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PRIORITIZATION OF THE REQUIREMENTS FORMULATED IN THE EUROPEAN STANDARD EN 206 IN ASSESSMENT OF CONCRETE QUALITY - MULTICRITERIA ANALYSIS USING THE AHP METHOD

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A b s t r a c t

The technological process of ready-mixed concrete production, which is designed to ensure the quality of concrete and the durability of the constructed buildings in accordance with the European Standard EN 206, consists of several stages. In this standard, to ensure the stability of both the concrete production process itself and its individual stages, appropriate requirements have been formulated. Some of these requirements pertain to the on-line stage of the production process, and some to the off-line stage. Some of these requirements, if not properly controlled, can disrupt the stability of the production process and also negatively impact the quality and durability of concrete structures. The article analyzes the significance of these standard requirements. For this purpose, the AHP method was used, and the Pareto principle was applied to interpret the results. The AHP analysis showed that three out of seven requirements have the most significant impact on the quality of concrete and concrete structures. These are: the constituents of concrete, the limitations for concrete composition, and the delivery of fresh concrete. The applied Pareto principle confirmed their dominant role. These three criteria account for almost 80% of the importance in ensuring the quality of concrete.

Keywords: concrete quality, standard requirements, AHP method, Pareto chart

1. INTRODUCTION

The basic requirements formulated in the European standard EN 206 [13] include not only the concept of integrating the current state of the art in concrete technology and in construction and execution, but are directed towards two main objectives in particular [28]:

- to combine the requirements/expectations of the designer of the construction work, the ready-mixed concrete producer and the construction contractor,

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- ensuring the durability of the designed structures.

For this reason, in the standard recommendations [13], primary importance is given to the prevention of corrosion of concrete and reinforcement and the indication of courses of action leading to this, including the definition of an exposure class. In the analysis of the causes and effects of the hazard, the required protection of the structure should be determined by taking into account the intended use of the concrete, the design life of the concrete structure, the maintenance programme and the environmental impacts. The European standard EN 206 specifies seven key requirements in order to achieve quality concrete [13]:

- the constituents of concrete;
- the properties of fresh and hardened concrete and their verification;
- the limitations for concrete composition;
- the specification of concrete;
- the delivery of fresh concrete;
- the production control procedures;
- the conformity criteria and evaluation of conformity.

The results of scientific research confirm and demonstrate the crucial importance of the requirements formulated in the standard in ensuring the quality of ready-mix concrete. The constituent materials, including cement, aggregates, water and additives determine the quality of concrete. The guarantee of the proper quality of the concrete produced is linked, among other things, to the use of ingredients for its production that comply with the requirements contained in the applicable technical specification [7, 12, 26]. Research on cement indicates its influence on the strength, durability and setting time of concrete [30]. The quality and type of aggregates have a significant effect on the strength, durability and texture of concrete [25]. The quality of water used in the concrete mix is equally important [1], and its purity can affect the durability and strength of concrete [20, 35, 36]. Additives, on the other hand, can significantly modify the properties of concrete, including its viscosity, setting time and strength [24, 34, 50]. The water/cement or water/binder ratio is a key determinant of concrete strength [4, 24, 30]. Critical to maintaining quality is ensuring that the concrete mix is properly transported and delivered to the construction site [2, 31, 41, 50]. Research indicates that production control procedures, including material quality control and compliance control, are an indispensable part of the production process. Unfortunately, scientific research has mainly focused on methods of assessing the effects of individual components on physico-mechanical properties [3, 11, 12, 15, 16, 17, 29, 30, 49] and few papers address the form of standard compliance criteria for their selectivity [5, 6, 43, 47].

Nowadays, the aspect of concrete durability, including its resistance to weather and chemical conditions, is widely discussed in the literature [30, 46, 48], which justifies the requirements formulated in the standard with regard to ensuring the durability of implemented concrete structures. Other research directions are environmental awareness in concrete production [18], including the use of recycled materials [14] and innovations in concrete technology, such as high-value, rolled concrete, are opening up new opportunities for the construction industry [33]. A new research direction is the use of advanced modelling tools to predict the behaviour of concrete [9, 23] or simulation, probabilistic or statistical methods in the evaluation of requirements or quality control procedures [44]. As shown, the literature indicates a number of requirements in the concrete manufacturing and control process, from raw materials to the final quality assessment. The quality of concrete is determined by the appropriate selection of ingredients, the manufacturing process, quality control, durability/corrosion resistance and the specification of the concrete, i.e. compliance with standards and regulations, and therefore on those factors/ parameters that coincide with the standard-defined requirements for concrete.

A direction that is gaining prominence in the modern concrete industry is the use of statistical methods in the evaluation of requirements or quality control procedures, so this approach is used in this paper. In this paper, the relevance of the requirements formulated in European Standard EN 206:2013 Concrete - Specification, performance, production and conformity [13] was assessed. The AHP multi-criteria method and the standard scale proposed by Saaty [38] were used for the analyses, and the Pareto principle was used to interpret the results obtained.

2. AHP METHOD

The AHP method (The Analytic Hierarchy Process) was developed at the turn of the 20th century by Saaty [37]. It is based on utility theory and is a widely used tool for making complex decisions based on an accepted number of criteria. There are 4 stages in the decision-making process [40]:

- defining the decision problem and the type of knowledge sought,
- creating a hierarchical structure containing the main objective, intermediate objectives (attributes/normal requirements) and decision alternatives,
- pairwise comparisons of the decision alternatives against each of the norm requirements and pairwise comparisons of the importance of each requirement,
- using the priority vectors obtained from the comparisons to arrive at a solution to the decision problem.

The definition of the decision problem and the construction of the hierarchical structure are closely linked. When applying the algorithm proposed by Saaty, it is necessary to check that the results obtained do not violate the principle of constancy of preference (validation of the results obtained). For this purpose, the coefficient λ_{max} is calculated (formula 2.6). In this method, it is a prerequisite to obtain the required consistency of the evaluations, expressed by the values of consistency index *CI* (formula 2.7) and consistency ratio *CR* (formula 2.8), whose value should not exceed 0.1.

The aggregation of assessments in the AHP method follows an additive utility function, synthesising the weight shares of the norm requirements and the values of the degree to which each requirement satisfies the fractional objective function. Ratings of the degree of fulfilment of these criteria for the decision options under consideration are obtained using the method of pairwise comparisons [10]. The rating scale proposed in [39], is a binary combination based on the comparison of elements (in the case analysed in this paper, these will be the standard requirements). Pairwise comparison is a fundamental step in the AHP process. For each pairing within each criterion, the better option is assigned a score on a scale from 1 (equally good) to 9 (absolutely better), while the other option in the pairing is assigned a score equal to the inverse of this value [37]. For the comparison matrix under consideration, a preference vector is determined according to formula (2.1), which represents the "strength" of the criteria being compared in the matrix.

$$[w_i, w_2, \dots, w_n]^T \tag{2.1}$$

The preference vector is determined by calculating equation (2.2) i.e. right-sided eigenvector matrix [40]:

$$M \times w = \lambda_{max} \times w \tag{2.2}$$

If there is a nonzero matrix eigenvalue λ_{max} then this means that the comparison matrix is consistent and is equal to the dimension of the matrix. On the other hand, w is the preference vector associated with the value of λ_{max} [40], which can be described by the relation (2.3):

$$\begin{array}{c} \\ M1 \\ M2 \\ . \\ . \\ Mn \end{array} \begin{array}{ccccc} M1 & & M2 & \dots & Mn \\ \left| \begin{array}{ccccc} \frac{w_1}{w_1}=1 & & \frac{w_1}{w_{n-1}} & & \frac{w_1}{w_n} \\ \frac{w_{n-1}}{w_1} & \dots & \frac{w_{n-1}}{w_{n-1}}=1 & \dots & \frac{w_{n-1}}{w_n} \\ \vdots & & \vdots & & \vdots \\ \frac{w_1}{w_n} & & \frac{w_{n-1}}{w_n} & & \frac{w_n}{w_n}=1 \end{array} \right| \end{array} \tag{2.3}$$

In contrast, the eigenvalue of the comparison matrix can be written in the form (formulae 2.4 - 2.6):

$$M \cdot w = \left| \begin{array}{ccccc} \frac{w_1}{w_1}=1 & & \frac{w_1}{w_{n-1}} & & \frac{w_1}{w_n} \\ \frac{w_{n-1}}{w_1} & \dots & \frac{w_{n-1}}{w_{n-1}}=1 & \dots & \frac{w_{n-1}}{w_n} \\ \vdots & & \vdots & & \vdots \\ \frac{w_1}{w_n} & & \frac{w_{n-1}}{w_n} & & \frac{w_n}{w_n}=1 \end{array} \right| \cdot \left| \begin{array}{c} w_1 \\ . \\ . \\ . \\ w_{n-1} \\ w_n \end{array} \right| \tag{2.4}$$

where: $i, j = 1,2,3, \dots, n$

$$M \cdot w = n \cdot \left| \begin{array}{c} w_1 \\ w_2 \\ w_3 \\ \vdots \\ w_{n-2} \\ w_{n-1} \\ w_n \end{array} \right| = \lambda_{max} \cdot w \tag{2.5}$$

$$\lambda_{max} = \frac{1}{n} \cdot \sum_{i=1}^{n} \frac{(M \cdot w)_i}{w_i} \tag{2.6}$$

The next step in the analyses is to check the consistency of the comparison matrix, which can be calculated by determining the consistency index CI and the consistency ratio CR, according to formulae (2.7) and (2.8) [38]:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2.7}$$

CR is obtained by comparing the CI with the mean Random Consistency Index RI:

$$CR = \frac{CI}{RI} \tag{2.8}$$

where:
RI – Random Consistency Index, a value depending on the dimension of the pairwise comparison matrix,
λ_{max} – maximum eigenvalue of matrix, for a coherent matrix $\lambda_{max} = n$,
n – matrix dimension.
Recommended values for the constant RI depending on the dimension of the pairwise comparison matrix [39] are shown in Table 1.

Table 1. The value of Random Consistency Index *RI* depending on the dimension of the matrix *n* [39]

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49	1.51	1.54	1.56	1.57	1.58

The workflow for determining the values of the weights, according to the proposed Saaty method, is shown in the block diagram below (Fig.1.).

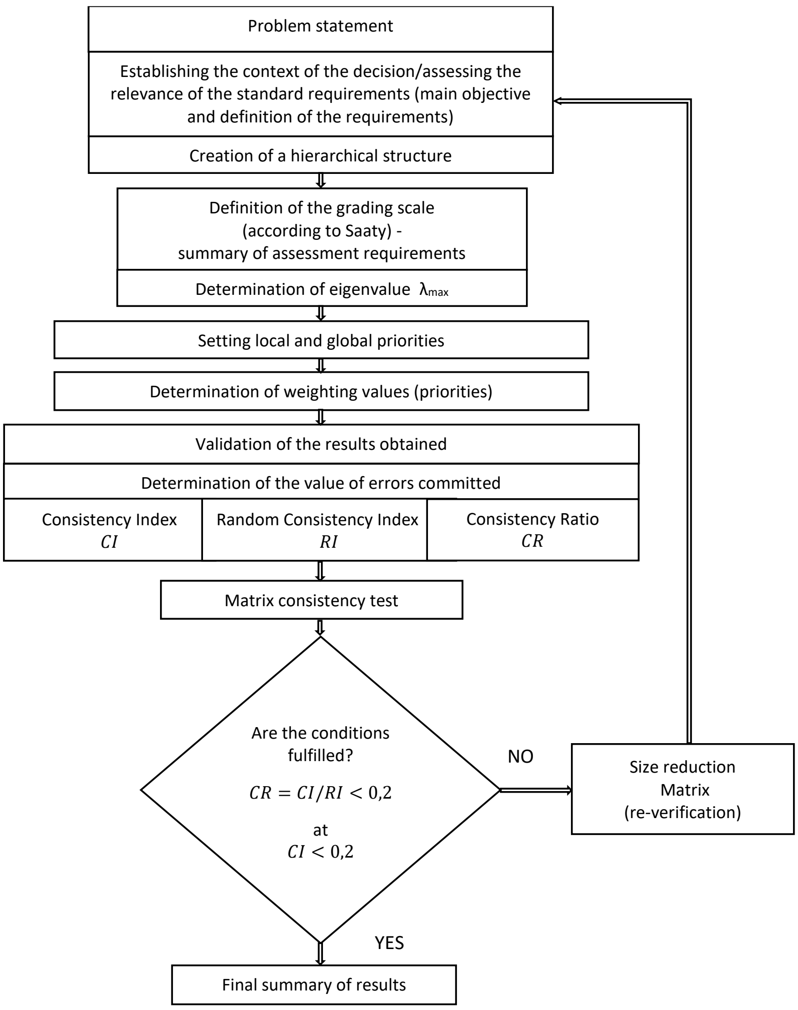

Fig. 1. Saaty method algorithm used to determine the weights

The AHP method is widely used in the literature to support decision-making processes. Such a process can be, for example, the selection of the optimal technology [8], the best material-technology-performance solution [19], tendering decisions [25, 22], energy efficiency [27, 42], the assessment of renovation works [21, 32], risk management on concrete structures [45]. On the other hand, this article deals with the use of the AHP approach in concrete technology and, more specifically, with the assessment of the relevance of the standard requirements, as defined in the EN 206:2013 [13] standard, determining the quality of concrete.

3. APPLICATION OF THE AHP METHOD FOR ASSESSING THE RELEVANCE OF STANDARD REQUIREMENTS

In the case considered in this paper, a set of seven norm requirements (criteria), as defined in the standard from EN 206:2013 [13], influencing concrete quality were adopted for analysis. Since AHP is a process that requires input from experts, therefore, managers of 12 concrete mixing plants from the south-eastern part of Poland were asked to determine the interrelationships between the individual norm requirements affecting concrete quality. The standard Saaty scale was used to determine these relationships, i.e. to assess them. All experts considered that:

- the constituents of concrete are considered to be very important as they have a direct impact on the quality of the final product;
- the properties of fresh and hardened concrete and their verification are also important, but slightly less so than the composition of the concrete;
- composition constraints and mix delivery are considered equally important;
- concrete specifications and production control procedures are important, but to a lesser extent.

Based on the scores obtained from the experts, average values were determined and then a final relationship matrix called the pairwise comparison matrix was developed (Table 2).

Table 2. The relationship matrix

Requirement/ Requirement	1. Constituents	2. Properties	3. Limitations	4. Specification	5. Delivery	6. Control	7. Conformity
1. Constituents	1	3	2	4	2	3	5
2. Properties	1/3	1	½	2	1/2	2	4
3. Limitations	1/2	2	1	3	1	2	3
4. Specification	1/4	1/2	1/3	1	1/3	1/2	2
5. Delivery	1/2	2	1	3	1	2	3
6. Control	1/3	1/2	½	2	1/2	1	3
7. Conformity	1/5	1/4	1/3	½	1/3	1/3	1

At this point, it is worth noting that the relationship matrix is a square matrix whose elements on the diagonal are equal to 1, as a result of the evaluation system adopted. The matrix is also a proportional matrix, meaning that the elements below the diagonal are the inverse of the elements above the diagonal. For example, if the composition compared to the properties is rated 3, then the properties compared to the composition are rated 1/3. The relationship matrix (Table 2) is then transformed into a standardised matrix (formula 2.3), which allows the next stage of the calculation to determine the weights for the individual standard requirements (formula 2.4), in order to prioritise them.

Table 3. Matrix of standardised values

Requirement/ Requirement	1. Constituents	2. Properties	3. Limitations	4. Specification	5. Delivery	6. Control	7. Conformity
1. Constituents	0.3209	0.3243	0.3529	0.2581	0.3529	0.2769	0.2381
2. Properties	0.1070	0.1081	0.0882	0.1290	0.0882	0.1846	0.1905
3. Limitations	0.1604	0.2162	0.1765	0.1935	0.1765	0.1846	0.1429
4. Specification	0.0802	0.0541	0.0588	0.0645	0.0588	0.0462	0.0952
5. Delivery	0.1604	0.2162	0.1765	0.1935	0.1765	0.1846	0.1429
6. Control	0.1070	0.0541	0.0882	0.1290	0.0882	0.0923	0.1429
7. Conformity	0.0642	0.0270	0.0588	0.0323	0.0588	0.0308	0.0476

The calculated values of the weights with their ranking for the standard requirements are shown in Table 4.

Table 4. Weights matrix with ranking

Standard requirement	Weight	Ranking
1. The constituents of concrete	0.3034	1
2. The properties of fresh and hardened concrete and their verification	0.1280	3
3. The limitations for concrete composition	0.1787	2
4. The specification of concrete	0.0654	5
5. The delivery of fresh concrete	0.1787	2
6. The production control procedures	0.1002	4
7. The conformity criteria and evaluation of conformity	0.0456	6

The final stage of the calculation was to determine the values of the inconsistency coefficients for the individual requirements (Table 5), and then, in accordance with formula 2.6, to determine the maximum value of the inconsistency coefficient λ_{max} and the values of the consistency index *CI* (formula 2.7) and consistency ratio *CR* (formula 2.8).

Table 5. Values of inconsistency coefficients for individual requirements (criteria)

Standard requirement	Sum of standardised assessments [M]	Weight [Wi]	Individual inconsistency coefficient λ [λ =Wi ·M]
1. The constituents of concrete	3.12	0.303	0.946
2. The properties of fresh and hardened concrete and their verification	9.25	0.128	1.184
3. The limitations for concrete composition	5.67	0.179	1.012
4. The specification of concrete	15.50	0.065	1.014
5. The delivery of fresh concrete	5.67	0.179	1.012
6. The production control procedures	10.83	0.100	1.086
7. The conformity criteria and evaluation of conformity	21.00	0.046	0.958

The values obtained for the individual coefficients and indices are: maximum inconsistency coefficient value λ_{max} = 7.1806, values for the indices: consistency index *CI* = 0.0301 and consistency ratio *CR* = 0.0228. It is usually assumed that if *CR* is less than 0.1, the comparison matrix is sufficiently consistent and therefore the weights were set correctly (Fig. 2).

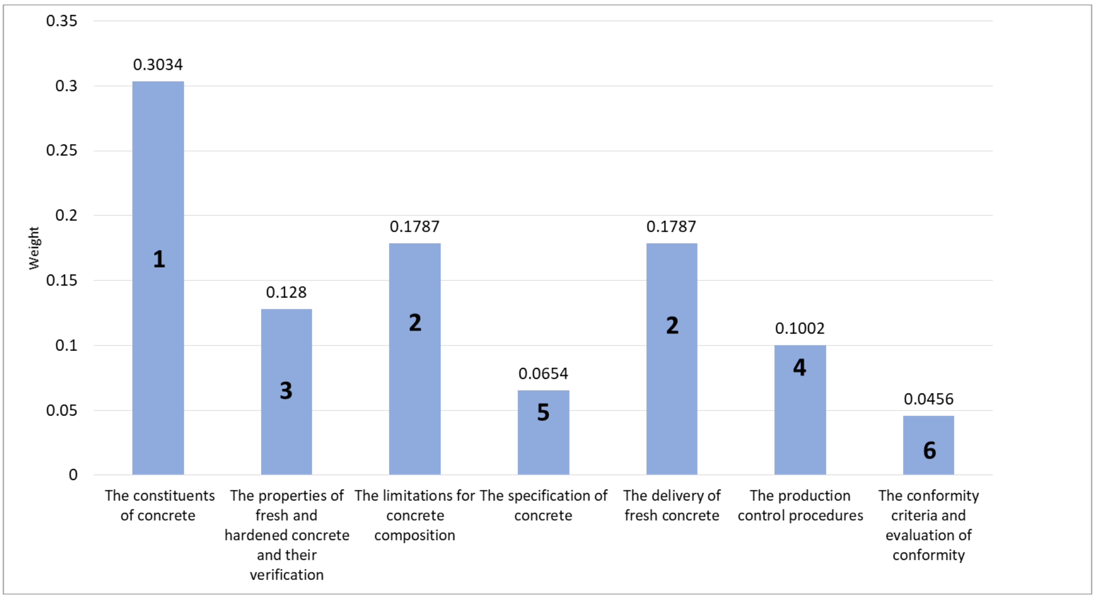

Fig. 2. Prioritisation of the standard requirements formulated in EN 206 based on the weights derived from the AHP analysis

4. DISCUSSION OF RESULTS

According to the analysis, the most important standard requirement determining the appropriate quality of concrete is the constituents of concrete, which has a technological justification, as the quality of the ingredients directly affects the quality of the final product. The following can be regarded as important requirements: the limitations on the composition of the concrete and the delivery of the concrete mix. These requirements take second place in the analysis. The least important in terms of standard requirements determining the quality of concrete was: the conformity criteria and evaluation of conformity.

By verifying the overall consistency of the developed comparison matrix, it can be concluded that it is sufficiently consistent, as indicated by the obtained low consistency ratio value CR= 0.0228 < 0.1. This means that the expert assessments are logical and consistent in the context of the analysis carried out. In order to confirm the conclusions formulated, an additional verification of the results obtained from the AHP method was carried out by applying the Pareto principle. A Pareto chart for the results from the AHP analysis of the requirements formulated in EN 206 is shown in Fig. 3.

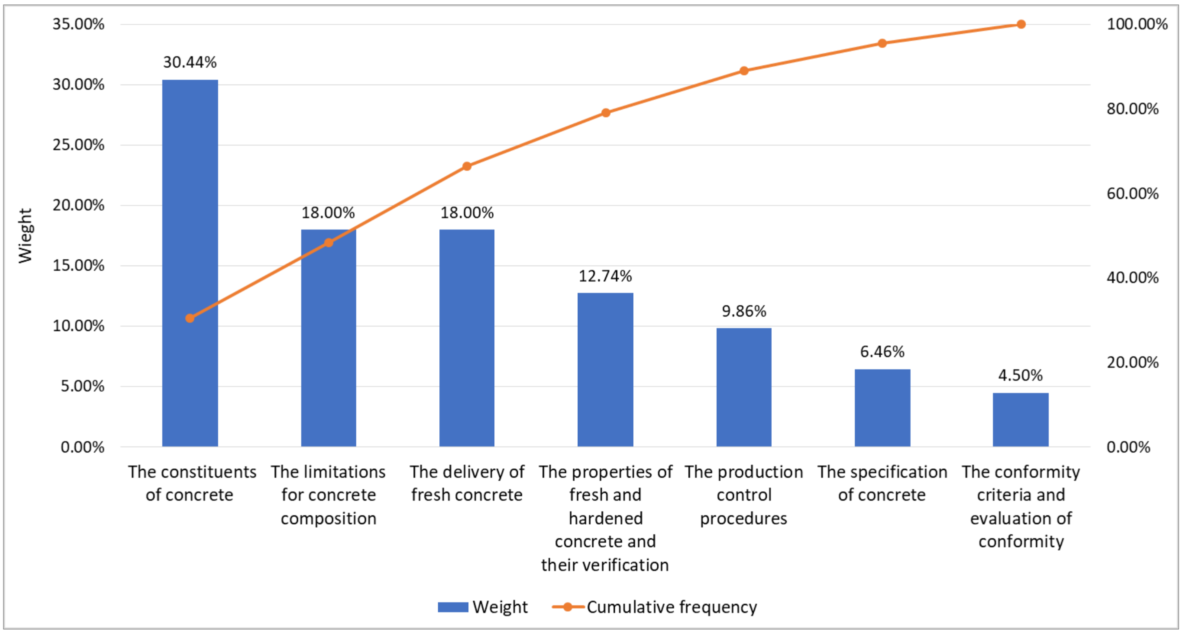

Fig. 3. Pareto chart based on the weights obtained from the AHP analysis for the standard requirements formulated in EN 206

Figure 3 shows both the individual weights of the criteria and their cumulative percentage. According to the Pareto principle, several criteria have a significant impact. It can be seen that the constituents of concrete, the limitations for concrete composition and the delivery of fresh concrete have the greatest impact on concrete quality and the durability of the structure. The cumulative percentage increases rapidly, reaching almost 80% with only the first three requirements, which shows their dominant role in the context of all the requirements formulated in EN 206. The remaining criteria, such as the specification of concrete and the conformity criteria and evaluation of conformity, have relatively less influence on the overall assessment and final quality of the hardened concrete mix material.

The low weight value of 6.46% for the specification of concrete requirement, confirms that in order to achieve a performance-based specification that would significantly affect the quality of concrete, the development and implementation into engineering practice of mathematical modelling of failure mechanisms to estimate the service life of structures is expected. This modelling should aim to guarantee the durability of the completed concrete structure under the specified exposure conditions. Performance criteria that have not been determined using mathematical models to predict the service life of a structure should not form the basis for the development of a performance-based concrete specification. In this case, as in the case of prescriptive specifications, the criteria become subjective and are not necessarily related to the service life of the structure or durability i.e. reliability over a given period of time. The implementation of concrete specifications based on results obtained from mathematical models to predict the service life of structures requires a change in the thinking of all participants actively involved in the construction process.

Based on the Pareto chart and the results obtained from the AHP analysis, there should be a redistribution of risks associated with failure to meet the quality of concrete and the durability of concrete structures, and the responsibilities of each professional should be clearly defined. Figure 2 can be helpful in identifying the areas that require the most attention in meeting the requirements of EN 206 standard that determine the quality and durability of both concrete and concrete structures.

5. SUMMARY

The paper assesses the relevance of the requirements formulated in the European Standard EN 206 that determine the quality and durability of concrete structures. AHP analysis was carried out to prioritise the standard requirements. The constituents of concrete emerged as the most important criterion, with a weighting of 30.44%, highlighting its significant impact on concrete quality. The second most important criteria were the limitations for concrete composition and the delivery of fresh concrete, each with a weight of 18.00%. The properties of fresh and hardened concrete and their verification were ranked fourth, indicating its moderate importance (12.74%). The production control procedures was rated fifth in importance with a weight of 9.86%. The specification of concrete received a lower weight, indicating its lower priority (6.46%). The least important requirement was: the conformity criteria and evaluation of conformity with a weighting of only 4.50%. The results show that the composition of the concrete mix is key to meeting the standards of EN 206 with regard to concrete quality assurance. The consistency index (*CI*) obtained was 0.0301, indicating good consistency in the expert assessments. The consistency ratio (*CR*) obtained was less than 0.1 (0.0228), confirming an acceptable consistency of the comparison matrix.

The Pareto chart illustrated the dominance of several criteria, according to the 80/20 rule. The constituents of concrete, the limitations for concrete composition and the delivery of fresh concrete accounted for about 80% of the total weight, indicating their importance in ensuring the quality of concrete. The other criteria, despite receiving lower weighting values, still influence the quality and durability of concrete structures and the fulfilment of the general standards and technical specifications recommended in EN 206. The results of the AHP analysis and the Pareto chart allow attention to be drawn to the key requirements of the standard, which determine the quality of concrete to as much as 80%. The analysis provides concrete indications for priority requirements in order to obtain concrete of the quality guaranteed by the European Standard EN 206.

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