0 Objective

The primary objective of this Inter-Laboratory Comparison (ILC) program was to evaluate the accuracy, consistency, and reliability of test results produced by multiple laboratories for unplasticized polyvinyl chloride (uPVC) pipes as per IS 4985. The study focused on five critical quality parameters: sulphated ash content, density, wall thickness, Vicat softening point (VSP), and opacity.

By comparing test data across 10 participating laboratories, the program aimed to:

- Benchmark the performance of individual laboratories.
- Identify sources of inter-laboratory variation.
- Promote standardization in test procedures and data interpretation.
- Strengthen confidence in laboratory test results among stakeholders including manufacturers, regulators, and end users.
- Provide data-driven insights to improve testing practices, operator training, and equipment calibration.

Ultimately, this ILC served as a diagnostic and developmental tool to foster harmonization and raise the quality of uPVC pipe testing in India.

3.0 Design of the Program

The ILC program was meticulously structured to ensure objective assessment and meaningful statistical analysis. The key components of the program design included:

3.1 Sample Selection and Distribution

- uPVC pipe samples were sourced from a BIS-certified manufacturer to ensure quality and consistency.

- Identical samples were distributed to all 10 participating laboratories.
- Each lab received three specimens to test each parameter, enhancing data robustness.

3.2 Parameter Selection

The following five parameters were selected based on their significance in evaluating the quality and suitability of uPVC pipes for potable water systems:

- Sulphated Ash Content
- Density
- Wall Thickness
- Vicat Softening Point
- Opacity

3.3 Standardized Test Procedures

- Laboratories were instructed to use the methods outlined in the relevant Indian Standards (e.g., IS 4985, IS 13360) for each test.
- Strict adherence to sample preparation, environmental conditions, and calibration protocols was emphasized.

3.4 Data Collection and Analysis

- Participating laboratories submitted raw and calculated data for each parameter.
- Statistical tools such as mean, standard deviation, and Z-score were employed to evaluate inter-laboratory variability.
- Graphical representations including box plots, bar charts, and Z-score plots were used to visualize performance trends and deviations.

The comprehensive and structured design of the ILC ensured that findings could be interpreted meaningfully and translated into practical improvements in laboratory operations and industry practices.

4. Materials and Methods

This section outlines the materials used in the Inter-Laboratory Comparison (ILC) program for uPVC pipes, the design of the study, and the methodologies employed for testing the specified parameters. The aim is to provide a clear and comprehensive understanding of the procedures followed to ensure the reliability and accuracy of the results obtained from the participating laboratories.

4.1 Materials

42.1.1 uPVC Pipe Samples

The primary material used in this study was unplasticized polyvinyl chloride (uPVC) pipes, which were sourced from a reputable manufacturer compliant with the Indian Standard IS 4985. The pipes were selected based on their intended application in potable water supply systems.

The samples were subjected to rigorous quality control measures to ensure uniformity in material properties across all samples distributed to the participating laboratories.

4.2 Design of the ILC Scheme

The ILC program was designed to assess the consistency and accuracy of laboratory testing methods for uPVC pipes across 10 participating laboratories. The design included the following key components:

4.2.1 Sample Distribution

Identical samples of uPVC pipes were prepared and distributed to each of the 10 laboratories. Each laboratory received three samples to conduct the tests for each parameter, ensuring that sufficient data could be collected for statistical analysis.

4.2.2 Parameter Selection

The following parameters were selected for testing based on their significance in determining the quality and performance of uPVC pipes:

a) Sulphated Ash Content
b) Density
c) Wall Thickness
d) Vicat Softening Point
e) Opacity

These parameters were chosen due to their critical role in assessing the mechanical properties, durability, and suitability of uPVC pipes for potable water applications.

4.3 Testing Methods

Each participating laboratory was instructed to follow the standard testing methods outlined in the respective Indian Standards for each parameter. The methodologies for each parameter are detailed below:

4.3.1 Sulphated Ash Content

Procedure: A known weight of the uPVC sample was combusted in a muffle furnace at 600°C for 1 hour. The residue was then cooled and weighed to determine the sulphated ash content.
Calculation: The sulphated ash content was expressed as a percentage of the original sample weight.

4.3.2 Density

Procedure: The density of the uPVC pipe samples was determined using the water displacement method. The samples were weighed in air and then submerged in water to measure the volume displaced.
Calculation: Density was calculated using the formula:

4.3.3 Wall Thickness

Procedure: The wall thickness of the uPVC pipes was measured at multiple points along the length of each sample using a digital caliper. The average wall thickness was calculated from these measurements.
Specification: The measured wall thickness was compared against the specifications outlined in IS 4985.

4.3.4 Vicat Softening Point

Procedure: The Vicat softening point was determined using a Vicat apparatus. A needle was placed on the sample, and the temperature was gradually increased until the needle penetrated the sample to a specified depth.
Measurement: The temperature at which this penetration occurred was recorded as the Vicat softening point.

4.3.5 Opacity

Procedure: The opacity of the uPVC samples was measured using a spectrophotometer. The samples were placed in the light path, and the percentage of light transmitted through the sample was recorded.

4.4 Data Collection and Analysis

Once the tests were completed, each laboratory submitted their results, including raw data and calculated values for each parameter. The data were compiled and analyzed using statistical methods to assess the variability and consistency of results across laboratories.

4.4.1 Statistical Analysis

Z-scores were calculated for each parameter to evaluate the performance of each laboratory. The Z-score is defined as:

$$\text{Z-Score} = \{X - X' / \sigma\}$$

Where:
X = laboratory result
X' = mean of all laboratory results
σ = standard deviation of all laboratory results

Z-scores were used to identify laboratories that performed within acceptable limits and those that exhibited significant deviations from the mean.

5. Results and Discussion

5.1 Overview of Results

The Inter-Laboratory Comparison (ILC) program on uPVC pipes, conducted across 10 laboratories, evaluated five key parameters: sulphated ash content, density, wall thickness, Vicat softening point (VSP), and opacity. The summarized results are tabulated in table-1.

5.2 Sulphated Ash Content

The sulphated ash content showed the widest variation among all parameters, ranging from 5.19% to 11.5%. Such variability can be attributed to differences in combustion conditions, residue handling, or weighing practices. Since this parameter reflects the inorganic filler content, excessive variation suggests non-uniformity in sample decomposition and ash quantification methods. Laboratories with Z-scores beyond ±2 must re-examine their furnace calibration and procedural compliance with IS test methods.

5.3 Density

Density results remained within a relatively narrow band (1.41–1.45 g/cm³), indicating good consistency among the laboratories. This suggests a better standardization in the execution of the displacement method and accuracy of analytical balances. Minor variations could stem from differences in air buoyancy corrections or specimen preparation (voids, bubbles, etc.).

5.4 Wall Thickness

The measured wall thickness across labs ranged from 2.88 mm to 3.10 mm. Though deviations were within the acceptable tolerance limits as per IS 4985, slight inconsistencies may arise from the selection of measuring points along the pipe circumference and the pressure applied while using calipers. It underscores the need for harmonizing measurement protocol and instrument calibration.

5.5 Vicat Softening Point (VSP)

VSP values spanned from 80°C to 86°C. The 6°C spread, though moderate, may indicate variations in heating rate, load application, or needle alignment. Since VSP directly impacts the pipe's thermal performance, ensuring precision in thermal gradient control and specimen thickness is vital for comparability.

5.6 Opacity

All participating laboratories reported opacity values between 0.00% and 0.02%, showing extremely tight agreement. This consistency reflects well-calibrated spectrophotometers and standardized sample thickness during testing. Opacity, while not always a critical mechanical property, becomes significant in applications involving light-sensitive fluids and UV exposure.

5.7 Inter-Laboratory Variability

The Z-score analysis revealed that while most laboratories fell within acceptable limits ($|Z| < 2$), a few outliers were observed particularly in sulphated ash content and VSP. These deviations highlight the importance of method harmonization, technician training, and equipment validation across all labs.

5.8 Key Observations

Sulphated ash content remains a critical parameter needing better procedural control across labs.

Density and opacity showed strong inter-laboratory consistency.

Minor variations in wall thickness and VSP point toward differences in instrumentation and operator techniques.

The overall performance of participating labs was satisfactory, but targeted corrective actions are necessary for outliers to enhance uniformity in test results. The Inter-Laboratory Comparison (ILC) program was conducted across 10 laboratories for five critical parameters of uPVC pipes: sulphated ash content, density, wall thickness, Vicat softening point (VSP), and opacity. The results, analyzed using statistical tools and Z-scores, provide insight into the accuracy, precision, and methodological consistency across the participating laboratories.

5.9 Distribution and Outliers

The box plots in Figure 1 show the statistical spread and distribution of test values for each parameter. A wide interquartile range (IQR) for sulphated ash content confirms greater dispersion and potential outliers. On the other hand, density and opacity show compact distributions, suggesting that most labs adhered to standard protocols with minimal deviation.

5.10 Laboratory Performance Evaluation

To assess each lab's performance statistically, Z-scores were calculated for each result. Figure 2 illustrates the Z-score distribution per parameter across labs. A Z-score within ±2 indicates acceptable performance, while those outside this range point to significant deviation from the mean. Multiple labs showed Z-scores beyond ±2 for sulphated ash and VSP, highlighting the need for methodological harmonization and possibly targeted training interventions.

5.11 Inter-Laboratory Variation

Figure3 presents a grouped bar chart showing the measured values from each lab for all five parameters. It is evident that while some parameters like density and opacity demonstrated high consistency, others—particularly sulphated ash content and VSP—exhibited noticeable inter-laboratory variation. This may stem from inconsistencies in sample preparation, furnace temperature calibration, or thermal profiling during Vicat testing.

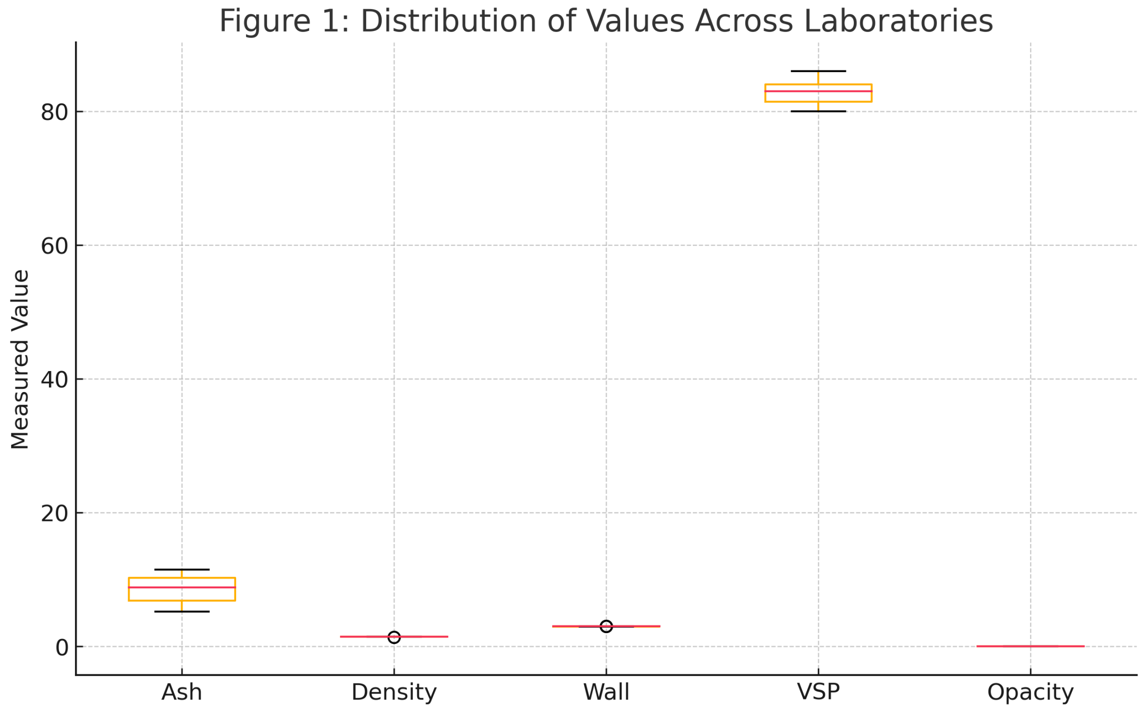

Figure 1: Distribution of Values Across Laboratories (Box Plot)

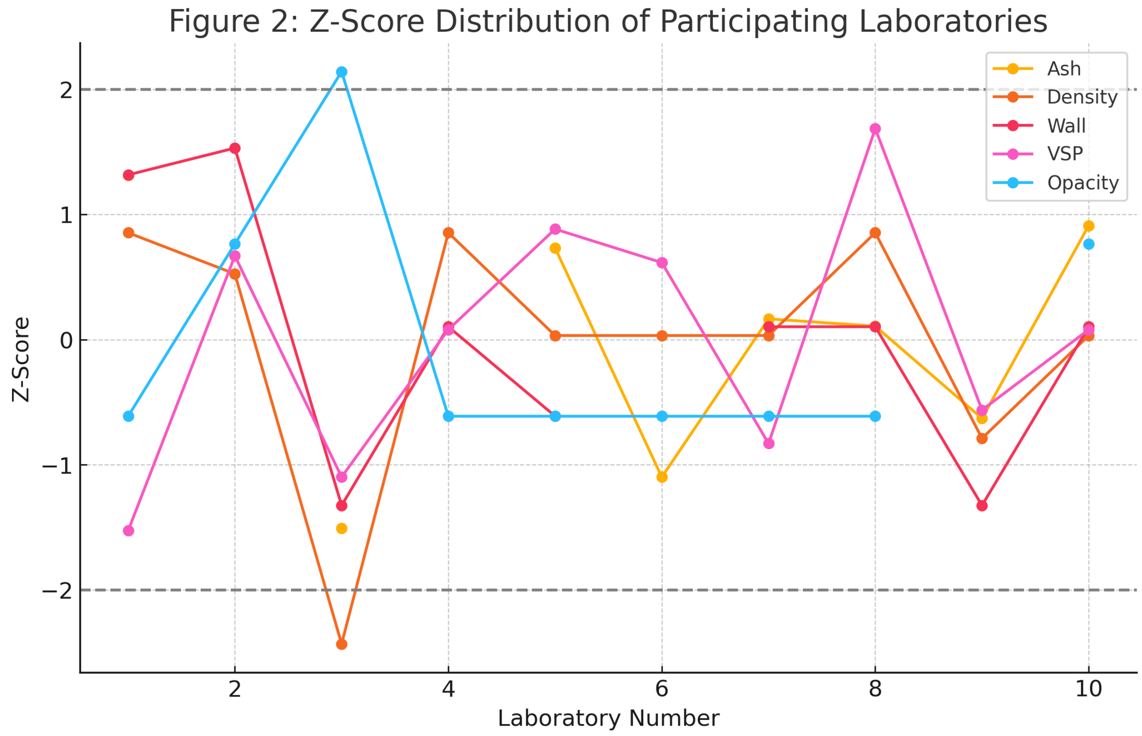

Figure 2: Z-Score Distribution of Participating Laboratories

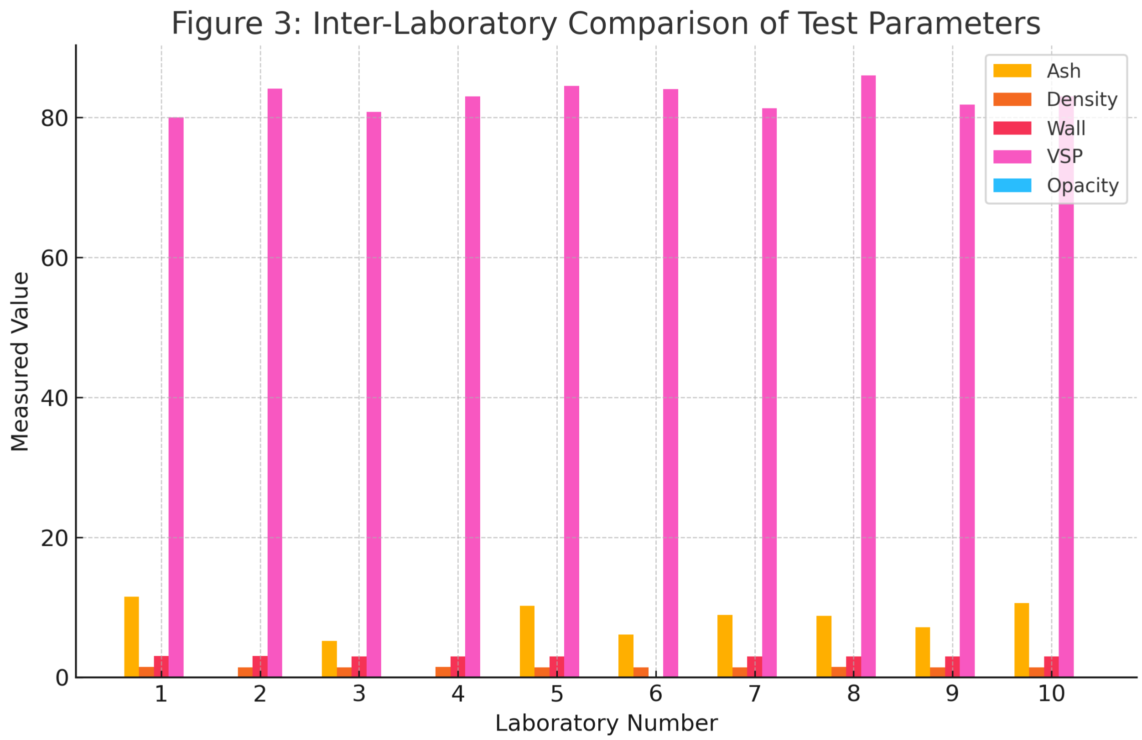

Figure 3: Inter-Laboratory Comparison of Test Parameters for uPVC Pipe Samples

5.12 Summary Statistics

The compiled summary statistics in Table 1 reinforce the graphical interpretations. Sulphated ash content had the highest standard deviation (2.24%), suggesting variable interpretation or execution of the ash test method. Density (SD: 0.012 g/cm³) and wall thickness (SD: 0.014 mm) showed minimal variance, indicating robust and reproducible testing. VSP exhibited moderate variability (SD: 1.87°C), while opacity, although low in range, showed measurable differences, possibly due to differences in spectrophotometer sensitivity.

Table 1: Summary Statistics of ILC Results for uPVC Pipes

Parameter	Unit	Minimum	Maximum	Mean	Standard Deviation (SD)
Sulphated Ash Content	%	5.19	11.50	8.56	2.24
Density	g/cm³	1.41	1.45	1.440	0.012
Wall Thickness	mm	2.98	3.02	2.999	0.014
Vicat Softening Point	°C	80.0	86.0	82.85	1.87
Opacity	%	0.00	0.02	0.0044	0.0073

5.13 Interpretation and Significance

These findings underline several key points:

- Sulphated ash testing needs immediate attention due to high variability. Consistency in muffle furnace conditions and post-ashing handling must be ensured.
- Density and wall thickness showed excellent reproducibility, reflecting strong adherence to standard protocols.
- VSP testing, while within standard bounds, showed enough variation to recommend periodic equipment calibration and procedural reviews.
- Opacity, despite being a non-structural parameter, benefits from high consistency, indicating well-maintained spectrophotometers and uniform sample thickness.

Overall, while most parameters were within acceptable reproducibility margins, outliers in ash content and softening point suggest targeted improvements in operator training, standard operating procedures (SOPs), and inter-laboratory benchmarking.

6. Recommendations for Improvement

Based on the findings of this ILC program, several recommendations can be made to improve the proficiency and reliability of testing laboratories:

a) Enhanced Quality Control: Implement standardized quality control measures across labs to minimize discrepancies in results.
b) Innovative Testing Methods: Adopt advanced testing methods to improve accuracy and reduce variability.
c) Training Programs: Regular training for laboratory personnel to ensure they are updated on the latest testing methodologies and standards.
d) Equipment Calibration: Regular calibration of testing equipment to ensure accurate measurements.

7. Implications for the uPVC Pipe Industry

The findings of this ILC program have significant implications for the uPVC pipe industry:

a) Operational Efficiency: Improved quality control and testing methods will enhance operational efficiency by reducing product failures.
b) Market Competitiveness: Companies investing in quality assurance will gain a competitive edge in the market.

c) Regulatory Compliance: Adopting stricter control methods will ensure compliance with national and international standards.

8. Training Methodologies for Laboratory Personnel

Training of laboratory personnel is essential for ensuring the accuracy and consistency of testing results. Training programs should cover both theoretical and practical aspects of testing uPVC pipes according to IS 4985. Continuous professional development opportunities should be provided to keep personnel updated on advancements in testing methodologies and standards.

9. Environmental Impact of uPVC Pipe Production

The production of uPVC pipes has several environmental implications. While the manufacturing process contributes to greenhouse gas emissions, uPVC pipes offer sustainability benefits, such as durability and recyclability. The long lifespan of uPVC pipes reduces the need for frequent replacements, conserving resources and minimizing waste.

10. Conclusion

The Inter-Laboratory Comparison (ILC) program conducted for uPVC pipes has provided valuable insights into the current state of testing practices across 10 laboratories. While the majority of laboratories demonstrated acceptable levels of consistency, significant variability was observed in sulphated ash content and Vicat softening point, indicating the need for improved procedural control, equipment calibration, and staff training.

Key findings include:

- High reproducibility in density, opacity, and wall thickness measurements.
- Notable inconsistencies in sulphated ash and VSP, likely due to differing furnace calibrations and heating protocols.
- Z-score analysis effectively identified outliers and offered a quantitative basis for performance evaluation.

These results underline the importance of harmonized methodologies, continual training of laboratory personnel, and regular inter-laboratory benchmarking. The program not only supports improved technical reliability but also strengthens regulatory compliance, product quality assurance, and stakeholder confidence in the uPVC pipe industry.

Moving forward, it is recommended that such ILC programs be institutionalized as part of routine quality assurance, with broader participation and an expanded scope to include additional parameters and material types.

Acknowledgment

The authors express gratitude to all participating laboratories for their contributions to this study.

Availability of Data and Materials

The data supporting the findings of this study are not publicly available to protect the privacy of laboratory participants. Requests for access to the data may be considered on a case-by-case basis.

Conflicts of Interest

The authors declare no conflicts of interest.

Funding

None.

Contribution
The corresponding author organized the ILC program and wrote the manuscript.

Abbreviations
uPVC: Unplasticized Polyvinyl Chloride
ILC: Inter-Laboratory Comparison
IS: Indian Standard

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