AGRICULTURAL ENGINEERING (ENGENHARIA AGRÍCOLA)

Revista Brasileira de Ciências Agrárias
ISSN (on line) 1981-0997
v.17, n.1, e1448, 2022
Recife, PE, UFRPE. www.agraria.pro.br
DOI: 10.5039/agraria.v17i1a1448 - Protocol 1448
Subm. 24/09/2021 • App. 29/11/2021 • Pub. 08/02/2022

Use of bench and portable rugosimeters in evaluating the internal roughness of PVC pipes of different diameters

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ABSTRACT: For the dimensioning of hydraulic systems used for water distribution, it is necessary to quantify the continuous head loss along the pipes. For this, one of the variables that influences this process is the surface roughness of these pipes, which, many times, does not have updated information and exact values for a correct dimensioning of the systems. An alternative to this is the measurement of these roughnesses through specialized instruments that determine various parameters of amplitude of irregularities. This work aims to analyze and compare the internal surface roughness, represented by the Ra parameter, through two measuring equipment (bench rugosimeter and portable rugosimeter), measured in PVC tubes used for water distribution, in addition to verifying the possibility of use of portable and easy-to-handle equipment. It was verified that the portable rugosimeter proved to be satisfactory for determinations of the roughness of the inner surface of PVC pipes, with smaller deviations than the bench rugosimeter, regarding the calculation off, and, in addition, it will serve the manufacturers to supply information related to the quality of the internal surface of your pipes.

Key words: bench rugosimeter; head loss coefficient; portable rugosimeter; water distribution systems

Utilização de rugosímetros de bancada e portátil em avaliação da rugosidade interna em tubos de PVC de diferentes diâmetros

RESUMO: Para o dimensionamento de sistemas hidráulicos utilizados para distribuição de água é necessário a quantificação da perda contínua de carga ao longo das tubulações. Para isso, uma das variáveis que influencia nesse processo é a rugosidade da superfície dessas tubulações, a qual, muitas vezes, não se tem informações atualizadas e valores exatos para um correto dimensionamento dos sistemas. Uma alternativa a isso é a medição dessas rugosidades através de instrumentos especializados que determinam diversos parâmetros de amplitude das irregularidades. Este trabalho tem por objetivo analisar e comparar a rugosidade superficial interna, representada pelo parâmetro Ra, através de dois equipamentos de medição (rugosímetro de bancada e rugosímetro portátil), medida em tubos de PVC utilizados para distribuição de água, além de verificar a possibilidade de uso de equipamentos portáteis e de fácil manuseio. Foi verificado que o rugosímetro portátil mostrou-se satisfatório para determinações da rugosidade da superfície interna de tubos de PVC, com desvios menores do que o rugosímetro de bancada, referente ao cálculo de f, e, além disso, ele servirá aos fabricantes o fornecimento de informações relacionadas à qualidade da superfície interna de suas tubulações.

Palavras-chave: rugosímetro de bancada; coeficiente de perda de carga; rugosímetro portátil; sistemas de distribuição de água

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Associate Editor: Edna Maria Bonfim Silva

Introduction

The Colebrook-White equation has been widely used to determine the head loss coefficient (Brkić & Ćojbašić, 2016; Zeghadnia et al., 2019) present in the Darcy-Weisbach formulation to measure the head loss of pipes. However, it is implicit with respect to the pressure drop coefficient, i.e., its resolution requires an iterative process (Díaz-Damacillo & Plascencia, 2019; Pérez-Pupo et al., 2020; Škopac et al., 2021).

Several researchers have endeavored to find explicit equations that could be used as alternatives to the Colebrook-White equation (Brkić & Praks, 2019; Minhoni et al., 2020; Niazkar, 2020), and, according to Bardestani et al. (2017), more complex relationships estimate the pressure drop coefficient more accurately.

In an analysis of explicit equations of the pressure drop coefficient, and, comparison with the Colebrook-White formulation, Pimenta et al. (2018) determined that the most accurate was the expression of Offor & Alabi (2016), valid for the range of Reynolds number of $4 \times 10^3 \leq Re \leq 10^8$ and relative roughness of $0 \leq \varepsilon/D \leq 5\times10^{-2}$.

Regarding pipe roughness, according to Bidmus et al. (2019), it is considered a property of the pipe material, being a measure of the irregularities of the pipe wall, and determined by the manufacturing process and tool. According to Rocha et al. (2017), if these inequalities are high and at high frequency, the surface is considered rough, and if the divergences are smaller, the surface is considered smooth.

Rough surfaces are found in many forms in engineering systems (Bons, 2010) and in the environment (Britter & Hanna, 2003). The presence of roughness is known to affect many properties of the turbulent flow near the pipe wall (Allen et al., 2007). Therefore, studying the influence of surface roughness on fluid flow has become necessary and important (Song et al., 2018).

Furthermore, according to Rocha et al. (2017), most of the tabulated values were obtained long ago and may not accurately reflect the roughness of current commercial pipes, given the changes in materials and in the pipe manufacturing processes. For this, specific equipment is used for measuring the surface roughness of pipes, such as bench rugosimeter and portable rugosimeter. Both devices read several roughness parameters, such as Ra, Rq, Rc, Rp, Rv, Rt, Rsk, Rz, Rku, among others. However, the average roughness (Ra) parameter is the most widely used for general quality control and surface roughness measurement (Kumar, 2019), and is present in virtually all surface roughness measuring devices.

Usually, in laboratories, bench rugosimeter are used that have software to visualize the measured parameters and their graphical representations. On the other hand, on factory floors, portable rugosimeters are used, which are practical, but often with limitations in visual capabilities (Rocha et al., 2017). However, today's portable equipment has good measurement accuracy, is easy to transport, and has a lower acquisition and maintenance cost than bench-top equipment. For this reason, it is extremely important to verify the roughness values measured with portable rugosimeters in relation to those on the bench, so that more practical and low-cost equipment can be used to determine the roughness of the internal surface of plastic pipes, such as polyvinyl chloride (PVC), widely used in irrigation systems, water distribution and sanitary sewage, hydraulic installations in buildings, among others.

Due to the above, this work aims to analyze and compare the internal surface roughness, represented by the Ra parameter, through two measurement devices (bench rugosimeter and portable rugosimeter), measured in PVC pipes used for water distribution, besides verifying the possibility of using portable and easy-to-handle equipment.

Materials and Methods

Brown PVC pipes of three different commercial brands were evaluated for diameters of 32, 50, and 75 mm. The NBR 5688:2018 (ABNT, 2018) that deals with PVC-U pipes and fittings for building systems for rainwater, sanitary sewage and ventilation - requirements, does not specify any information regarding the internal surface roughness of these pipes. The choice of materials was determined by the fact that there are not enough roughness data in the literature for the brown material, which can be used, with low cost and ease of acquisition, for irrigation of small flows, such as localized irrigation.

The specimens were taken from 6 m long PVC tubes, and were made up of 1 m equidistant cuts, disregarding 50 cm from each end of the tube, thus forming 6 semi-cylindrical samples. This occurred for each of the 3 diameters and each of the 3 commercial brands, totaling 54 specimens. The roughness measurement was analyzed in 3 different positions for each sample (one at each end and one in the middle), in the direction longitudinal to the fluid flow direction, thus totaling 162 different internal roughness measurements.

In order to compare the values of the Ra parameter obtained by the bench rugosimeter with the portable rugosimeter, the measurements, in both devices, were performed in the same positions of the specimens, that is, in the same three places.

The internal roughness measurements of the pipes were performed using a bench rugosimeter at the Laboratório de Ensaios de Material de Irrigação (LEMI), a laboratory linked to the Instituto Nacional de Ciência e Tecnologia - Engenharia de Irrigação (INCT-EI) and located at the Departamento de Engenharia de Biossistemas of the Escola Superior de Agricultura "Luiz de Queiroz" (ESALQ/USP), in Piracicaba, SP, Brazil.

The equipment is specific for roughness measurement with micro geometric precision, which is connected to a computer unit with specific software (Surftest SV-600/Mitutoyo®) for operation, reading and interpretation of measurements, measured daily with a standard sample of known roughness, with Ra = 2.94 µm. The feed unit allows the probe to be positioned on the specimen supported in the vice of the equipment by means of vertical and horizontal displacements on a support column, with the entire assembly supported on a static bench (Rocha et al., 2017).

The equipment is basically composed of a diamond probe tip, whose cross-section radius and tip angle are 2.0 µm and 60°, respectively, which is in accordance with the indications of NBR ISO 3274 (ABNT, 2008). The rugosimeter was set to move at a constant speed of 0.1 mm s^{-1} over the inner surface of the tube, with five cut-off values (λ = 2.5 mm), resulting in 15 mm for the evaluation path (since the device disregards ½ λ at the beginning and end of sampling for reading stability) and 9600 points sampled on the surface to plot the measured profile.

In the Laboratório de Metrologia of the Colégio Técnico Industrial de Santa Maria (CTISM), located at the Universidade Federal de Santa Maria (UFSM), in Santa Maria, RS, Brazil, the measurements of the internal roughness of the pipes were performed with a portable rugosimeter model RP-200 from Instrutherm®, with maximum precision of ±10%, which was measured daily with a standard sampling plate (Ra = 1.58 µm), and composed basically of a diamond probe tip, whose cross-section radius and tip angle are 2.0 µm and 90°, respectively.

To measure the roughness of a surface, the probe is placed on the surface of the part and traced in constant proportion, obtaining the surface roughness by the needle. The portable rugosimeter was set to move at a constant speed of 0.1 mm s^{-1} over the inner surface of the pipe, with five cut-off values equal to 2.5 mm resulting in 12.5 mm for the evaluation path and 8192 points sampled on the surface to draw the measured profile.

In both measurement equipments, the readings were taken in a controlled environment with a temperature of 20 °C, in order to minimize the environment's interference in the quality of the readings and measurement results, as well as the possible influence of external noise or instability of the evaluation bench.

To verify the roughness values obtained with the two measuring devices, regression analysis was performed with a 1:1 straight line fit. In addition, Offor & Alabi (2016) equation was used to determine the pressure drop coefficient (f), as expressed in Equation 1.

$$\frac{1}{\sqrt{f}} = -2\log\left\{\frac{\varepsilon}{3.71D} - \frac{1.975}{Re}\left[\ln\left(\left(\frac{\varepsilon}{3.93D}\right)^{1.092} + \left(\frac{7.627}{Re+395.9}\right)\right)\right]\right\} \quad (1)$$

where:

f - pressure drop coefficient (dimensionless);
D - pipe diameter (m);
ε - absolute pipe roughness (m); and,
Re - Reynolds number (dimensionless).

To determine f, values of Re were calculated using Equation 2, with velocities between 0.5 and 3.0 m s^{-1}, diameters of 32, 50 and 75 mm, and a kinematic viscosity of water at 20 °C with a value of 1.003×10^{-6} m^2 s^{-1}.

$$Re = \frac{V \cdot D}{\upsilon} \quad (2)$$

where:

V - flow velocity of the fluid (m s^{-1}); and,
υ - kinematic viscosity of the fluid (m^2 s^{-1}).

Also, for absolute roughness, we considered the values measured of the Ra parameter through the bench rugosimeter (Ra1) and Ra values measured through the portable rugosimeter (Ra2). Both were used to calculate the f and compared with the f calculated with the roughness proposed by Uribe et al. (2015), with a value of 1.5 µm.

In order to evaluate which measurement equipment provides the best performance, the statistical performance index root mean square error (RMSE) was used, exposed in Equation 3.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(O_i - P_i\right)^2} \quad (3)$$

where:

RMSE - root mean square error;
n - number of observations;
O_i - observed values; and,
P_i - estimated values.

In addition to RMSE, graphical error analysis is a useful tool for quantifying forecast errors associated with their frequency of occurrence (Sobenko et al., 2018). For this, the relative error (δ) was used as a predictive error indicator (Equation 4). The smaller the δ, the better the performance of the model.

$$\delta = \left|\frac{O_i - P_i}{O_i}\right| \cdot 100 \quad (4)$$

where:

δ - relative error (%).

Results and Discussions

Table 1 shows the roughness values measured by the bench rogosimeter (Ra1) and the portable rugosimeter (Ra2) on PVC pipes with nominal diameters of 32, 50 and 75 mm.

From Table 1 it can be seen that the internal surface roughness values measured by the different rugosimeters showed a discrepancy between the diameters evaluated, and thus it is understood that the adoption of specific roughness values for each diameter contributes to the quality of the results related to the determination of the head loss of the

Table 1. Internal surface roughness and confidence interval measured by bench rugosimeter (Ra1) and portable rugosimeter (Ra2) on PVC pipes.

DN (mm)	Ra1 (µm)	Ra2 (µm)
32	0.7548	0.9027
50	1.3478	1.5002
75	0.6200	0.6664
Average	0.9075 ± 0.08	1.0231 ± 0.08

pipes. According to Rocha et al. (2017), such a difference is not about the response of the parameters to a treatment, but about the difference in quality of the internal surface of the tubes, resulting from their manufacturing process.

Moreover, it is noted that both rugosimeters showed a confidence interval of 0.08, which may indicate that the two devices have similar uncertainty margin, with the same potential probability of representing the real characteristics of the measured surface.

For PVC plastic pipes, Porto (2006) determined the roughness to be between 1.5 and 10 μm, without specifying their diameter. In contrast, Rocha et al. (2017) found experimentally, for the Rc parameter, values of 4.431 μm in PVC pipes with diameters from 32 to 75 mm. Uribe et al. (2015) used roughness values for PVC pipes, in any diameter, of 1.5 μm. Azevedo Netto & Fernández (2015) propose that the roughness value in PVC pipes, in any diameter, should be 5 μm. And finally, Kellner et al. (2016) experimentally found a value of 26.65 μm for the Ra parameter of PVC pipes between 50 and 75 mm in diameter.

In view of the roughness values found by several authors, it is noted that there is variation between them, which, in agreement with Andrade & Carvalho (2001), who stated that the roughness values found in technical bibliographies are quite variable, presenting, for the same type of material, wide range of values. This can often cause difficulties for decision making by the technical designer.

In order to verify the internal surface roughness found in the two rugosimeters in relation to the roughness value of the standard plate of each, Figure 1 is presented.

It can be seen from Figure 1A that the average internal surface roughness values found in the bench rugosimeter are below the value of the standard plate with Ra = 2.94 μm, with deviations of approximately 70%. As the device was calibrated in all the measurements taken, this may have occurred because the degree of roughness varies with the manufacturing process and surface finish. Nunes (2011) states that the roughness of a surface is controlled by several parameters, such as the machine, tool, workpiece material properties, tool geometry and material, fluid application techniques, atmosphere, and machining process.

In Figure 1B it can be seen that the average values of the internal surface roughness obtained smaller variations in relation to the roughness of the standard plate of the portable rugosimeter, with deviations of 35%, a fact that may have occurred for the same reason previously mentioned.

To verify the relationship between the roughness measurements between the two pieces of equipment, Figure 2 is presented, in which lines with relative deviations between Ra1 and Ra2 were plotted, represented by the dashed lines, and the ideal fit in the continuous line.

It can be seen from Figure 2 that the relative deviations between Ra1 and Ra2 are within the ±25% range, with some values showing deviations of 50%. This fact may justify the value of the coefficient of determination (R^2) having a value of 0.857, showing a less than perfect agreement between the

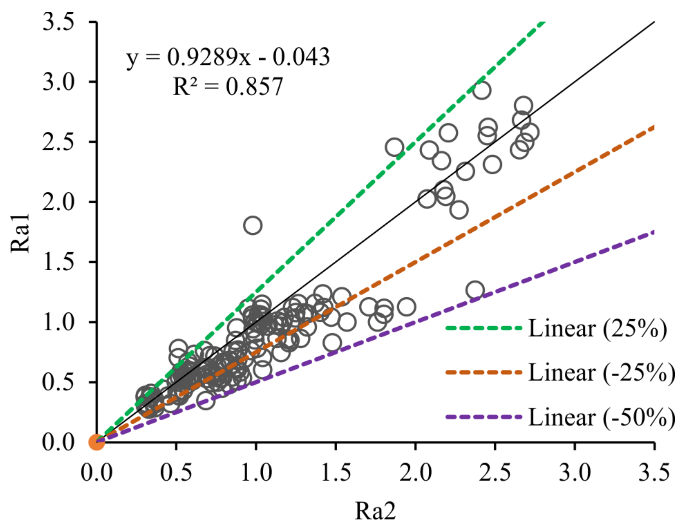

Figure 2. Comparison between Ra1 and Ra2 measurements on 32, 50 and 75 mm diameter PVC pipes.

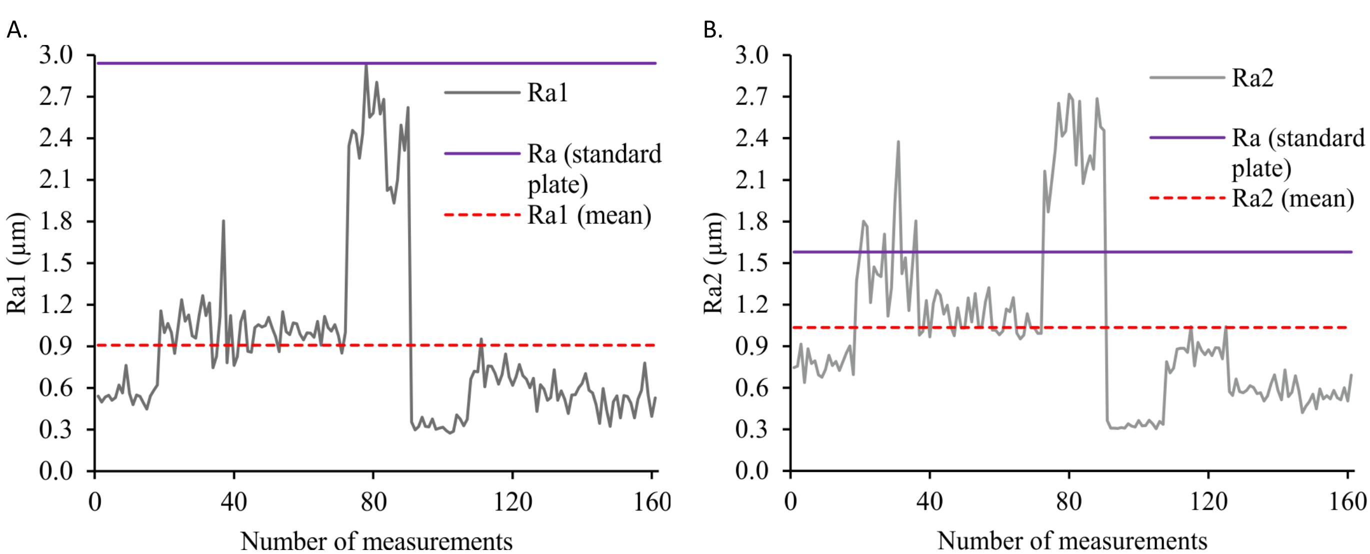

Figure 1. Internal surface roughness values in relation to the standard plate value for the bench rugosimeter (A) and portable rugosimeter (B), on 32, 50 and 75 mm diameter PVC pipes.

data. Furthermore, these points with greater deviations are justified by the difference in roughness values between the diameters evaluated, confirming what can be seen in Figure 1, where there are more pronounced peaks in relation to the average line.

In order to determine the fit between Ra1 and Ra2, regression analysis was performed and line fit plotted against Ra1, as shown in Figure 3.

With the adjustment between the Ra1 and Ra2 values one can accurately determine measurements between the portable and bench rugosimeters, and accurate Ra measurements can be obtained, even with the portable rugosimeter, which can be used satisfactorily by designers and technicians in the calculation of the f-factor.

Figure 4 shows the relation between f, calculated by Equation 1, and Re, calculated by Equation 2, so that the behavior of the roughness Ra1 and Ra2 in relation to the flow regime can be understood.

It can be seen that the roughness values measured by the two rusogimeters provide a good fit with respect to the

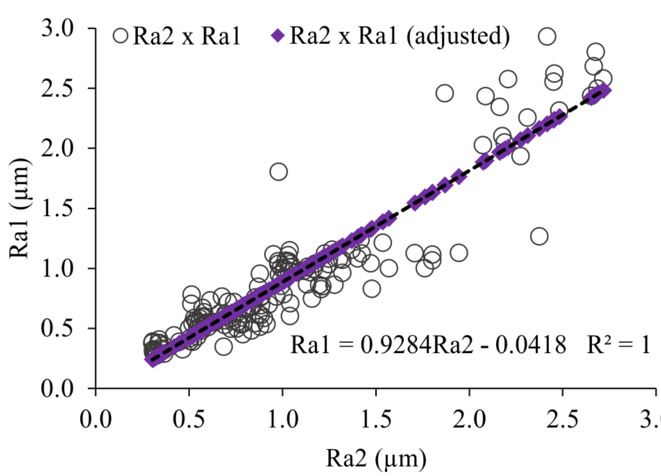

Figure 3. Adjustment between Ra1 and Ra2 measurements for 32, 50 and 75 mm diameter PVC pipes.

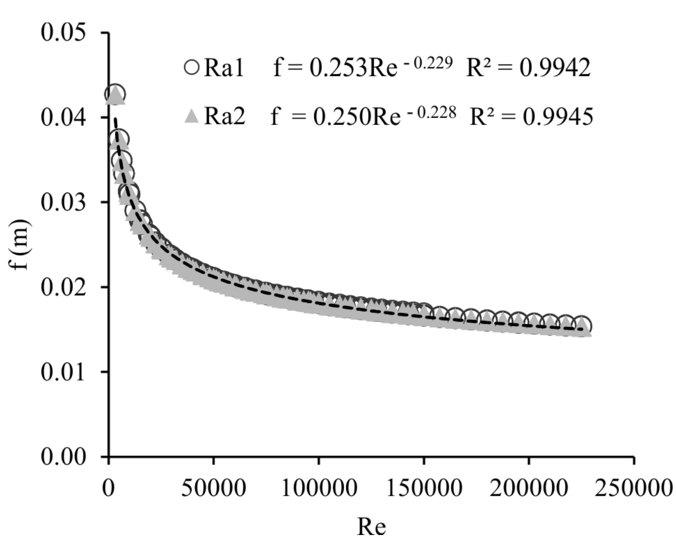

Figure 4. Relation of the pressure drop coefficient (f) with the Reynolds Number (Re) for PVC pipes with diameters of 32, 50 and 75 mm.

Moody diagram, which serves, among other functions, to stipulate the surface roughness. This diagram shows f as a function of relative roughness and Re, and also represents three flow regimes: laminar, transitional, and turbulent.

To determine the flow regimes provided by the analyzed data, the Nikuradse equation $(Re\sqrt{f})/(D/\varepsilon) < 14.14$ was used to determine whether the flow regime is smooth turbulent, and, in all measured data, values lower than 14.14 were obtained, proving that they are under such flow condition. It can be seen from Figure 4 that the behavior, for both roughnesses evaluated, is in agreement with the Blasius equation ($f = 0.32\ Re^{-0.25}$), valid for hydraulically smooth turbulent flow regime ($4{,}000 < Re < 100{,}000$).

This fact impacts, because, for smooth pipes, the surface roughness does not influence the f-factor, being more expressive for this work range the contribution of the Reynolds number. Thus, for any experimental values of the roughness measured in the rugosimeters, the same values of f would be obtained, which, consequently, would cause erroneous estimates of the head loss of the pipes.

To apply the roughness values determined with the two-measurement equipment, the estimated f was calculated using Equation 1, and compared with the observed f values with the roughness proposed by Uribe et al. (2015), which can be seen in Figure 5.

As can be seen in Figure 5, the relationship between the observed and estimated f has an excellent fit with both Ra1 and Ra2 measurements, which can be justified by the data analyzed being under smooth hydraulic regime, in which only Re influences the f calculations. In addition, the RMSE for Ra1 and Ra2 was calculated using Equation 3 and obtained values of 0.008 and 0.007%, respectively, showing that the deviations obtained with the portable rugosimeter are smaller than the deviations with the bench rugosimeter.

Figure 6 shows the distribution of the frequency of occurrence of the relative error, calculated by Equation 4, with the roughness Ra1 and Ra2 and compared with the roughness proposed by Uribe et al. (2015).

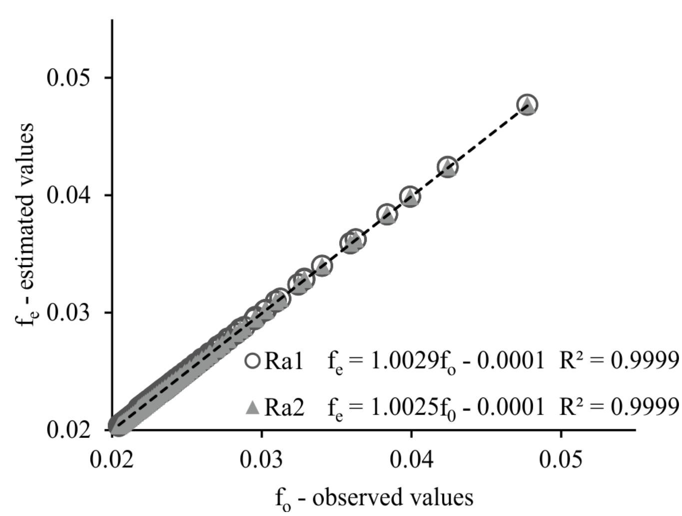

Figure 5. List of observed and estimated head loss coefficients for PVC pipes with diameters of 32, 50 and 75mm.

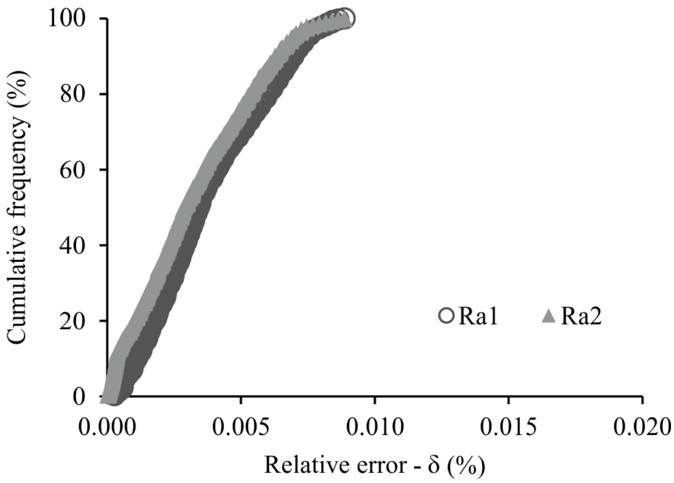

Figure 6. Frequency distribution of occurrence of the relative error (δ) for the head loss coefficient (f) calculated with the roughness Ra1 and Ra2 in relation to the roughness proposed by Uribe et al. (2015) for PVC pipes with diameters of 32, 50 and 75 mm.

It can be seen from Figure 6 that 95.00% of their predictions had a relative error of up to 0.0074% for the Ra1 parameter and 0.0070% for Ra2, and that 50.00% of the predictions had 0.0034 and 0.0029% relative error for the Ra1 and Ra2 parameters, respectively.

It can be concluded that the portable rugosimeter obtained lower errors compared to the bench rugosimeter, and can be used accurately for surface roughness measurements of PVC pipes, with the advantage of being more practical, lower cost of acquisition and easy mobility.

Conclusions

The portable rugosimeter proved to be satisfactory for determining the roughness of the internal surface of PVC plastic pipes, with smaller deviations than the bench rugosimeter, referring to the calculation of f.

The portable rugosimeter may hold promise for enabling manufacturers to provide information related to the internal surface quality of their pipes, which may allow designers to be more accurate in their calculations of f and hf.

Even with different roughness values, similar values were obtained for the f-factor, due to the condition of hydraulically smooth flow regime.

Compliance with Ethical Standards

Author contributions: Conceptualization: BDP, ADR, MXP; Data curation: BDP; Formal analysis: BDP, HSR, LRS, CGC; Funding acquisition: BDP, ADR, MXP; Investigation: BDP, HSR, LRS, CGC; Methodology: BDP, ADR, MXP; Project administration: BDP, ADR, MXP; Resources: BDP, HSR, LRS; Supervision: ADR, MXP; Validation: BDP, ADR, MXP; Validation: ADR; Visualization: BDP; Writing – original draft: BDP, HSR, LRS, CGC; Writing - review & editing: BDP, ADR, MXP, HSR, LRS.

Conflict of interest: We declare that there are no conflicts of interest.

Financing source: Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), through the granting of a scholarship.

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