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Statistical Testing of the Bedoya Cone for Concrete Slump Tests: An Ecological Contribution from the Economy of Materials

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Abstract This study shows the modification of the cone of Abrams. A new device size was obtained, with 68% savings in terms of the material. Similarly, we explored the contribution to the aspect of occupational health since, from an ergonomic perspective, the test can be developed at a more comfortable and safe height for the person. Furthermore, we found equivalence between the ranges of the Abrams cone and the Bedoya cone. According to the tests performed, it is possible to significantly reduce the consumption of materials for the slump test without affecting the quality of the result. It improves the ergonomics condition of laboratory workers, especially for women who are not allowed to lift heavy loads due to occupational health regulations. More than 60 tests were carried out in universities, construction sites, precast industries and nationally and internationally accredited laboratories. The methodology used consisted of carrying out the test using the same mixture and finding the slump with the Abrams cone and the Bedoya cone simultaneously under the same conditions of temperature, time and humidity. One important aspect is the possibility of using in mixtures with coarse aggregates of sizes 9.5 mm (3/8"), 13 mm (1/2"), 19 mm (3/4"), and 25.4 mm (1"), being these the most commercially made worldwide. The results and the statistical analysis allow us to conclude that it is possible to use the Bedoya cone to determine the concrete slump in the fresh state, since its ranges are directly applicable with respect to the Abrams cone. As it is a test that continues to be carried out daily in all countries of the world, this research is also a social and environmental contribution. The cone of Bedoya is registered in Colombia under the patent of invention number NC2016/0001514, and is being applied in Undergraduate, Master's and Doctorate research in this country and in México.

Keywords Concrete, Workability, Slump, Sustainable Construction, Ergonomics

1. Introduction

After performing an exercise of proportionality between the cone of Abrams and a new device. The new device has the advantages of reducing the material size and enhancing the measurement accuracy of the test and its results. We obtained a conical trunk mold with the following dimensions: height (203 mm), larger diameter (135 mm), and smaller diameter (68 mm); the metal rod required for a 25 compactness is 300 mm long and 10 mm in diameter, as shown in Figures 1, 2 and 3. Although there are other devices known as mini-cones on the market and in the academy, these are used for slump in pastes, mortars and grouts [1]. The Bedoya cone, on the other hand, is suitable for conventional concrete for massive use in construction and engineering, using coarse aggregates of a wide range of application.

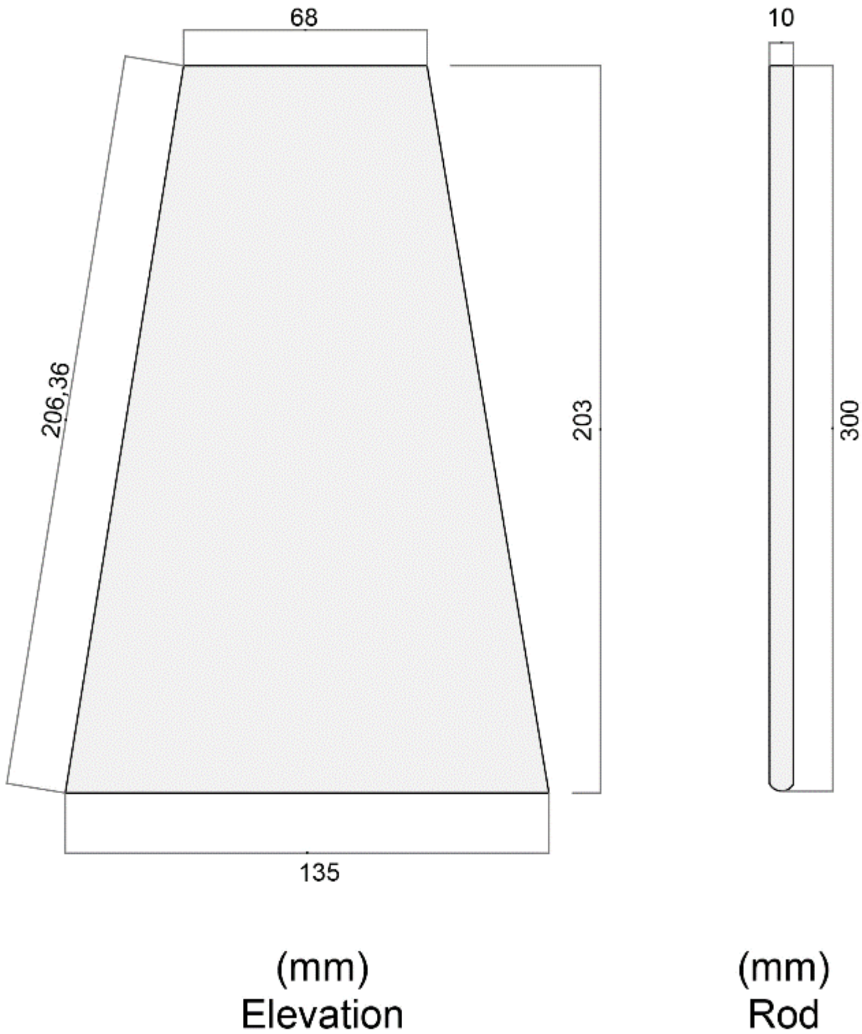


Figure 1. Dimensions of the modified cone of Bedoya

(Source: Bedoya, C.; 2014).

Figure 2. The modified cone of Bedoya (yellow) compared to the cone of Abrams

(Source: Bedoya, C.; 2019).

Figure 3. Comparison of cylindrical molds and cones

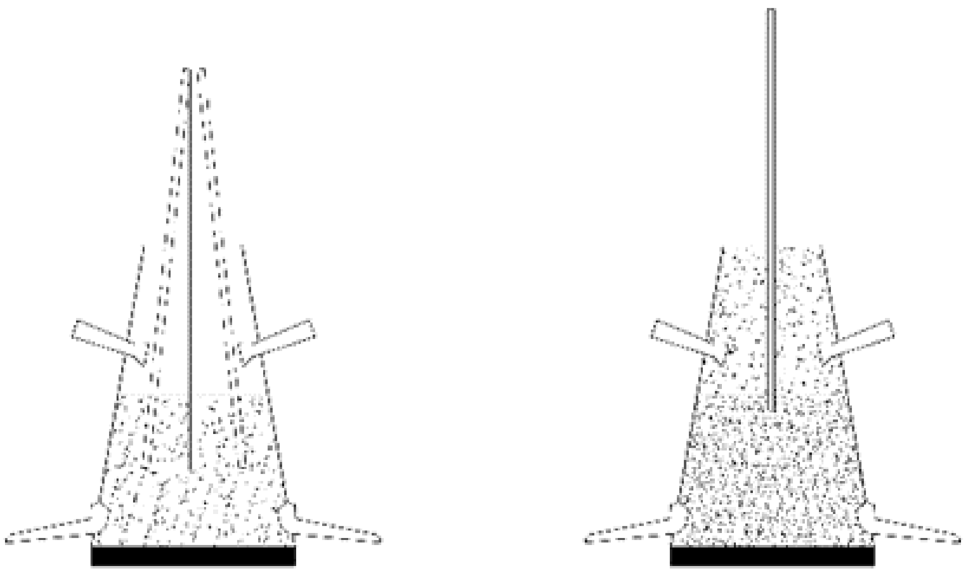
2. Materials and Methods

We carried out the work with concrete mixtures widely used in construction and design laboratories: 21–28 MPa resistance to compressive strength. We performed 50 slump tests in different university laboratories, construction sites, and certified laboratories with the following aggregate sizes: 9.5 mm (3/8"), 13 mm (1/2"), 19 mm (3/4"), and 25.4 mm (1"). The types of cement used were ordinary Portland cement and early strength cement. We used different water/cement ratios to various slumps. The mixtures made with plasticizing additives and without additives present the same behavior concerning the correlation between the Abrams [2, 3] and the Bedoya cones.

The following section presents the procedures for the slump test with the Bedoya cone and the comparison images between the tests carried out with both cones. Thus, the ergonomic aspect, which represents an improvement in the posture and effort of the person performing the test, can be identified. Subsequently, we present the statistical analysis.

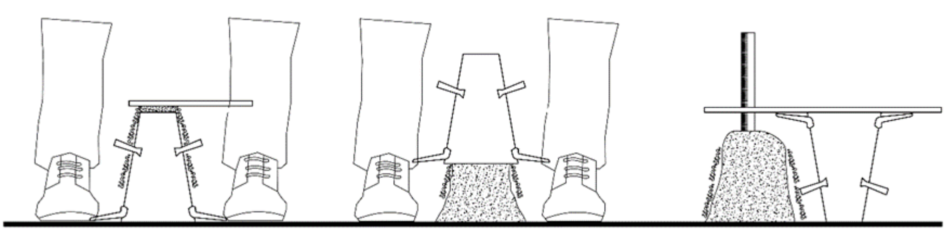
2.1. Test Procedure

The test with the Bedoya cone is made by compacting two layers with 25 repetitions in each layer and leveling the cone to raise it at a time of 4 ± 1 s. Furthermore, we placed the mold next to the mix and measured the slump with the help of a metal rod for the Abrams cone (see Figures 4 and 5). We also worked with different water-cement ratios to cover a wide variety of slumps.



(Source: Bedoya, C. and López, P.; 2019).

Figure 4. The process with two layers



(Source: Bedoya, C. and López, P.; 2019).

Figure 5. Tests were performed on the floor.

(Source: Unimedios; 2019).

Figure 6A, 6B and 6C. Slump test process with Abrams cone

(Source: Unimedios; 2019).

Figure 7A, 7B and 7C. Slump test process with the Bedoya cone

Figures 6A, 6B, 6C and 7A, 7B, 7C show the slump test process with the two devices. From 6A, 6B and 6C with the cone of Abrams and 7A, 7B and 7C with the Bedoya cone.

Although there is research in which the slump test can be automated [4], this is still a manually performed procedure. As observed in the sequences of the images, the ergonomic position with the Abrams cone represents much effort for the student who performs the test [5]. Whereas, with the modified cone of Bedoya, the test can be done at the height of the laboratory's bench, allowing the laboratory worker posture to be ergonomically healthier since the spine is in a straight position and the compaction effort is less. Additionally, the vertical elevation of the cone improves due to the shorter distance to be lifted, since the height of the Bedoya cone is 2/3 with respect to the Abrams cone and, as for the weight of the mold, 52% less (see Figure 8). Finally, it increases the accuracy of the slump measurement by reducing the parallax effect. Another vital aspect is that the metal rod of the Abrams cone weighs 942 g, and that of the Bedoya cone weighs 169 g, which affects the motor gesture of the person performing the test significantly, considering that the 75 compactions −Abrams− are reduced to 50 −Bedoya− [6].

We collected 50 paired observations of concrete slump with the Abrams cone and the Bedoya cone from 6 laboratories and 4 types of aggregates according to diameter size.

The descriptive statistical analyses carried out include the following: tables of frequencies, quartiles, means, and standard deviations of the concrete slump measurements with the reported methods, as well as the proportional relationship of the paired samples.

The study assessed the effect of covariates on slump measurements using analysis of variance (ANOVA), adjusting the linear regression model between the methods, and validating the assumptions of the model according to [7]. We assessed the normality using the Shapiro–Wilks test and heteroscedasticity of the residuals using the Breush–Pagan test. The data were analyzed using R programming language version 4.0.5 at a 5% significance level.

(Source: Unimedios; 2019).

Figure 8. The compared volume between both devices

2.1.1. Descriptive Analysis

The results of concrete slump measurements with the Bedoya cone show a relationship of approximately 50% compared with the Abrams cone throughout the measurement domain (see Table 1).

The relational behavior of the results of the Bedoya cone concerning the Abrams cone maintains a 2:1 relationship, regardless of the laboratory in which the test was performed (see Table 2).

Table 1. Statistical analysis of slump tests

Cone	n	Mean cm	SD cm	Min cm	Q1 cm	Q2 cm	Q3 cm	Max cm
Abrams	50	10.84	5.24	1.5	7.00	10.00	16.23	20.00
Bedoya	50	5.28	2.51	0.70	3.50	5.00	7.07	10.00

Table 2. Data collection from slump tests

Cone	Lab.	n	Mean. cm	SD cm	Min cm	Q1 cm	Q2 cm	Q3 cm	Max cm
Abrams	Arconsa	4	17.25	3.43	12.50	15.88	18.25	19.62	20.00
	ConcreLab	2	18.25	1.06	17.50	17.88	18.25	18.62	19.00
	IUCMA	16	11.81	6.16	2.50	6.88	9.70	17.92	19.70
	J and C	4	7.67	3.27	4.10	5.30	8.05	10.43	10.50
	UNAL	21	9.24	3.74	1.50	7.00	8.50	11.00	18.00
	Various	3	7.67	2.52	5.00	6.50	8.00	9.00	10.00
Bedoya	Arconsa	4	8.30	1.59	6.00	7.88	8.85	9.27	9.50
	ConcreLab	2	9.60	0.57	9.20	9.40	9.60	9.80	10.00
	IUCMA	16	5.62	2.97	1.50	3.08	4.60	8.15	10.00
	J and C	4	3.80	1.77	1.90	2.50	3.90	5.20	5.50
	UNAL	21	4.59	1.63	0.70	3.50	5.00	5.50	8.00
	Various	3	3.40	0.79	2.50	3.10	3.70	3.85	4.00

Similarly, the type of aggregate seems not to affect the relationship between the cones; this suggests that when applying the Bedoya method, the settlement level can be approximated by multiplying the measurement by two (see Table 3).

Table 3. Data collection of slump tests according to aggregates

Cone	Aggregate	n	Mean. cm	SD cm	Min cm	Q1 cm	Q2 cm	Q3 cm	Max cm
Abrams	1	4	17.25	3.43	12.50	15.88	18.25	19.62	20.00
	1/2	14	13.32	6.45	2.50	6.62	17.25	18.90	19.70
	3/4	27	9.57	3.41	4.10	7.05	8.50	11.00	18.00
	3/8	5	5.68	3.08	1.50	4.60	5.80	6.50	10.00
Bedoya	1	4	8.30	1.59	6.00	7.88	8.85	9.27	9.50
	1/2	14	6.56	3.23	1.50	3.17	7.75	9.43	10.00
	3/4	27	4.58	1.50	1.90	3.50	5.00	5.50	8.00
	3/8	5	3.10	1.61	0.70	2.50	3.50	3.80	5.00

The graph below shows the behavior of the slump in Abrams Cone and Bedoya Cone, multiplying the latter by two (see Figure 9).

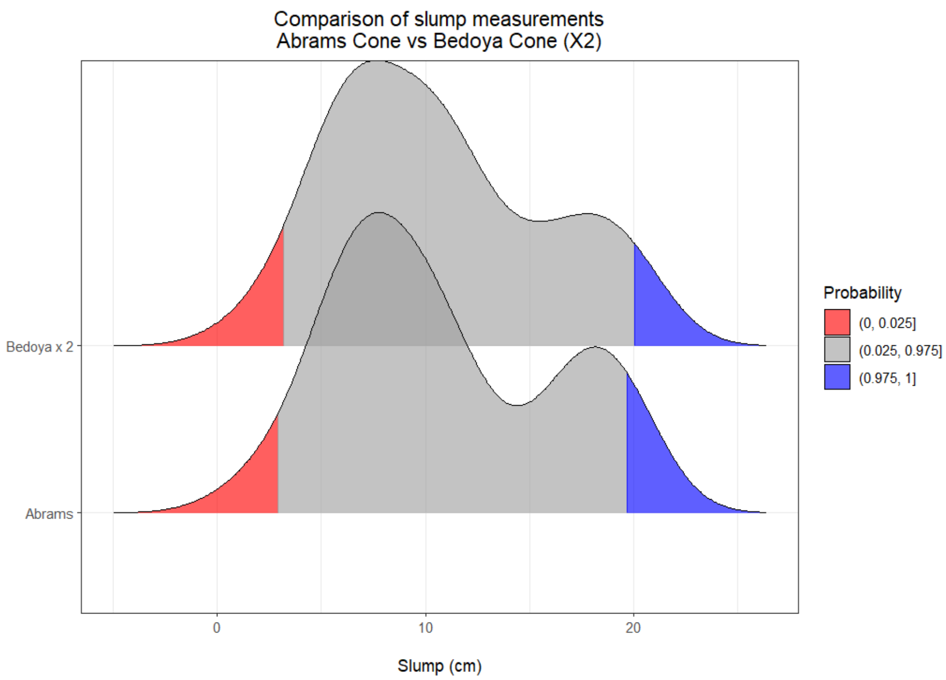


Figure 9. **S**lump essay Abrams=2 Bedoya

The different-mixing designs in each test explain the asymmetric behavior in both results since this preparation depends on the expected slump level established by Abrams. Since it is a table of intervals, it is impossible to establish a more specific expected value of slump; therefore, few samples were obtained for the 10 cm to 20 cm interval. However, multiplying the slump results with the Bedoya cone by two units reproduces the behavior of the obtained slump with the Abrams cone, including the confidence bands in the two methods, which are equivalent (see Table 4).

Table 4. Equivalence of the Abrams and Bedoya slump test

Cone	n	Mean cm	SD cm	Min cm	Q1 cm	Q2 cm	Q3 cm	Max cm
Abrams	50	10.84	5.24	1.50	7.0	10.0	16.23	20.0
Bedoya x 2	50	10.57	5.02	1.40	7.0	10.0	14.15	20.0

2.1.2. Analytical results

The descriptive analysis showed a 2:1 relationship between the Bedoya cone and the Abrams cone. Also, the Laboratory and Aggregate covariates do not affect the slump response. We divide the result of the slump with the Bedoya cone by the Abrams cone results to calculate the paired samples' proportional relationship to verify the above result.

Table 5. Analysis of covariates using ANOVA

	Sum Sq	Df	F value	Pr(>F)
Laboratory	0.0082	4	0.7834	0.5424
Aggregate	0.0101	2	1.9369	0.1568
Residuals	0.1098	42	0.7834	

The study evaluates the covariate effects of the unbalanced data using ANOVA to determine whether conducting the tests in a laboratory or having different types of aggregates affects the slump in any methods (see Table 5).

The effects of the Laboratories and types of aggregates are not significant, p-value = 0.5424 and p-value = 0.1568, respectively, which indicates that concrete slump measurements are not affected by these covariates, and this suggests that a regression model that relates to the Bedoya cone measurements to the Abrams cone can be built.

The graph below (Figure 10) shows a strong linear relationship between the concrete slump measurements with the Bedoya and Abrams cones since the correlation between both is 0.9809.

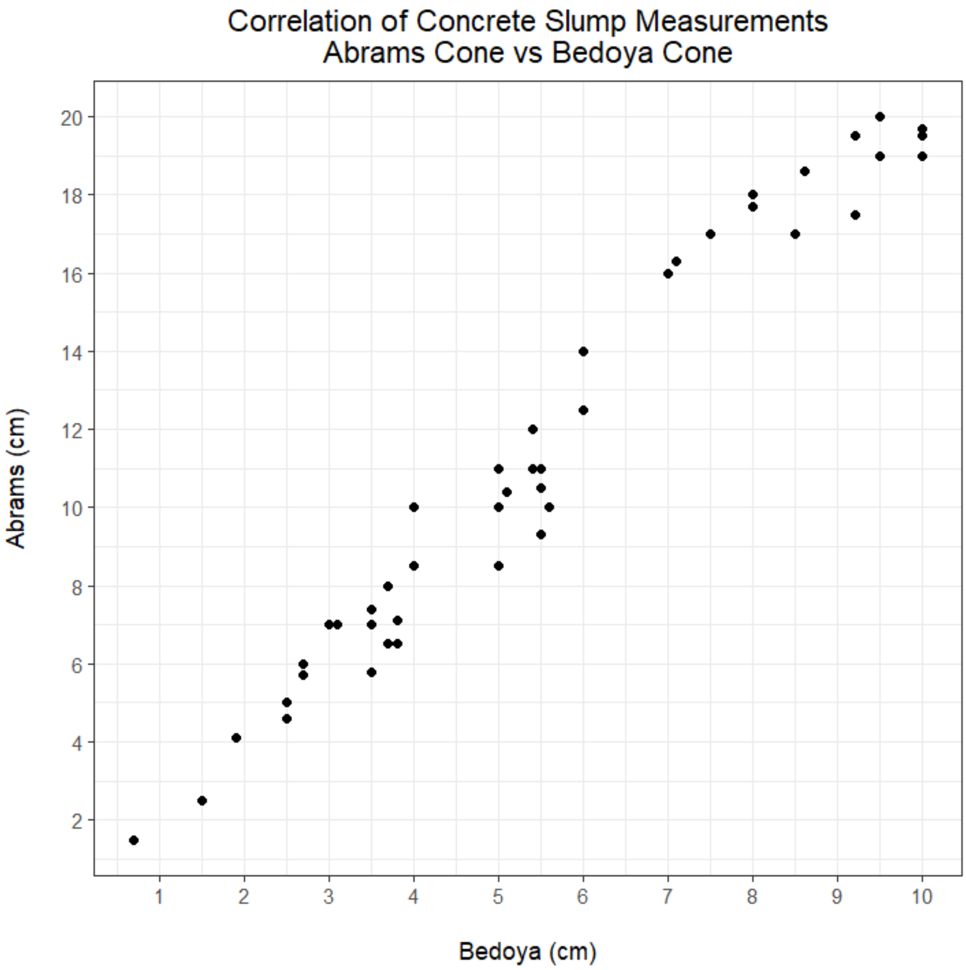


Figure 10. Correlation of concrete slump Abrams cone vs Bedoya cone

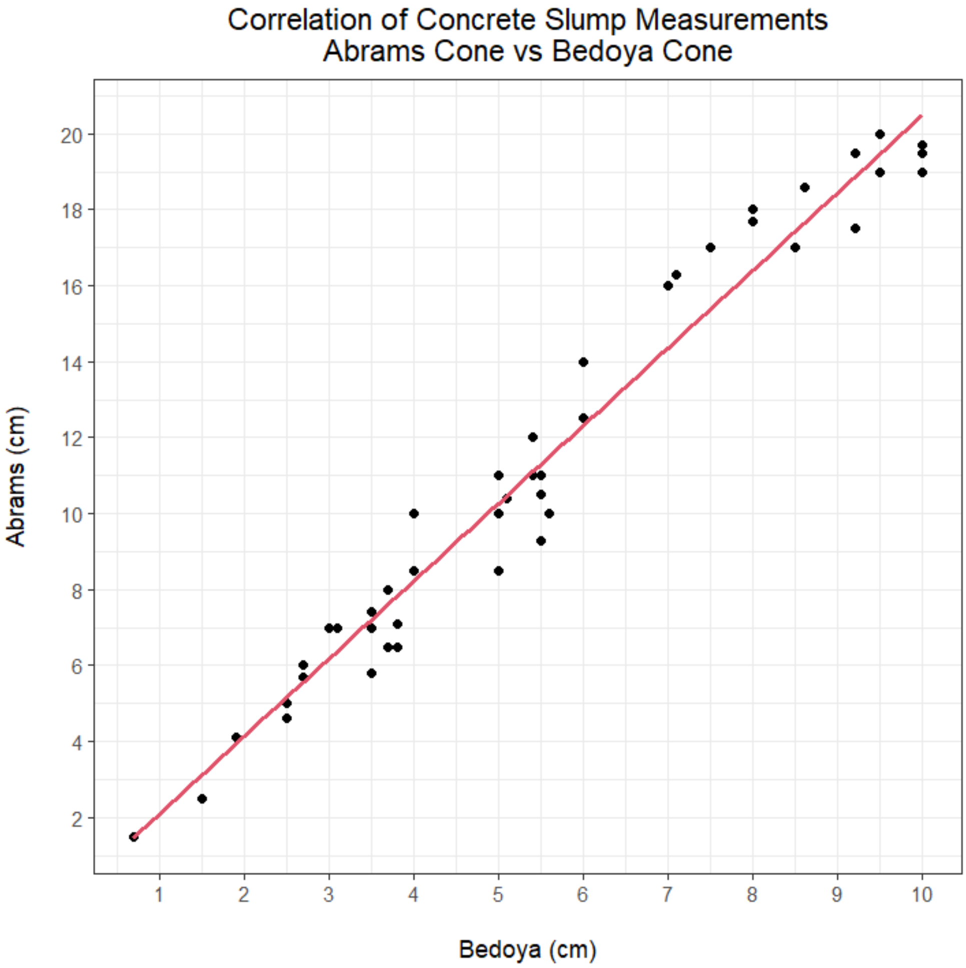


Figure 11. Abrams cone vs Bedoya cone concrete slump correlation graph

The graph above (figure 11) shows the linear relationship that exists between the Abrams and Bedoya measurements. The following are the results of the linear regression model (see Table 6).

Table 6. Linear relationship that exists between the measurements of Abrams and Bedoya

	Abrams		
Predictors	Estimates	CI	p-value
(Intercept)	0.03	−0.65 to 0.72	0.920
Bedoya	2.05	1.93 to 2.16	**<0.001**
Observations	50		
R2/ R2(adjusted)	0.962/0.961		

The result shows that the intercept is not significant, which is meaningful because there is no measurement with the Bedoya cone in the regression model. Similarly, we obtained an estimate of 0.03 cm for the Abrams cone. The measurement scale is a ratio, and the zero results are not arbitrary. Therefore, we can consider the model without intercept.

Table 7. Results linear regression that exists between the measurements of Abrams and Bedoya

	Abrams		
Predictors	Estimates	CI	p-value
Bedoya	2.05	2.00 to 2.10	**<0.001**
Observations	50		
R2/ R2(adjusted)	0.993/0.993		

As shown in Table 7, the model is significant, and the Abrams cone values can be predicted from the concrete slump measurement results with the Bedoya cone with a high discriminative ability (R^2=0.993). The residuals are normally distributed and present a homogeneous variation. This result satisfied the normality assumption of the residuals in the model.

Table 8. Statistical validation of results

n	Mean cm	SD cm	SE cm	Shapiro–Wilks (p)	Breush–Pagan (p)
50	0.0063	1.0174	0.1439	0.2927	0.1051

As shown in Table 8, the Abrams cone level of uncertainty of the Bedoya cone was 0.1439 cm, as shown by the dispersion indicators of the residuals. This means that a measurement error of 1.439 mm, would be expected in the Bedoya cone for measurements using a flexometer, which is unnoticeable to the human eye.

Alternatively, the standard deviation of the residuals is 1.0174 cm, which indicates the total difference between the measurements using the Bedoya cone and the Abrams cone. Although the dispersion is very low, this is explained by the parallax effect in the measurement of the settlement with the Abrams cone. Essentially, the test requires the equipment to be on the ground and the subject with the flexometer to measure from the top of the cone; this measurement error was 1.0174 cm.

Thus, the model equation for predicting the slump of the Abrams cone with measurements of the Bedoya cone is

$$\text{Abrams} = 2.051 \times \text{Bedoya}$$

3. Results

At the environmental level, we obtained a material saving of 68%. 17% of the saved materials were Portland cement, with a carbon footprint of 1.0 kg of CO_2 per 1.0 kg of the cement produced [8, 9]. Rubble is reduced to the same percentage, reducing the environmental damage caused by extracting non-renewable raw materials and the final disposal of CDW in landfills.

The test took less time in the case of the modified cone since it passes from three to two layers of compaction. Thus, it reduces the effort of the arm since the weight of the rod is also reduced by 82 %.

Greater ergonomic accessibility by occupational health standards: we observed that when the test was performed on the floor and at the laboratory table, the effort of the spine was less. The straight position of the person and proximity to the table reduce the bending moment or torque generated between the arm and the back (see Figures 12, 13 and 14).

(Source: Bedoya, C.; 2019).

Figure 12. Test performed in the accredited laboratory; Abrams cone

(Source: Bedoya, C.; 2019).

Figure 13. Test performed in the accredited laboratory; Bedoya cone

(Source: Bedoya, C.; 2019).

Figure 14. Measuring slump in the accredited laboratory; Bedoya cone

Furthermore, the tests performed at the university laboratories were in externally accredited laboratories. Figures 12, 13, and 14 show the test performed at the laboratory accredited by the National Accreditation Organism of Colombia (ONAC, in Spanish). Similarly, these photographs show the position of the laboratory worker who performed the test with the Abrams cone (on the floor) and the Bedoya cone (on a table).

The Bedoya cone is different from the minicones used for slump in mortars, pastes and grouts [10].

4. Conclusions

The equivalences between the values of the Abrams Cone and Bedoya Cone, making tests with different water/cementitious ratios, gave an average of 50% of the second compared with the first, as shown in Table 9.

Table 9. Relationship of Abrams cone and Bedoya cone

Slump Cone of Abrams (%)	Slump Cone of Bedoya (%)
100.00	50.00

The slump in percentages: comparison between the cone of Abrams and Bedoya cone.

Nevertheless, as in the Abrams cone, there are ranges to determine the consistency of the mix in the Bedoya cone. For example, a soft concrete mix has a slump range of 6.0 to 9.0 cm, whereas the Bedoya cone ranges from 3.0 to 4.5 cm (see Table 10).

Table 10. Slump values according to UNE-EN 12350–2:2009.

Consistency	Slump Cone of Abrams (cm)	Slump Cone of Bedoya (cm)
Dry (D)	0–2	0–1
Plastic (P)	3–5	1.5–2.5
Soft (S)	6–9	3.0–4.5
Fluid (F)	10–15	5.0–7.5
Liquid (L)	16–20	8.0–10.0

The use of the modified cone in the academy and the construction industry has numerous benefits, such as environmental, economic, and ergonomic benefits; for this, it is necessary to continue with the recognition of this device by the technical norms.

The development of new devices and methodology that can reduce material consumption and still maintain the high-quality standard in construction is a significant achievement for academics, the construction industry/modern concrete technology, and the economy [11].

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