SPANISH VERSION

Factores influyentes en la calidad del concreto: una encuesta a los actores relevantes de la industria del hormigón

Factors influencing concrete quality: a survey to the principal actors of the concrete industry

M. Orozco [1]*, Y. Avila *, S. Restrepo *, A. Parody **

*Universidad de la Costa (CUC), Barranquilla, COLOMBIA
**Universidad Libre, Barranquilla, COLOMBIA

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Abstract

Concrete is the most used building material worldwide, involving thousands of field, academic and laboratory professionals in its production, transportation and its application, which creates a great margin of possible error that may yield in a poor quality concrete. Each professional takes care of the concrete quality according to his/her experience or academic knowledge/expertise. In order to analyze the factors that concrete workers in Barranquilla (Colombia) perceive as the most important for achieving a high-quality concrete, a survey was made to both academic and field experts with different years of experience and analytic hierarchy process (AHP) was applied to weigh the perception of each factor in the concrete quality. Results have shown that for the survey respondents one of the most important factors is the environment; this may be associated with geographic location of the city, which is in a coastal region.

Keywords: *Concrete quality, concrete, analytic hierarchy process, quality control*

Resumen

El concreto es el material de construcción más utilizado en el mundo, involucrando en su uso a miles de profesionales de campo, académicos y de laboratorio en su producción, transporte o aplicación, lo cual genera un gran margen de error que puede tener como consecuencia un concreto de baja calidad. Cada profesional controla la calidad del concreto de acuerdo con su experiencia o su conocimiento académico. Con el fin de analizar los factores que los actores relevantes del concreto perciben como los más importantes para obtener una alta calidad del mismo, se realizó una encuesta en Barranquilla (Colombia) a académicos y expertos de campo con diferentes años de experiencia y se aplicó el método de análisis jerárquico para determinar la ponderación de cada factor en la calidad del concreto. Los resultados muestran que el factor más importante para los encuestados es en el entorno ambiental; la metodología utilizada y los resultados obtenidos pueden ser extrapolables a otras realidades.

Palabras clave: Calidad del concreto, concreto, análisis jerárquico, control de calidad en obra

1. Introduction

Currently, concrete is the construction material most used by humans. Studies undertaken by Mobasher (Mobasher, 2008) determined that the concrete production has doubled since the decade of 1990, going from 170 million m^3/year to more than 330 million m^3/year in 2004; these values include both vibrated concrete and self-compacting concrete. Its manufacturing uses raw materials such as sand and rocks, which constitute approximately 65% to 75% of the concrete's total volume, as well as water, cementitious material and different additives that represent the remaining volume. Thus, at global level, this means a demand of several million tons of raw materials that are processed annually (Sabău et al., 2015; Becker, 2013).

However, despite the evident importance of this material, sometimes the manufacturing, placement or curing procedures are not the adequate ones, thereby directly affecting the concrete's performance and quality. The factors influencing its quality may be classified into Materials, Labor, Methods, Machinery and Environment.

In relation to the first factor, the research of Chan Yam et al. (Chan Yam et al., 2003) mentions that it is necessary to know and control the characteristics of the aggregates, such as the size absorption percentage and the shape coefficient, since they determine the workability of fresh concrete. Likewise, the fact of knowing the attributes like texture, bond capacity and mineral composition, which significantly influence the transition zone, allow determining whether the mechanical strength of concrete will be affected or not. As for the mixing water, Rodriguez et al. (2012) indicated that, if potable water is not available on the site, it is possible to use water with considerable chemical loads, as long as the reduction of the compressive strength of concrete does not exceed 10% maximum, compared with concrete made of the same material, but mixed with potable water.

Regarding the labor factor, which generally implies long working days in the construction sector, a research made in the United States by Gillen & Gitleman (Gillen & Gitleman, 2013) concluded that the workers' physical exhaustion is intensified by the fact that they are often exposed to direct sunlight, which makes them vulnerable to high temperatures and puts at risk their health, thereby reducing their productivity at work. Li et al. (Li, Chow, Zhu & Lin, 2016) used regression models to analyze the impact of the hour of the day (by effect of the temperature) on the workers' productivity in reinforced concrete works, and they

[1] Autor de correspondencia:

Universidad Militar Nueva Granada, Bogotá, COLOMBIA
E-mail: mauricio.orozco@unimilitar.edu.co

concluded that the temperature does have a negative effect on the direct working time and a positive effect on the idle time. Furthermore, for each additional Celsius degree of temperature, the direct working time decreases by 0.57% and the idle time increases by 0.74%. Additionally, age has a negative influence on productivity, while the experience and body mass index of the worker has a positive impact. Consequently, providing adequate working conditions can improve the productivity, which is reflected upon the good quality of the works.

With regard to the machinery, the study of Walker (Walker, 1976) indicated that the placement of premixed concrete requires specialized equipment and tools, with the aim of minimizing the variation in the quality of the product during the casting stage. Concerning this subject, Navarrete and López (2016) modelled the separation of the aggregate from the mortar through a concrete stability analysis and they found that the tendency of concrete to remain uniform can be mainly controlled by the mix design. Moreover, Banfillet et al. (2011) analyzed how the vibration speed of the concrete mix affects its performance in terms of fluidity, concluding that the operational range increases as yield strength reduces and the plastic viscosity increases. Finally, Safawi et al. (Safawi Iwaki & Miura, 2005) studied the application of vibration on the concrete, with introduction of superplasticizers, demonstrating that the segregation tendency decreases in this type of mix, due to the presence of the strengthening agent.

Formwork is another relevant aspect regarding the machinery and tools used for concrete placement. Zhang et al. (2006) studied the main factors acting on the lateral pressure of the formwork and they found that the casting speed, the vibration mode and the settling of concrete can influence the pressure; the collapse risk may increase if these aspects are not properly controlled.

Finally, in relation to the environmental factor, the temperature when casting plays an important role. Starting with a temperature of 23°C, the research of Burg (Burg, 1996) demonstrated that concrete settling decreases or increases by 20 mm per every 10°C of temperature increase or decrease respectively. Furthermore, there is a 50% variation in the settling time for every 10°C change in the temperature. As for the design strength development, concrete cured at a temperature of 23°C developed a strength at 7 days, similar to the strength developed by concrete cured for 3 days at a temperature of 32°C.

Based on the above, cases were collected at global level, where the quality of concrete was affected by the lack of control of the factors already mentioned. Ahmed and Ahmed (1996) studied the aspects that rapidly deteriorated the Char Alexander warehouse located in Bangladesh, thereby determining that the sand did not meet the classification limits and the aggregates were low-quality broken brick chips with high content of salt and chlorine, while the porosity was high and the employed concrete had a low strength. Likewise, lack of equipment and qualified labor force, and deficient quality control at the site, were also evidenced. Moreover, Koehn and Ahmmed (Koehn & Ahmmed, 2001) determined that the deck failure of two bridges exposed to flood during the rainy season was caused by low-strength concrete. Furthermore, in 2013 in Colombia, the tower 6 of the Space building collapsed, where 12 people died, as a result of a series of detonating factors, such as the lack of structural capacity of the columns, deficiency in the dimensioning of the elements according to the properties of the materials, and non-compliance with the minimum strengths specified for the concrete (Universidad de los Andes, Faculty of Engineering, 2014).

Finally, in relation to the city of Barranquilla, which concerns the present study, Incosuelos, the company performing laboratory tests on materials, reported that, from 331 concrete cylinders subjected to failure between January and August of 2013, and manufactured on site, 43.8% reached an average strength of 73% of the expected design strength. Among the causes reported were the content of clay or vegetable material, segregation and insufficient mixing (Incosuelos LTDA., 2016).

The present research evaluates the perception of different agents of the construction industry in relation to different factors influencing the quality of concrete, as reported in the literature.

2. Methodology

A questionnaire survey approach was adopted with the aim of identifying, through a structured analysis system, the factors with more or less influence on the quality of concrete, according to the perception of experts on the matter. The different stages are described in the following paragraphs.

2.1 First Stage: Survey Design and Validation

The structure of the survey was based on the structured analysis system of continuous improvement, known as 5M (in Spanish), that is, using the five factors discussed in the previous section: Labor, Machinery, Materials, Methods and Environment. The survey validation was carried out by four academics with experience in related areas, who assessed the structure of each question and gave their approval to apply them in the form of a questionnaire through a virtual platform.

2.2 Second Stage: Conduction of the Survey

The survey was conducted through a virtual platform and aimed at a specific audience composed of engineers, architects and technicians related to the construction field, with varying years of experience and education level. They selected the level of influence on the concrete quality for each question on the survey, where 1 was the lowest and 5 was the highest level of influence. One hundred (100) surveys were obtained following this methodology.

2.3 Third Stage: Statistical Analysis

The analytic hierarchy process (Saaty, 1990) was used to analyze the perception of the survey respondents and determine each weighting factor (labor, materials, construction methods, environment, equipment and tools). Considering that the practical experience and the education are reasonably influencing factors when making a professional decision, three different analysis were undertaken: a first analysis considering the total number of surveys, called global analysis; a second analysis using the professional experience and, finally, the education level as differentiating criteria. Likewise, this procedure was applied to the subfactors within each factor, with the aim of identifying which one represents the highest relevance for the respondents.

In order to verify the importance of the experience or the education level in the opinion of the interviewees, the *non-parametric Kruskal-Wallis test was run for the most relevant subfactors of each factor. This test evaluated the p-value under the null hypothesis that the medians of each level of professional experience or education were equal by subfactor; thus, if the p-value is equal or higher than 0.05 there is no statistically significant difference showing that the medians of the subfactors are affected by the experience or education levels. On the other hand, if the p-value is lower than 0.05, there is enough statistical evidence showing that there are significant differences between the medians; therefore the null hypothesis is rejected.*

In order to make the analysis of the symmetry, maximum and minimum values, means, and notched medians, box and whiskers plots were carried out for the subfactors representing significant differences.

3. Results and analysis of the results

3.1 Global analysis

Weighting of each factor by applying the hierarchy method (see Figure 1) (Labor, Machinery, Materials, Methods, Environment)

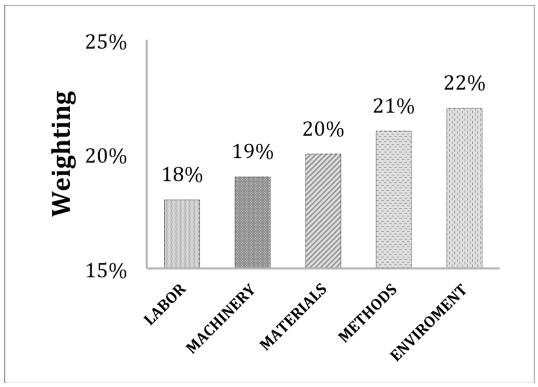

Figure 1. *Weighting of factors for the global analysis*

According to the respondents' perception, the factor that most influences the quality of concrete is the environment, with 22%, which may be due to the geographical location of Barranquilla. The city has average temperatures of 28.5°C, with maximum values ranging between 31°C and 35°C and minimum values between 23°C and 24°C, average relative humidity of 79% to 81% and average wind speed of 3.9 m/sec (CIOH, 2016), which represent adverse environmental conditions for the durability of the structures and the quality of concrete (Osorio, 2011). Under these conditions, the water demand for the curing process is higher than in cool weather, thereby modifying its performance, both in the fresh and hardened states (Espinoza, 2015), which can generate an increase of the plastic contraction during the set, due to the fast evaporation of water. This phenomenon contributes to the formation of cracks (Aníbal Maury, 2007) and allows the penetration of high concentrations of salts and sulfates which are present in the humid air of Barranquilla. Thus, even if the structures are not in contact with the sea, they are affected by the chemical degradation of the concrete and the corrosion of the reinforcing steel (Vargas, 1998).

Following the environment factor, the second factor that most influences the concrete quality, with 21.2%, are construction methods. This reflects a concern arising from the lack of control that guarantees acceptable construction procedures and verifies the compliance with technical specifications and quality standards, both regarding the materials, labor force and availability of equipment in optimal conditions, and the work itself in relation to its overall aspects of construction, structures, facilities, finishes, details, etc. (Carcaño, 2004), since all of these factors have an impact on and are the result of good and bad concrete construction methods (Palomino Sepulveda, 2014).

The quality of the materials represents 20% of the influence on the quality. Since it is premixed concrete, the producing plants are assumed to fulfill the proportioning of each material and the quality standards. Nevertheless, there are structures where concrete has not reached the optimal design compressive strength; clear examples thereof is the Altinbasak building in Turkey (Kaltakci et al., 2013) and the tower 6 of the Space building in Colombia. These results may be the consequence of a series of external factors ranging from the manufacturing process in the concrete mixer, due to materials not complying with the international or Colombian Technical Standards (NTC), inefficient transport system, inappropriate concrete placement due to bad mixing or excessive vibration in the compaction that allows the segregation of the mix, to inadequate curing that can alter the water/cement ratio and reduce its strength.

The equipment and tools used in the concrete placement influence its quality by 19%. According to the survey respondents, the bad condition of the equipment due to lack of maintenance or overuse can negatively affect the concrete finish, thus reducing its strength over time. Therefore, it is important to have the following tools in good condition: pumping equipment, vibrator, formworks and lighting tools that can optimize the concrete placement. This weighting factor confirms the reports of other authors like

Navarrete et al., who have highlighted the importance of the equipment and tools in the placement of premixed concrete.

Labor is at the bottom of the ranking, with an influence of 18% on the quality of concrete. It is considered the least influencing factor, maybe because workers are directed and supervised by trained staff, who are responsible for all the activities executed by them.

3.2 Analysis by Education Level

This section determines how the education level affects the perception about these factors. Therefore, the same procedure with the hierarchy method was carried out, but this time the responses of people with technical, professional and expertise training are consolidated in the first analysis

(see Table 2); the second analysis groups people with a Master or PhD (see Table 3). The weighting factors are calculated based on the pairwise comparison matrix (see Figures 2 and 3).

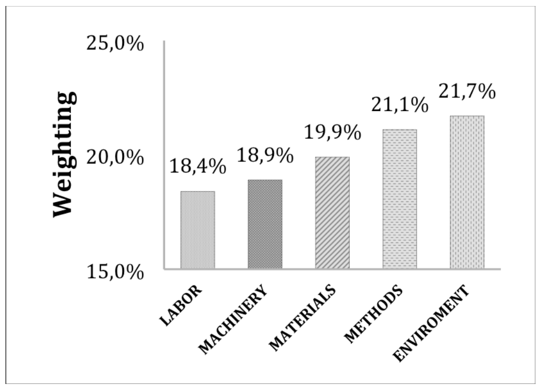

Figure 2. *Weighting of factors, low-medium education level*

According to the respondents with low to medium education level, the factor that most influences the concrete quality is the environment, with 21.7%; and that least influences the quality is labor, with 18.4%.

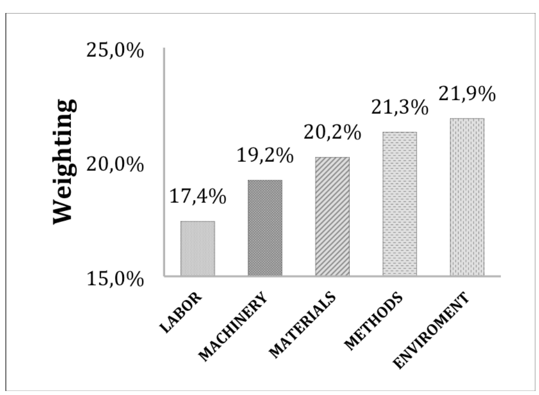

Figure 3. *Weighting of factors, high education level*

Likewise, according to the perception of the respondents with higher education level, the factor that most influences the quality of concrete is the environment, with 21.9%, and the factor with least influence is labor with 17.4%.

Consequently, it can be inferred that the education level does not significantly affect the perception about the factors on the quality of concrete.

3.3 Analysis by Professional Experience

This section studies how the perceptions of the respondents vary according to the professional experience. Tables 4 and 5 show the pairwise comparison matrix, considering less than 5 years of experience and more than five years of professional experience, respectively. The weighting factors are calculated based on Tables 4 and 5 (see Figures 4 and 5).

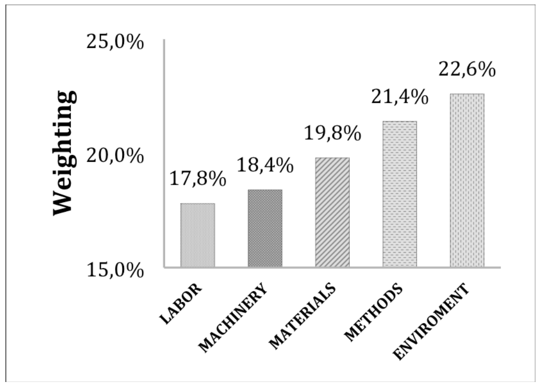

Figure 4. *Weighting of factors, less experience*

For the respondents with less professional experience (Figure 4), the factor that most influences the concrete quality is the environment, with 22.6%, and the least influencing factor is labor, with 17.8%.

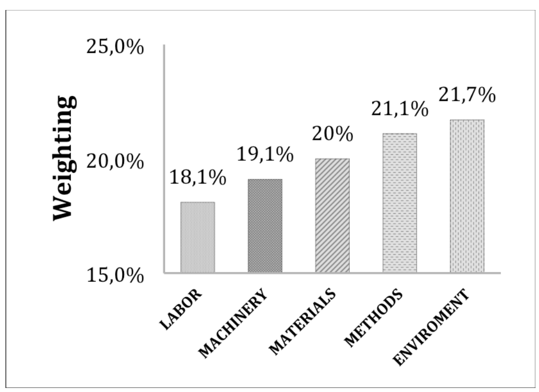

Figure 5. *Weighting of factors, more experience*

According to the interviewees with more years of experience, the factor that most influences the quality of concrete is the environment, with 21.7%, and the least influencing factor is labor, with 18.1%. When comparing the results of Figures 4 and 5 with the global analysis results, it can be inferred that the professional experience does not have a significant impact on the perception about the factors that affect the quality of concrete.

Following the determination of the factors having a higher perception of importance among the respondents, it is interesting to observe which variables identifying the respondents were related to their responses and, therefore, to the resulting weighting. In order to do this, a multifactorial ANOVA was performed, with the following independent variables: Profession, Education Level and Years of Experience; the dependent variable was the average score obtained among all the factors. But first, a summary table of the descriptive statistics was generated (Table 1), according to each independent variable.

Table 1. *Statistical Summary for Average Score*

Statistical Summary for Average Score				
Factors		***Average***	***Standard Deviation***	***Coefficient of Variation***
Profession	*Mechanical Engineer*	*3.40*		
	Architect	*3.89*	*0.34*	*8.67%*
	Industrial Engineer	*3.80*	*0.00*	
	Environmental and Sanitary Engineer	*3.80*		
	Civil Engineer	*3.81*	*0.50*	*13.10%*
	Civil Works Inspector	*4.05*	*0.07*	*2%*
	Construction Technician	*4.18*	*0.30*	*7.26%*
	Sanitary Engineer	*4.30*		
	Civil Works Technician	*4.40*		
Education Level	*Master*	*3.84*	*0.53*	*13.91%*
	PhD	*3.50*	*0.30*	*8.62%*
	Specialization	*3.81*	*0.44*	*11.49%*
	Undergraduate	*3.99*	*0.37*	*9.15%*
	Technical	*4.18*	*0.26*	*6.11%*
Years of Experience	*<2*	*3.70*	*0.60*	*16.10%*
	2 to 5	*3.89*	*0.45*	*11.55%*
	5 to 10	*3.84*	*0.48*	*12.59%*
	>10	*3.86*	*0.44*	*11.45%*

Table 2 shows the multifactorial ANOVA results.

Table 2. *Multifactorial ANOVA for average scores.*

Multifactorial ANOVA	
Factors	*P-value*
Years of Experience	*0.673*
Profession	*0.478*
Education Level	***0.0162***

The ANOVA indicated that the Education Level variable was the only one related to the survey scores considering the 5 factors, since the obtained p-value was less than 0.05 with a 95% confidence level.

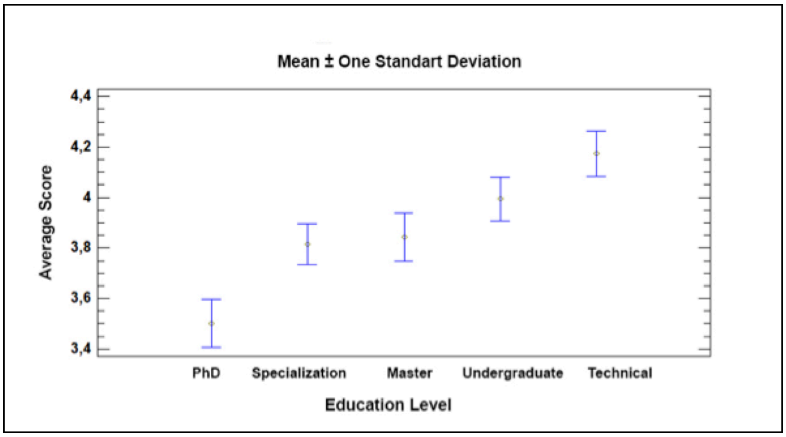

Figure 6. *Chart of means within one standard deviation.*

A chart of means within one standard deviation (Fig 6) was generated to determine the influence of the Education Level on the scores; the results show that the highest scores were obtained in the Technical Education, and the lowest were at the PhD level.

Likewise, the analysis was repeated, but this time focused on Factor 5, associated to the Environment, because it obtained the highest weighting factor. Initially, the Table 3 shows the descriptive statistics of the variables associated to the answer to the questions conforming Factor 5.

Table 3. *Statistical Summary for Factor 5: Enviroment*

Statistical Summary for Factor 5: Environment				
Factors		Average	Standard Deviation	Coefficient of Variation
Profesión	Mechanical Engineer	3.70		
	Architect	3.98	0.71	17.88%
	Industrial Engineer	4.35	0.50	11.38%
	Environmental and Sanitary Engineer	4.00		
	Civil Engineer	4.30	0.73	17.10%
	Civil Works Inspector	4.65	0.50	11%
	Construction Technician	4.60	0.59	12.77%
	Sanitary Engineer	4.70		
	Civil Works Technician	4.70		
Education Level	Master	4.40	0.70	15.91%
	PhD	3.93	0.63	16.10%
	Specialization	4.13	0.76	18.37%
	Undergraduate	4.29	0.72	16.77%
	Technical	4.63	0.48	10.45%
Years of Experience	<2	4.00	0.21	5.30%
	2 to 5	4.46	0.54	12.15%
	5 to 10	4.36	0.85	19.60%
	>10	4.08	0.70	17.20%

Table 4 shows the multifactorial ANOVA results.

Table 4. *Multifactorial ANOVA for Environment.*

Multifactorial ANOVA	
Factors	***P-value***
Years of Experience	*0.84*
Profession	*0.271*
Education Level	***0.162***

The ANOVA showed that none of the variables were significantly related to the scores obtained in the answers to the questions associated to Factor 5, since all p-values were higher than 0.05.

At the same time, this survey was applied to the subfactors to determine which one has the highest influence on the quality of concrete, according to the perception of the survey respondents. Tables 5 to 9 indicate the ranking of the subfactors.

Table 5. *Ranking of the Labor Subfactors*

Labor		
Ranking	***Level of Influence:***	***%***
1	*Specific experience*	*21.60*
2	*Training received*	*21.60*
3	*Time of day on the worker's performance when casting*	*17.98*
4	*The noise*	*14.65*
5	*The worker's age*	*12.56*
6	*The income*	*11.59*

Table 6. *Ranking of the Machinery Subfactors*

Machinery		
Ranking	***Level of Influence:***	***%***
1	*Lighting in the working area*	*14.56*
2	*Vibrator availability*	*14.39*
3	*Availability of pumped concrete equipment*	*13.99*
4	*Type of formwork*	*13.31*
5	*Equipment age*	*11.75*
6	*Own availability of test equipment*	*11.10*
7	*Power source of the equipment*	*10.85*
8	*Possession of formwork*	*10.05*

Table 7. *Ranking of the Materials Subfactors*

Materials		
Ranking	**Level of Influence:**	**%**
1	Mix design	20.82
2	Type of curing	18.93
3	Source of the materials	18.84
4	Reputation of the concrete mixer	15.24
5	Plant-works distance	13.88
6	Cost of the materials	12.30

Table 8. *Ranking of the Construction Methods Subfactors*

Methods		
Ranking	**Level of Influence:**	**%**
1	Technical supervision	22.17
2	Quality tests	21.33
3	Working site organization	20.54
4	Quality management system	18.80
5	Sample gathering site	17.16

Table 9. *Ranking of the Environment Subfactors*

Environment		
Ranking	**Level of Influence:**	**%**
1	Temperature when casting	34.29
2	Wind and humidity	32.86
3	Environmental aggression	32.86

According to the ranking, the most important subfactors for each factor are the following: 1) the temperature when casting with 34.3%; 2) the technical supervision with 22.2%; 3) the specific experience of the labor force with 21.6%; 4) the mix design with 20.8%; and 5) the lighting in the working area with 14.6%. Once the most relevant subfactors were identified, the non-parametric Kruskal-Wallis test was run for each of the five subfactors, in order to determine if the years of experience or the education level affect their perception.

3.3.1 Influence of the years of experience on the perception of the subfactors

Table 10 shows the results of the non-parametric Kruskal-Wallis test, considering the years of experience for the following subfactors: specific experience, lighting in the working area, mix design, technical supervision and temperature when casting. The sample size was 98 interviewees.

Table 10. *Perception of the subfactors according to the years of experience*

Subfactor	**< 2**	**≤ 5**	**≤ 10**	**> 10**	**p-value**	**Significant Difference**
Specific experience	5	5	5	5	0.657	NO
Lighting of the working area	4	4	5	4	0.848	NO
Mix design	5	5	5	5	0.087	NO
Technical supervision	5	5	5	5	0.914	NO
Temperature when casting	4	5	5	4	0.04	YES

The test results regarding the years of experience show that in four of the five most important subfactors there is no statistically significant difference in the perception of the respondents. However, in the subfactor concerning the temperature at the time of casting, a statistically significant difference is observed. The analysis of the data median shows an asymmetric distribution, since the data are not concentrated in the same range of values (see Figure 7).

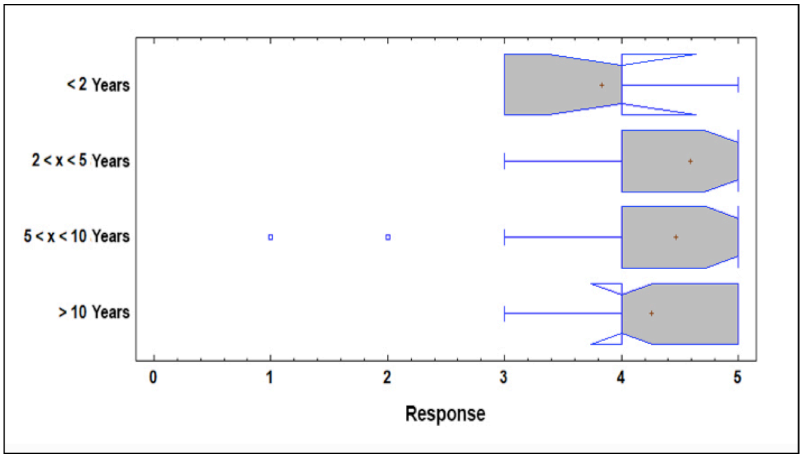

Figure 7. *Box and whiskers plot of the subfactor: Temperature when casting*

3.3.2 Influence of the education level on the perception of the subfactors

With regard to the education level, the Kruskal-Wallis test shows that three of the five most important subfactors have no statistically significant differences that allow stating that the education level affects the perception about the influence of those subfactors on the quality of concrete (see Table 11).

Table 11. *Perception of the subfactors according to the education level*

Subfactor	Tech.	Undergrad.	Spec.	MSc	PhD	p-valor	Significant Difference
Specific experience	5	4	5	5	4	0,238	NO
Lighting in the working area	5	5	4	5	3	0,007	YES
Mix design	5	5	5	5	5	0,798	NO
Technical supervision	5	5	5	5	5	0,536	NO
Temperature when casting	5	5	4	5	4	0,017	YES

However, the perception about the lighting in the working area and the temperature when casting do show statistically significant differences. For example, the lighting median for respondents with PhD is 3 over 5, which indicates that persons with the highest education level do not believe that this subfactor has a relevant influence on the quality of concrete (see Figure 8).

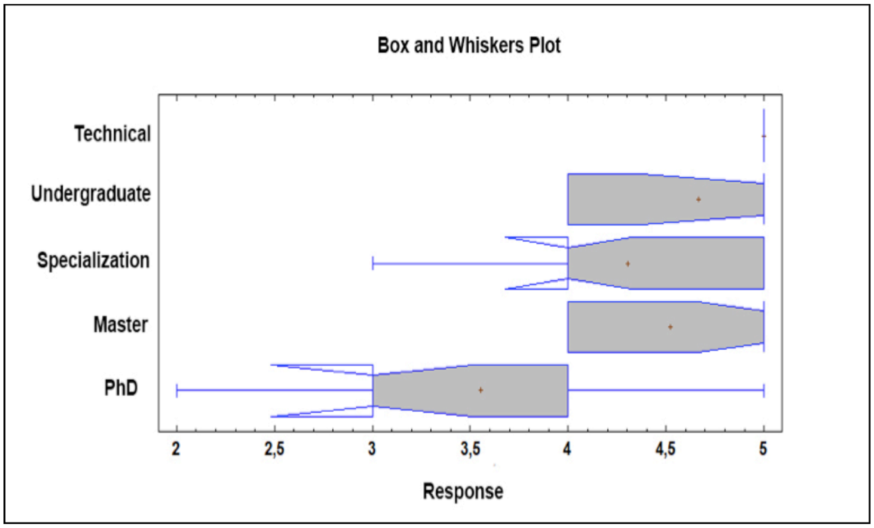

Figure 8. *Box and whiskers plot of the subfactor: Lighting in the working area*

Figure 9 shows the median for each education level regarding the subfactor Temperature when casting, whose data distribution is asymmetrical, because some of the data are concentrated in one region and the others are concentrated in a different value range.

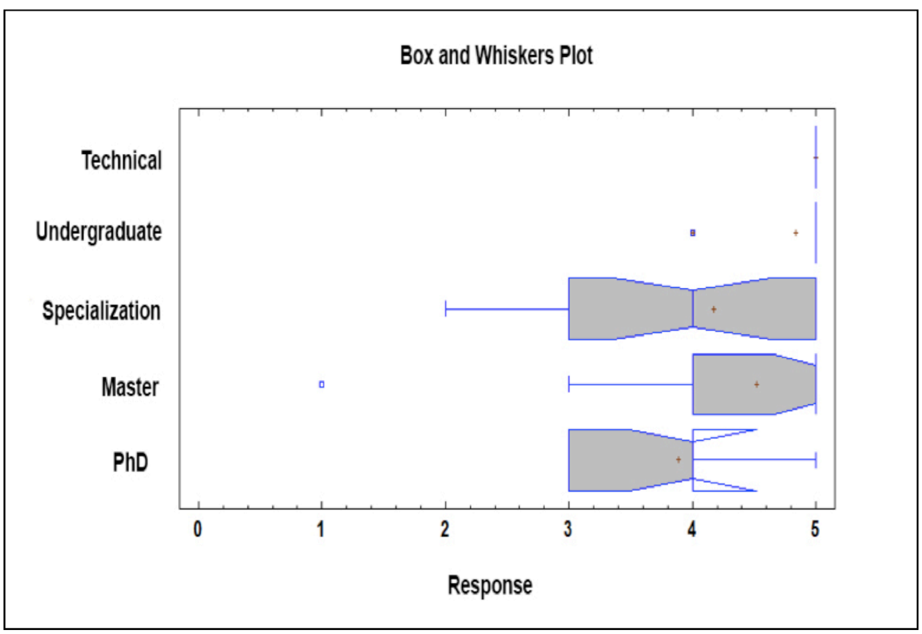

Figure 9. *Box and whiskers plot of the subfactor: Temperature when casting*

4. Conclusions

The present study allowed determining the weighting factors that significantly influence the quality of concrete, based on the opinion of experts from the field of construction and materials. The five studied factors show a similar weighting (around 20%), which can be seen as a generalized awareness on the importance of adequately developing each *factor to guarantee the quality of concrete.*

The most important subfactor was determined for each factor; in relation to the environment factor, the temperature is the subfactor that mostly affects the quality of concrete, with 34.3%. Regarding the factor of construction methods, the subfactor causing the highest impact is the technical supervision, with 22.2%. In relation to the materials factor, the mix design subfactor was considered the most important, with 20.8%. According to the respondents, within the machinery factor, the optimal lighting subfactor is important when placing the concrete, with 14.6%. Finally, concerning the labor factor, the subfactor of specific experience of the workers was considered the most important by the interviewees, with 21.6%.

The results demonstrate that more attention is currently given to the control of environmental factors, since the main failure cause found by controlling the concrete quality in the studied cases was the bad quality of the materials.

In general, the statistical analysis showed that there is no statistically significant difference indicating that the years of experience and the education level influence the perception about the factors that affect the quality of concrete. However, it was observed that the higher the education level, the higher the variability in the perception.

Based on the obtained data, the expert's perception was standardized to identify these factors, with the purpose of establishing a guide for the quality control of concrete, mainly in warm weathers, as in the city of Barranquilla. Therefore, it is recommended to broaden the scope of this research and apply it in different contexts to be able to compare this perception.

7. Referencias

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