IBRACON Structures and Materials Journal
Revista IBRACON de Estruturas e Materiais
ISSN 1983-4195 ismj.org

ORIGINAL ARTICLE

Concrete mix design method for durability based on particle packing concept

Método de dosagem de concretos visando a durabilidade com base no conceito de empacotamento de partículas

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Received 3 April 2023
Accepted 7 August 2023

Abstract: Concrete presents complex behavior, being a difficult material to define the ideal proportion of its constituents. To overcome this challenge, many mix design methods have been developed over time. However, most of these methods do not consider durability parameters during the procedure. Thus, the objective of this article is to present a mix design method for concrete, with properties of workability (slump rating from 50 mm to 220 mm), axial compressive strength (class of 25MPa to 55MPa), and durability as response parameters. From the application of the proposed method, it was possible to create mix design and performance diagrams. It was noticed that all concretes fell into the pre-established consistency class and presented axial compressive strength results close to the predetermined values. Moreover, it was possible to obtain indications of the material's durability.

Keywords: durability, Alfred model, mix design, performance diagram.

Resumo: O concreto apresenta um comportamento complexo, sendo uma atividade difícil definir a proporção ideal dos seus constituintes. A fim de superar esse desafio, muitos métodos de dosagem foram desenvolvidos, ao longo do tempo. Entretanto, a maioria desses métodos não considera parâmetros de durabilidade durante o procedimento. Assim, o objetivo deste artigo é apresentar um método para dosar concretos, tendo como parâmetros de resposta propriedades de trabalhabilidade (valores de abatimento de 50 mm a 220 mm), de resistência à compressão axial (classe de 25MPa a 55MPa) e de durabilidade. A partir da aplicação do método proposto, foi possível elaborar os diagramas de dosagem e de desempenho. Percebeu-se que todos os concretos se enquadraram na classe de consistência pré-estabelecida e apresentaram resultados de resistência à compressão axial próximos aos valores pré-determinados. Além disso, foi possível obter indicativos da durabilidade do material.

Palavras-chave: durabilidade, modelo de Alfred, dosagem, diagrama de desempenho.

How to cite: L. A. Silva, W. K. D. Silva, A. E. B. Cabral, G. M. Pinheiro, and A. M. Oliveira, "Concrete mix design method for durability based on particle packing concept," *Rev. IBRACON Estrut. Mater.*, vol. 17, no. 4, e17404, 2024, https://doi.org/10.1590/S1983-41952024000400004

1 INTRODUCTION

Concrete is the most employed construction material in infrastructure and buildings, and is used worldwide [1]. This material is expected to fulfill three basic functions: workability, mechanical strength, and durability. Durability can be defined as the ability of the material to maintain mechanical strength and other functions during its service life, under the environmental conditions to which the structure will be exposed [2]. Thus, structure durability is a factor that

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Financial support: The present study was funded by Research Foundation of Ceará State (FUNCAP) from Brazil, with resources from the Technological Innovation Fund – FIT.
Conflict of interest: Nothing to declare.
Data Availability: data-sharing is not applicable to this article as no new data were created or analyzed in this study.

directly impacts the economy and the environment, given that the more durable the construction, the lower the cost of renovations, demolitions, losses, and reconstructions [3].

Large concrete structures in areas of severe exposure typically have a rather high recovery cost and often make repair impossible. As an example, we have offshore wind farms located in the marine environment that are subjected to the effects of tides and waves, in addition to enduring the action of aggressive seawater ions. These farms have a significantly higher cost than the onshore ones and more difficult access [4]. For Li et al. [5], a more rigorous and specified quality control is required during the construction of concrete structures in a marine environment to provide the constructed elements with a durability performance compatible with the service life design. Hence, it is important to use durability parameters in the concrete mix design.

One of the factors that interferes with concrete performance is the packing density of the constituent materials, since the higher the packing, the smaller the space for degradation mechanisms to infiltrate and, as a result, the greater the durability [6]. This factor is usually considered for high-strength concrete, and less used for conventional concrete, although the advantages exist for them both [7]. Aggregate packing optimizes the concrete mixtures, and reduces the space between the grains, in addition to providing positive results concerning mechanical strength and reducing the consumption of cementitious materials [8]. Among the used packing methods, the Alfred model (modified Andreassen method) is one of the most accepted, being used to define the volume of solid materials and the best packing density of the mixture [9], [10]. Although the concept of packing materials is already used, more studies are needed to analyze the mechanical and durability properties of concrete, highlighting the application of this methodology [11].

Concrete presents complex behavior in the fresh and hardened states, being a difficult material to define the ideal proportion of its constituents cost-effectively and appropriately [7]. Optimizing the concrete mix design is a challenge, given that concrete properties are influenced by the types and contents of its constituents and their physical and chemical properties [12].

Several concrete mix design methods [13], [14], [15], [16] were developed over time with axial compressive strength as a basic parameter of the material, related to the w/c ratio. Although high-performance concretes have high durability as one of their characteristics, there are methods for this type of concrete [17], [18], [19] that do not provide indications of durability.

Therefore, the proportion of concrete constituents must be defined to meet workability, axial compressive strength, and durability requirements. However, most existing methods do not address all three requirements. Thus, the objective of this study is to propose a mix design method for durable concretes based on aggregate packing, with properties of workability, axial compressive strength (w/c ratio), and durability as parameters.

2 PROPOSED MIX DESIGN METHOD

The proposed mix design method for durable concretes was based on already-known methods: the O'Reilly method [15], for conventional concrete; the Aïtcin method [19], for high-performance concrete; and IPT/EPUSP method [16], for conventional concrete. The best concepts applied by these three procedures were integrated with new steps, to obtain denser concretes with durability indications. The proposed method was divided into five steps, shown in Figure 1.

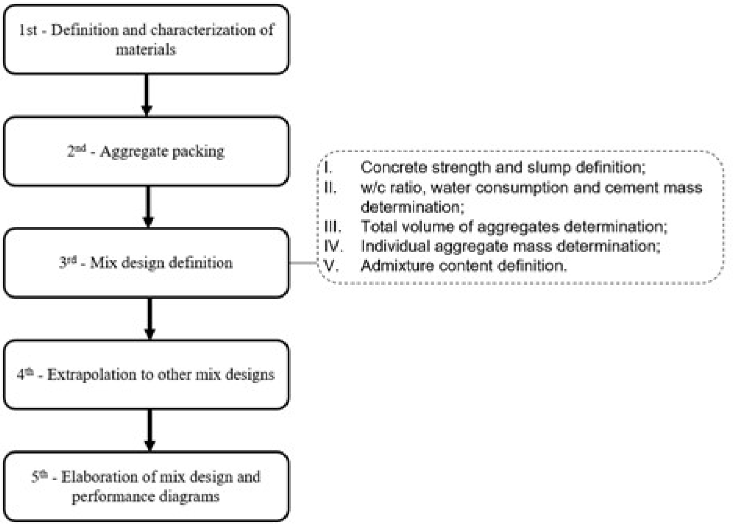

Figure 1. Mix design steps

2.1 1st Step – definition and characterization of materials

The type of cement must be defined according to the structure's purpose. For constructions exposed to aggressive environments, it is recommended to use cement with additions, for example. This is because additions tend to densify the concrete's microstructure and thus reduce the infiltration of aggressive agents [20]. In addition, for constructions with mass concrete, cement with low heat of hydration must be used to reduce cracks caused due to the thermal energy generated during the exothermic reactions and the possible formation of delayed ettringite [21]. Regarding the aggregates, it is advisable to use different grading ranges to allow better packing of the materials. These aggregates must be within the limits of the grading curves proposed by NBR 7211 [22]. As for additives, it is recommended that a comparison be made to find the best ratio between their content and the desired performance. Moreover, the water used must meet the requirements assigned by NBR 15900-1 [23].

After defining the materials, the characterization of these constituents must be carried out. For this, it is necessary to get the specific gravity of all the solid materials and their particle size distribution.

2.2 2nd Step – aggregate packing

Initially, a theoretical packing between the aggregates must be carried out using the Elkem Materials Mixture Analyzer (EMMA) software, which is based on the Alfred model. This software requests the definition of a particle size distribution modulus (q), and it is recommended to adopt the value of 0.37 [24]. To execute the packing, it is necessary to provide the software with grading and specific gravity data of each aggregate, obtained experimentally. After providing the data, different proportions of each material in the mixture are tested and those that result in grading curves closer to the model provided by EMMA are verified, that is, with a lower void content. The theoretical packing speeds up the process of defining the aggregate proportions since only the best combinations are experimentally tested.

After the theoretical packing, the experimental packing of the aggregates must be performed, using the three best combinations provided by EMMA. The experimental process of packing the aggregates was done according to NBR 16972 [25], as this method considers the real interaction between the aggregate particles (shape and surface textures). Thus, the mixture with the lowest void content presents the best packing. It should be noted that the packing must be carried out initially between the materials with the larger size, and the smaller aggregates must be inserted afterward. This configuration guarantees a higher proportion of coarse aggregate and, consequently, better concrete strength, in addition to decreasing the specific surface area of the grains, which reduces the amount of water necessary to achieve the expected workability [26]. Moreover, it guarantees a lower consumption of binder, ensuring cost-effectiveness.

2.3 3rd Step – mix design definition

The water/cement ratio (w/c) must be determined first, according to Figure 2. This graph was produced based on a database of field tests, considering the use of Blast Furnace Portland Cement (CP III). Thus, real data was used, because, sometimes, the values suggested by other dosage methods are not feasible in the field. After defining the w/c ratio, the amount of water is determined based on Table 1, which was also developed from the field data.

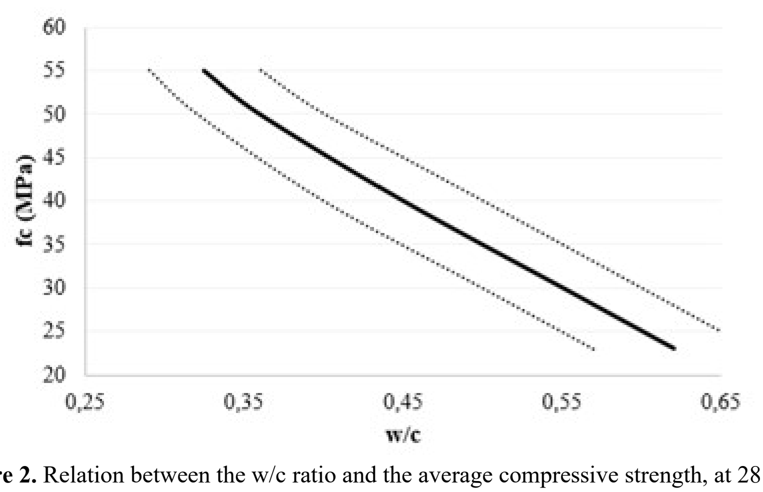

Figure 2. Relation between the w/c ratio and the average compressive strength, at 28 days

Table 1. Relation between concrete slump and water consumption

Class	Slump (mm)	Water consumption (kg/m³)		
		Minimum	Recommended	Maximum
S50	50 - 100	170	190	210
S100	100 - 160	180	200	220
S160	160 - 220	190	210	230

Using the w/c ratio and the amount of water, the amount of cement is determined. The entrapped air content in the concrete must also be determined. According to Aïtcin [19], this volume partially depends on the design proportions and ranges from 1% to 3%. Thus, it is suggested to use 1.5%.

The total volume of aggregates (Vol.aggr.) is defined by the Absolute Volume Method, i.e., calculating the volume (Vol.) of all materials already selected to achieve the aggregate volume required for one cubic meter of concrete. Note that the admixture volume was disregarded, given the small amount used. Hence, in Equation 1 there are:

$$Vol.aggr. = \ 1\,m^{3}\,of\ concrete\ -\ Vol._{(water)} - Vol._{(cement)} - Vol._{(air)} \tag{1}$$

Then, the mass of each aggregate must be determined, considering that the material is dry. The total mass of aggregates must be calculated using the specific gravity of the set of aggregates (ρ) and their total volume (Vol.aggr). This specific gravity is obtained from the aggregate proportions found in the packing and the individual specific gravity of the grain, according to Equation 2. So,

$$\rho\ =\ \%aggregate_1\ x\ \rho_1\ +\ \%aggregate_2\ x\ \rho_2\%\ +\ ... \tag{2}$$

Where $\%aggregate_1$, $\%aggregate_2$, … = percentage of aggregate 1 found through packing, percentage of aggregate 2 found through packing, etc.; and ρ_1, ρ_2, ... = aggregate 1 specific gravity, aggregate 2 specific gravity, etc.

After obtaining the specific gravity of the aggregate set, the total mass of aggregates can be found. Then, through Equation 3, there is:

$$Maggr._{(t)} = \ Vaggr._{(t)}\ x\ \rho \tag{3}$$

Where $Maggr._{(t)}$ = total mass of aggregates (m^3); $Vaggr._{(t)}$ = total volume of aggregates (m^3); and ρ = specific gravity of the aggregate set (kg/m^3).

To find the mass of each aggregate (ma), just multiply the total mass of aggregates by the aggregate proportions defined by packing, according to Equations 4.a and 4.b. Thus,

$$ma_1\ = Maggr._{(t)}\ x\ \%aggregate_1 \tag{4.a}$$

$$ma_2\ = Maggr._{(t)}\ x\ \%aggregate_2 \tag{4.b}$$

The next step is to determine the amount of admixture. The high technology in current superplasticizer admixtures makes it possible to use small amounts of material to produce concretes with very low water content and high workability. Hence, different levels are suggested according to the type of admixture (preferably high performance), the concrete strength class, and practical tests based on suggested initial values. Thus, for low-strength concrete (20 MPa), it is suggested to add 0.20% of the material. For intermediate-strength concrete (40 MPa), 0.40% of admixture is used and, for high-strength concrete (> 50 MPa), 0.50% is initially added. These contents are measured in relation to the mass of cement used in the concrete. Note that corrections can be made to these values according to practical tests. In this way, the mix design and consumption of all materials are obtained.

If the mix design in volume is needed, the specific gravity of the materials can be used to make the conversion. In this case, if the fine aggregate is wet, it is necessary to correct its volume, considering its swelling. The correction is made by Equation 5:

$$V_{fine.aggr(w)} = V_{fine.aggr(d)} \; x \; SR \tag{5}$$

Where $V_{fine.aggr(w)}$ = volume of wet sand; $V_{fine.aggr(d)}$ = volume of dry sand; and SR = aggregate swelling ratio.

2.4 4th Step – extrapolation to other mix designs

The mix design procedure is simplified when it is required to produce concretes with other strengths but with the same consistency and materials as one previously designed by the proposed method. In this case, Inge Lyse's Rule should be used. This rule states that concretes with the same consistency and produced with the same materials have a total amount of water virtually constant [27]. The analytical expression of this rule is written in Equation 6:

$$H = \frac{w/c}{1+m} \tag{6}$$

Where H = water content/dry materials of the mixture (%); w/c = water/cement ratio; m = a + b = total aggregate content of the dry mixture per kilogram of cement (kg); a = dry fine aggregate content per kilogram of cement; and b = dry coarse aggregate content per kilogram of cement.

As two concretes with different axial compressive strength, but with the same materials and constant slump, present the same H value, by Equation 7 there are:

$$H_1 = H_2 \rightarrow \frac{w/c_{(1)}}{1 + m_{(1)}} = \frac{w/c_{(2)}}{1 + m_{(2)}}$$

$$H_1 = \frac{w/c_{(2)}}{1+m_{(2)}} \tag{7}$$

The w/c ratio of the second concrete ($w/c_{(2)}$) must be calculated as follows in Figure 1 and H1 has already been obtained for the first designed concrete. Thus, the m_2 value can be found. To find the individual contents of aggregates, multiply m_2 by the corresponding percentages, obtained through aggregate packing, according to Equations 8 and 9. So,

$$a = m_2 \; x \; \%fine \; aggregate \tag{8}$$

$$b = m_2 \; x \; \%coarse \; aggregate \tag{9}$$

Finally, the cement consumption must be found and, thus, the amount of each material. For this, Equation 10 must be used. In addition, the superplasticizer admixture content is determined based on the values suggested in the previous step and practical tests. Therefore, it is possible to determine the mix design and consumption of materials.

$$C = \frac{1m^3 - Vol._{(air)}}{\frac{1}{\rho_C} + \frac{a}{\rho_a} + \frac{b1}{\rho_{b1}} + \frac{b2}{\rho_{b2}} + \frac{a/c}{\rho_{wat.}}} \tag{10}$$

Where C = cement consumption (kg/m^3); Vol. $_{(air)}$ = entrapped air volume in concrete (m^3); ρ_C = specific gravity of cement (kg/m^3); ρ_a = specific gravity of the fine aggregate (kg/m^3); ρ_{b1} and ρ_{b2} = specific gravity of coarse aggregates (kg/m^3); and $\rho_{wat.}$ = specific gravity of water (kg/m^3).

2.5 5th Step – elaboration of mix design and performance diagrams

The last step comprises the preparation of mix design and performance diagrams. For this, it is necessary to produce at least 3 concrete mixtures considering different axial compressive strengths, which can be evaluated at different ages of wet curing according to NBR 5739 [28]. Furthermore, these concretes will be analyzed concerning the durability properties, at 28 days, and different tests may be carried out. Three tests are suggested: water absorption by immersion, according to NBR 9778 [29], electrical resistivity, following the recommendations of ASTM C1876 [30], and chloride ion penetration, according to ASTM C1202 [31]. The water absorption test is one of the most used techniques as a durability indicator, as it has a simple methodology [32]. Electrical resistivity is a good indicator of durability and is obtained quickly and easily [33]. Moreover, one of the main factors that interfere with structure durability is the corrosion associated with chloride ion penetration [34], and it is important to have a parameter that assesses this property.

After every test has been carried out, mix design and performance diagrams are drawn up. The mix design diagram relates the axial compressive strength (fc) to the water/cement ratio (w/c) in the first quadrant; the w/c ratio to the aggregate content "m" in the second quadrant; and "m" to the cement consumption (C) in the third quadrant. The performance diagram, on the other hand, consists of the association of axial compressive strength with durability properties. Thus, in the first quadrant, fc is related to water absorption by immersion (WA); in the second quadrant, WA to electrical resistivity (ER); and in the third quadrant, ER to the charge passed (CP). From these diagrams, it is possible to obtain the behavior equations and the coefficients of determination (R^2). Based on the equations, concrete might be measured from any initial condition, considering the analyzed range. This concludes the concrete mix design using the proposed method.

3 APPLICATION OF THE PROPOSED MIX DESIGN METHOD

To confirm the applicability of the proposed method, three concrete mixtures were measured, aiming to achieve average strengths of 30 MPa, 40 MPa, and 50 MPa, at 28 days, and a very low or negligible probability of chloride ion penetration. These concretes will be used in foundations and wind tower segments onshore, which are massive concrete structures and thus require cement with low heat of hydration. The mix design was executed with the aid of Microsoft Office Excel software.

3.1 1st Step – definition and characterization of materials

The following materials were chosen for the production of concrete: sulfate-resistant Portland cement class 40, sand, gravel ranging from 4.75 mm to 12.5 mm (G1), gravel ranging from 9.5 mm to 25.0 mm (G2), superplasticizer admixture MC-PowerFlow 3100 and water. Figure 3 shows the grading curve of the aggregates, while Table 2 presents the data regarding the specific gravity of the solid materials used in this study. The aggregates were dried before mixing, having an initial water amount equal to zero.

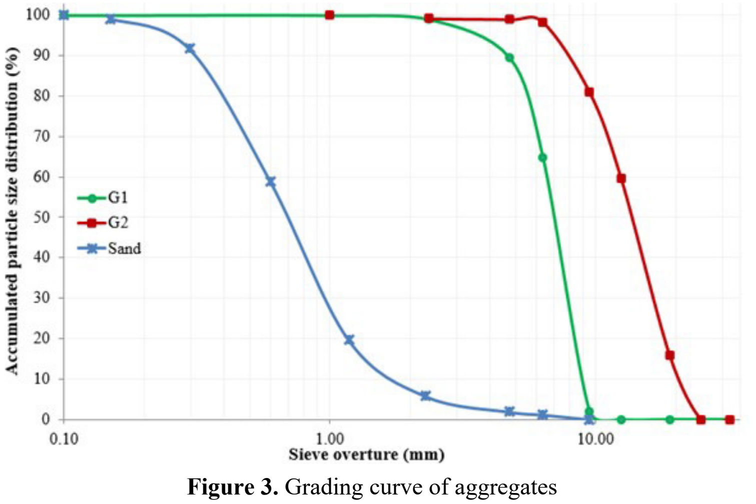

Figure 3. Grading curve of aggregates

Table 2. Characterization of materials

Material	Specific gravity (kg/m ^{3})
Cement	3057
Sand	2626
G1	2617
G2	2629

3.2 2nd Step - aggregate packing

A particle size distribution modulus (q) of 0.37 was adopted, as recommended by the method, aiming for the lowest void content. The gravels' packing was carried out first. The three best gravel combinations provided by EMMA were selected (Figure 4): 35% G1 and 65% G2 (1); 40% G1 and 60% G2 (2); and 45% G1 and 55% G2 (3). These proportions were tested through experimental packing to define the optimal gravel content. Then, a new theoretical packing was carried out in EMMA between the gravel and the sand.

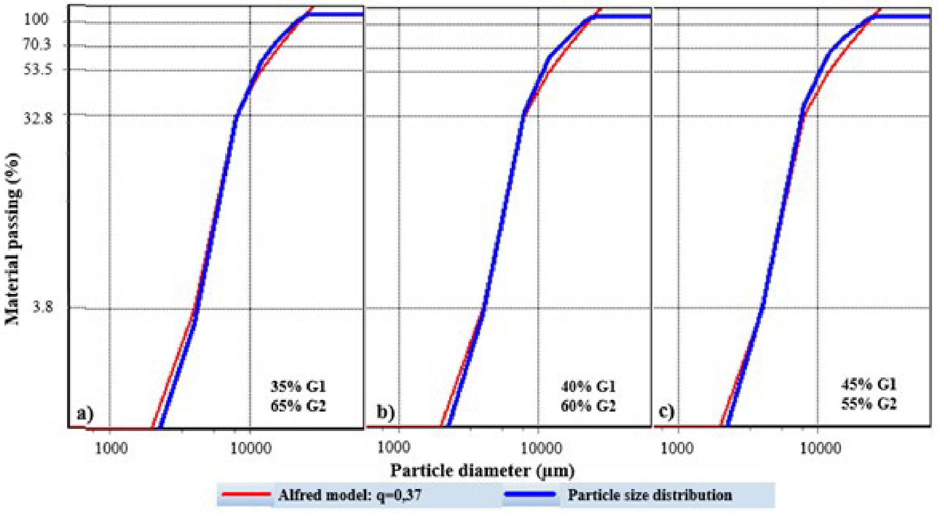

Figure 4. Gravel particle size distribution by EMMA

From the experimental packing, the Figure 5 graph was drawn with the void content and the bulk density of each combination. As can be seen, Combination 2 (40% G1 and 60% G2) presented the lowest void content (41.37%) and the highest bulk density (1.536 kg/dm^3) and was thereby selected to carry out the packing with the sand.

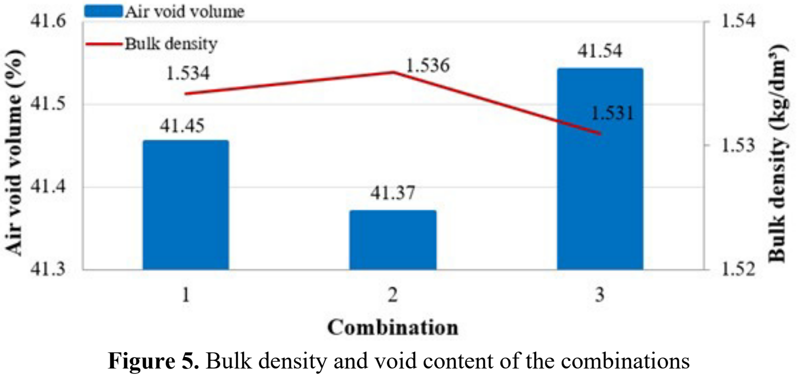

Figure 5. Bulk density and void content of the combinations

The packing between Combination 2 of the gravels and the sand was carried out through EMMA, obtaining the curves seen in Figure 6. The mixtures chosen were 35% Sand and 65% Combination 2 (1), 40% Sand and 60% Combination 2 (2), and 45% Sand and 55% Combination 2 (3) for experimental packing.

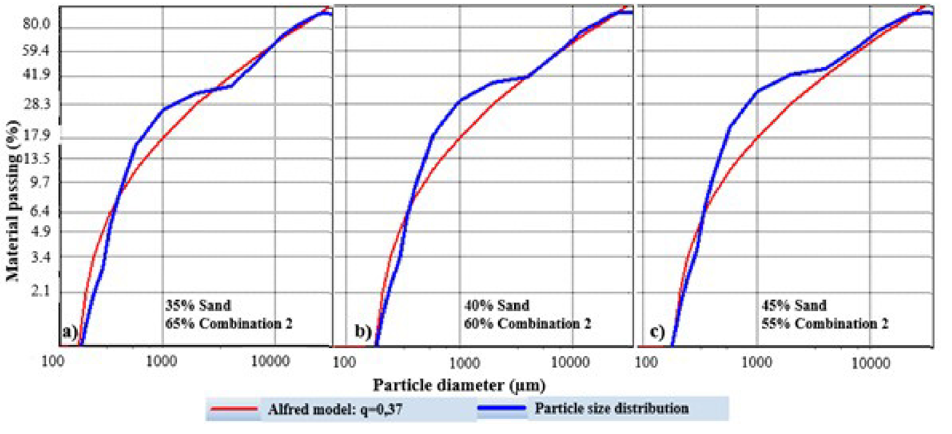

Figure 6. Gravel and sand grading curves by EMMA

Figure 7 shows the void content and the bulk density of the mixtures between the gravels (Combination 2) and the sand. Note that mixture 2 presented the lowest void content (32.65%) and the highest bulk density (1.768 kg/dm^3), and was therefore used in this research. Thus, the final proportion of aggregates was established at 40% Sand, 24% Gravel 4.75 – 12.5 mm, and 36% Gravel 9.5 – 25.0 mm, by mass.

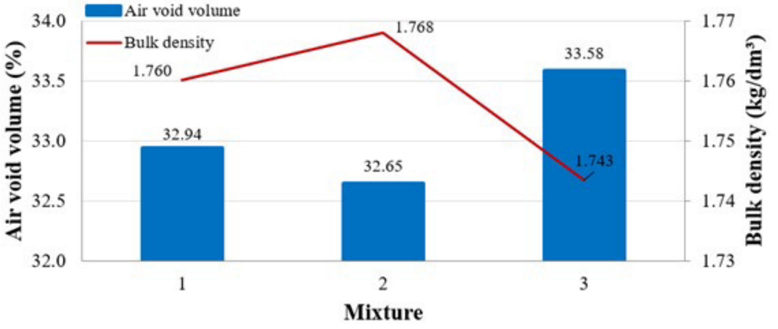

Figure 7. Bulk density and void content of mixtures

3.3 3rd Step - mix design determination

The 30 MPa concrete was designed first. It was decided to frame the concretes within the consistency class S100 [35] with a slump greater than or equal to 100 mm and less than 160 mm, since this range is frequently used in the concrete elements of onshore wind towers.

The w/c ratio was 0,56 for 30 MPa strength, defined according to Figure 1. In addition, the amount of water adopted was 200 kg/m^3 according to Table 1. The cement mass was determined considering these two factors, resulting in 357.1 kg/m^3. The cement volume was calculated using the material's specific gravity (3,057 kg/m^3), resulting in 0.12 m^3. It was considered an entrapped air content of 1.5%. Total volume of aggregates (Vaggr.(t)) could be determined by Equation 1, resulting in the Equation 11:

$$V_{aggr.(t)} = 1\,m^3 - 0.2\,m^3 - 0.12\,m^3 - 0.015\,m^3 = 0.67\,m^3 \quad (11)$$

As the values obtained in the packing were 40% Sand, 24% G1, and 36% G2, the specific gravity of the aggregate set (ρ) is determined by Equation 2. Thus, Equation 12 is:

$$\rho = 0.40 \, x \, 2626 \frac{kg}{m^3} + 0.24 \, x \, 2617 \frac{kg}{m^3} + 0.36 \, x \, 2629 \frac{kg}{m^3} = 2624.9 \, kg/m^3 \quad (12)$$

Given the aggregate volume of 0.67 m^3, the aggregate mass corresponds to 1758.7 kg/m^3 (0.67 m^3 x 2624.9 kg/m^3), according to Equation 3. Thereby, the individual mass of the aggregates can be determined by Equation 4, resulting in the Equations 13, 14 and 15. Thus:

$$Sand \; mass = 0.40 \, x \, 1758.7 \, kg/m^3 = 703.5 \, m^3 \quad (13)$$

$$G1 \; mass = 0.24 \, x \, 1758.7 \, kg/m^3 = 422.1 \, m^3 \quad (14)$$

$$G2 \; mass = 0.36 \, x \, 1758.7 \, kg/m^3 = 633.1 \, m^3 \quad (15)$$

Next, the superplasticizer content was determined, using 0.30% in relation to the cement mass. The mass of all the concrete constituent materials was obtained and the mix design was determined according to Table 3.

Table 3. 30 MPa concrete

Concrete strength 30 MPa	**Cement**	**Sand**	**G1**	**G2**	**Water**	**Admixture**
Consumption (kg/m^3)	357.1	703.5	422.1	633.1	200	1.1
Mix design	1	1.97	1.18	1.77	0.56	0.003

3.4 4th Step - extrapolation to other mix designs

As all concretes in this study fell within S100 consistency class and were composed of the same materials (Equation 16), the designs for 40 MPa and 50 MPa concretes were determined using Lyse's Rule. Thus, according to Equation 7, water content/dry materials of the mixture is (Equation 17):

$$H_{(30 \, MPa)} = H_{(40 \, MPa)} = H_{(50 \, MPa)} \quad (16)$$

$$H_{(30 \, MPa)} = \frac{0.56}{1+1.97+1.18+1.77} = 0.095 \quad (17)$$

The w/c ratio for 40 MPa and 50 MPa mixtures were 0.45 and 0.37, respectively, obtained based on Figure 2. For 40 MPa concrete, there is (Equation 18):

$$H_{(40 \, MPa)} = 0.095 = \frac{0.45}{1+m} \rightarrow m = 3.74 \quad (18)$$

From the previously done packing (section 3.2), the proportions between the aggregates are known. The proportions of the aggregates can then be calculated (Equations 19, 20 and 21):

$$Sand \; content = 0.40 \, x \, 3.74 = 1.50 \quad (19)$$

$$G1 \; content = 0.24 \, x \, 3.74 = 0.90 \quad (20)$$

$$G2\ content\ =\ 0.36\ x\ 3.74\ =\ 1.35 \quad (21)$$

Equation 10 was used to define the cement consumption (C) presented in Equation 22.

$$C = \frac{1m^3 - 0.015m^3}{\frac{1}{3057}+\frac{1.50}{2626}+\frac{0.90}{2617}+\frac{1.35}{2629}+\frac{0.45}{1000}} = 446.6\ kg/m^3 \quad (22)$$

The admixture content was established at 0.45% according to Table 1 and practical tests. Table 4 presents the mix design and consumption of all materials.

Table 4. 40 MPa Concrete

Concrete strength 40 MPa	**Cement**	**Sand**	**G1**	**G2**	**Water**	**Admixture**
Consumption (kg/m^3)	446.6	669.9	401.9	602.9	200.1	2.0
Mix design	1	1.50	0.90	1.35	0.45	0.0045

Following the same procedure for the 50 MPa concrete, the mix design and material consumption obtained are presented in Table 5.

Table 5. 50 MPa concrete

Concrete strength 50 MPa	**Cement**	**Sand**	**G1**	**G2**	**Water**	**Admixture**
Consumption (kg/ m^3)	547.8	635.4	378.0	569.7	202.7	3.0
Mix design	1	1.16	0.69	1.04	0.37	0.0055

3.5 5th Step – elaboration of mix design and performance diagrams

To elaborate the concrete mix design and performance diagrams, 10 specimens of each mixture were produced for a total of 30 samples. Out of the 10 specimens, 06 were used for the axial compressive strength (fc) test at different wet curing ages (07 days, 28 days, and 56 days), which was carried out following NBR 5739 [28]. Furthermore, two specimens were evaluated for water absorption by immersion (WA), as indicated by NBR 9778 [29], and two others were used in the chloride ion penetration test (CP) according to ASTM C1202 [31]. The volumetric electrical resistivity (ER) was also assessed according to ASTM C1876 [30] in four specimens, the same ones adopted in the axial compressive strength test. The resistivity was measured first and the compressive strength test was carried out next.

Table 6 presents the results of these tests and also shows the slump values (Sl.) obtained for each mix design. Note that all concretes fell into the pre-established consistency class (S100). In addition, the axial compressive strength results were close to the predetermined values, reaching a maximum variation of approximately 3% for 30 MPa concrete.

Table 6. Test results

Concrete (MPa)	**w/c**	**Sl. (mm)**	**$fc_{(7)}$ (MPa)**	**$fc_{(28)}$ (MPa)**	**$fc_{(56)}$ (MPa)**	**m**	**C (kg/m^3)**	**WA (%)**	**CP (C)**	**ER (kΩm)**
30	0.56	150	25.9	31.0	34.0	4.9	357.1	5.5	584.8	4.8
40	0.45	145	32.5	40.5	42.5	3.8	446.6	5.0	555.7	5.0
50	0.37	155	38.6	50.9	51.4	2.9	546.0	4.5	472.4	5.6

As already reported in the literature [36], the w/c ratio directly impacts the concrete axial compressive strength, as well as the durability properties; the lower this ratio is, the better the concrete performance. Therefore, the results of this study are in accordance with the literature, as the concretes with the lowest w/c ratio had the highest strength at all observed ages. Moreover, the best durability results were obtained for the 50 MPa concrete, which achieved the lowest water absorption, the lowest charge passed, and the highest electrical resistivity. It is noteworthy that the w/c ratio is one of the most important factors during the corrosion initiation phase, having a fundamental role in the service life of the structures [37].

Based on the results, the diagrams were drawn and the behavior equations were obtained. Figures 8 and 9 present the concrete mix design and performance diagrams, respectively. Notice that all equations have R^2 equal to or close to 1, representing the data appropriately. Based on the equations, concretes can be designed from any initial condition, considering the analyzed range.

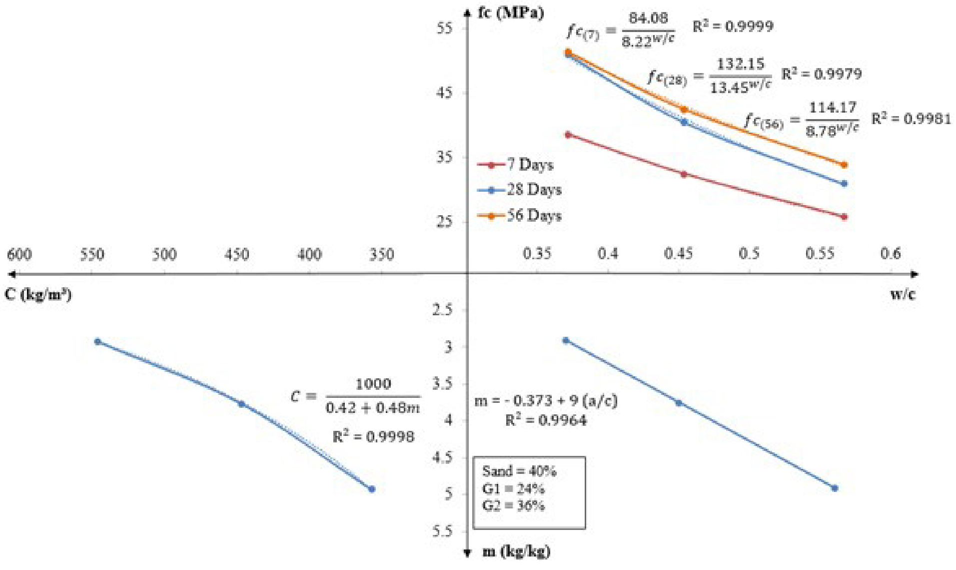

Figure 8. Mix design diagram

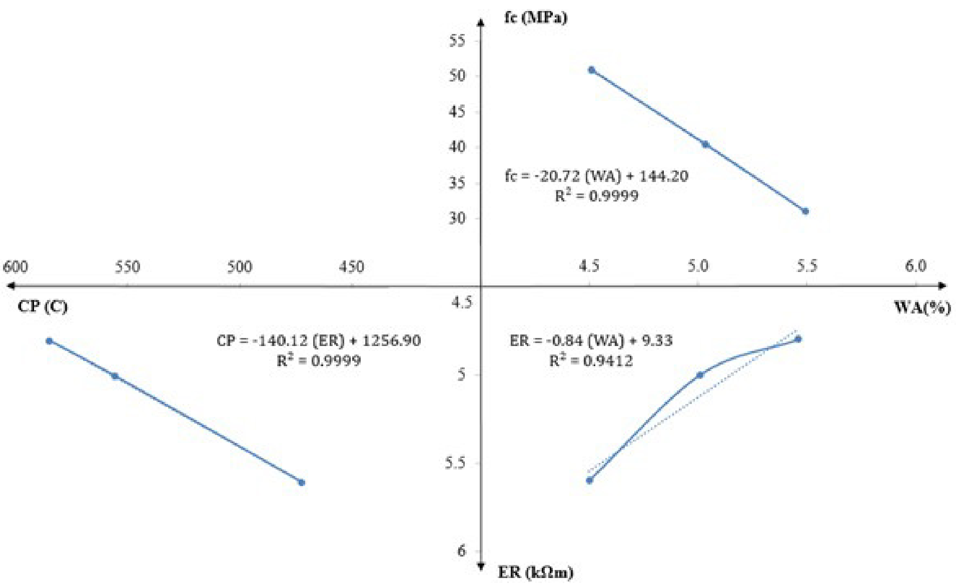

Figure 9. Performance diagram

Table 7 presents a concrete classification established by C1202 [31] and AASHTO 358 [38], enabling the assessment of chloride ion penetration risk according to the charge passed and electrical resistivity, which were determined in the tests. Although water absorption is one of the most used tests to evaluate concrete, no boundaries have been found in the literature to classify the material. However, most good concretes have water absorption well below 10%, by mass [39].

Table 7. Performance parameters

Carge Passed (C)	Electrical resistivity (Ωm) *	Chloride ion penetration - Concrete
> 4000	<120	High - Very poor
2000 - 4000	120 - 210	Moderate - Poor
1000 - 2000	210 - 370	Low - Normal
100 - 1000	370 - 2540	Very Low - Good
< 100	> 2540	Negligible - Excellent

*Saturated specimens

4 CONCLUSIONS

This study proposed a new method for concrete mix design, considering workability, compressive strength, and durability parameters. Based on the results, it can be concluded that the procedures adopted are efficient for obtaining concretes that meet the pre-established requirements for axial compressive strength, workability, and durability. Furthermore, it was noted that the proportion of materials was satisfactory, resulting in concretes with suitable consistency and few apparent air voids. However, it is suggested the evaluation of other materials with the consideration of different strengths in order to validate and improve the dosage procedure.

The proposed method presents relative ease of execution and provides indications of the material's durability, which enables a possible estimation of the structure service life. Therefore, this method makes it possible to more appropriately select concretes according to their purpose, as materials with low durability tend to be used in simpler structures, while large constructions require high-durability concretes.

The use of electronic spreadsheets is suggested to simplify and speed up the calculations. Moreover, the use of a data range that covers all the concretes that will be produced at the construction site is recommended, striving to analyze the largest possible number of samples to provide greater accuracy to the results.

ACKNOWLEDGEMENTS

We thank to Research Foundation of Ceará State (FUNCAP) for financial support.

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Editors: Antonio Carlos dos Santos, Guilherme Aris Parsekian.