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Evaluation of mechanical properties of concrete produced with binary and ternary mixtures of aggregate

Avaliação de propriedades mecânicas de concreto produzido com misturas binárias e ternárias de agregado

Evaluación de las propiedades mecánicas del hormigón producido con mezclas binarias y ternarias de áridos

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Abstract
Cement is the costlier component of concrete, and its productive process causes considerable environmental impact. Thus, alternatives are studied to reduce the amount of cement used. An option is the use of optimized grain size curves of aggregates, aiming to achieve a higher compactness of concrete. An ideal grain size distribution results in a higher mechanical resistance of concrete, providing a reduction in cost and consumption of materials, and, consequently, in environmental impacts. Therefore, the present study aims to improve the properties of conventional concrete through optimized grain size distributions. In this research, concrete was produced with binary mixtures with rolled pebbles from Belém region, in Pará state, and ternary mixtures of granitic crushed stone from the metropolitan region of Recife, in Pernambuco state, and concrete properties in the hardened state were studied. The mix design IPT/EPUSP method was used and grain size composition, unit weight, water absorption by capillarity, and compressive strength tests were performed. It was observed an increase in compressive strength with for higher fine contents. Furthermore, for both aggregates studied, there was no loss in strength with the lower amount of cement used, due to the increased compactness of the concrete, indicated by the unit weight of the aggregate mixture. Therefore, the optimization of the grain size composition of the coarse aggregate provided a reduction in the cement consumption for the same required strength and for both analysed aggregates.
Keywords: Concrete; Strength, Grain size composition; Binary mixtures; Ternary mixtures.

Resumo
O concreto possui como componente mais oneroso o cimento, cujo processo produtivo causa grande impacto ambiental. Desta forma, estudam-se alternativas para reduzir a quantidade de cimento utilizada na sua produção. Uma opção é a utilização de curvas granulométricas de agregados otimizadas, objetivando uma maior compacidade do concreto. A composição granulométrica ideal resulta em um concreto de maior resistência mecânica. Assim, tem-se uma redução de custos e de consumo de materiais e, consequentemente, de impactos ambientais. Com isto, o presente estudo visa ao melhoramento das propriedades do concreto convencional através de composições granulométricas otimizadas. Para o estudo, foram realizadas análises de propriedades de concretos no estado endurecido produzido com misturas binárias de seixo rolado da região de Belém, no Pará, e ternárias de brita de rocha granítica da região metropolitana de Recife, Pernambuco. O método de dosagem IPT/EPUSP foi utilizado e os ensaios realizados foram de granulometria, massa unitária, absorção por capilaridade e resistência à compressão. Observou-se um aumento na resistência à compressão com uma maior quantidade de finos. Além disso, para ambos os agregados estudados, não houve perda de resistência com a diminuição da quantidade de cimento utilizada, devido ao aumento da compacidade do concreto, observada através da massa unitária dos agregados. Desta forma, depreende-se que a otimização da composição granulométrica do agregado graúdo proporciona redução do consumo de aglomerante para uma mesma resistência requerida e para ambos os agregados analisados.
Palavras-chave: Concreto; Resistência; Composição granulométrica; Misturas binárias; Misturas ternárias.

Resumen
El cemento es el componente más costoso del hormigón, y su proceso de producción provoca un gran impacto ambiental. Así, se estudian alternativas para reducir la cantidad de cemento utilizado. Una opción es utilizar curvas granulométricas optimizadas de áridos, buscando una mayor compacidad del hormigón. La composición granulométrica ideal resulta en un hormigón con mayor resistencia mecánica. De esta forma, se reducen los costos y el consumo de materiales y, en consecuencia, los impactos ambientales. Por lo tanto, el presente estudio tiene como objetivo mejorar las propiedades del hormigón convencional mediante composiciones granulométricas optimizadas. Para el estudio, se realizaron análisis de propiedades del hormigón en estado endurecido producido con mezclas binarias de guijarros de la región de Belém, en Pará, y ternarios de roca granítica de la región metropolitana de Recife, Pernambuco. El método de dosificación IPT / EPUSP fue utilizado, así como ensayos de granulometría, masa unitaria, absorción por capilaridad y resistencia a compresión. Se observó un aumento de la resistencia a compresión para una mayor cantidad de finos. Además, para los dos áridos estudiados, la disminución en la cantidad de cemento utilizado no resultó en pérdida de la resistencia por causa del aumento en la compactación del hormigón, indicado por la masa unitaria de los áridos. Así, la optimización de la composición granulométrica del árido grueso proporciona una reducción en el consumo de aglutinante para la misma resistencia requerida y para los dos áridos analizados.
Palabras clave: Hormigón; Resistencia; Composición granulométrica; Mezclas binarias; Mezclas ternarias.

1. Introduction

In recent years, there is an increasing requirement to produce concretes that meet technical specifications, reducing costs and environmental impacts (Silva et al., 2020). Several studies have focused on the use of materials with superior performance considering mechanical behaviour and durability to produce concrete (Castro & Pandolfelli, 2009). One approach adopted is to optimize the concrete mix design to increase the packing density (Robalo et al., 2021), which could reduce the paste volume and, consequently, the amount of cement used (Campos, Klein, & Marques Filho, 2020). In this regard, numerous studies have addressed the aggregate portion, which represents 80% of the concrete composition, and contributes to the specific gravity, elastic modulus, and dimensional stability (Metha & Monteiro, 1994).

The behaviour of the aggregate in concrete can be analysed by its grain size curve, which can be continuous, discontinuous, or uniform. A continuous curve is considered well graded when there are small fractions in sufficient quantity to fill the spaces between the bigger particles, decreasing the maximum volume of voids and increasing the packing density. This filling effect, known as filler effect, results in the decrease of porosity of a granular set, increasing its packing density (Alexander & Mindess, 2005; Salvador Filho, 2007). In contrast, uniform particles (grains of the same size) cannot reach a high packing density (Lenz, 2016).

The first study about packing of concrete particles was published by Féret, in 1892, and indicated that the maximum strength is obtained when the initial porosity of the matrix is minimum and the packing density is maximum (Larrard & Sedran, 1993; Aiqin, Chengzhi & Ningsheng 1997, 1999; Castro & Pandolfelli, 2009). Since the study of Feret, several packing models have been proposed to determine the packing density of particles, aiming to optimize the granular mixtures of concrete (Castro & Pandolfelli, 2009). Fuller (1907) developed a study to dose concretes from mixtures of aggregates with different grain size compositions, aiming to achieve a higher compactness of the aggregate, as each group of aggregates presented an ideal proportion in the mixture. Furnas (1931) proposed that the ideal grain size composition to dose a concrete could be obtained by the equation of a geometric progression (GP), as follows:

$$Sn = A\ (1\text{-}Pr.n)/(1\text{-}Pr) \tag{1}$$

where Sn is the sum, A is the first term, Pr is the ratio, and n is the number of terms of the G.P.

Carneiro & Cincotto (1999), concluded that it is possible to obtain high-strength concretes by a rational dosage of aggregates. Fuller (1907) and Furnas (1931) affirmed that the increase in the continuity of grain size distribution increases the mechanical resistance and reduces the kneading water for the same workability. The mixtures are more economic, as they demand less cement paste (Damineli, 2013; Pileggi, 2001; Wong, Chan, & Kwan 2013; Londero et al., 2017). Thus, the particle size distribution has fundamental importance to achieve optimum mix performance in the field (Baghaee Moghaddam & Baaj, 2018).

In addition, the initial fluidity of concentrated suspensions, such as concrete, depends on physical considerations of the aggregates, namely grain size distribution, particle index, and surface texture of particles (Bonen & Sarkar, 1995). These aggregate characteristics affect the concrete properties in fresh and hardened states (Weidmann, 2008).

Thus, binary and ternary grain size compositions of concretes with higher compactness and continuity will result in concretes with better mechanical properties, reduction in the consumption of binder and kneading water, and consequently reduction of costs. In addition, it is considered that the concrete will have higher durability regarding aggressive agents.

In this context, the present study aimed to improve the properties of conventional concrete by optimization of grain size compositions. For the study, concrete was produced using binary mixtures of rolled pebbles from the region of Belém, in Pará, where there is prevalence of this type of aggregate, and ternary mixtures of granitic crushed stone from the metropolitan region of Recife, Pernambuco. Concrete properties in the hardened state were analysed.

2. Methodology

The materials and methods used in the study are described as follows.

2.1 Materials

The materials used, as well as their characteristics, are detailed below.

2.1.1 Cement

The cement used for the concrete composition was pozzolanic cement CP II Z 32. The specific area by the Blaine method, determined following NBR 16372:2015, was 3450 cm²/g and the fineness, determined using the sieve of opening 0.075 mm, was 2.4%.

2.1.2 Aggregates

The fine and coarse aggregates employed in the experiment have quartz nature. The coarse aggregates and the mixtures were characterized regarding their grain size and unit weight. For the natural sand, it was also determined the grain size curve and unit weight.

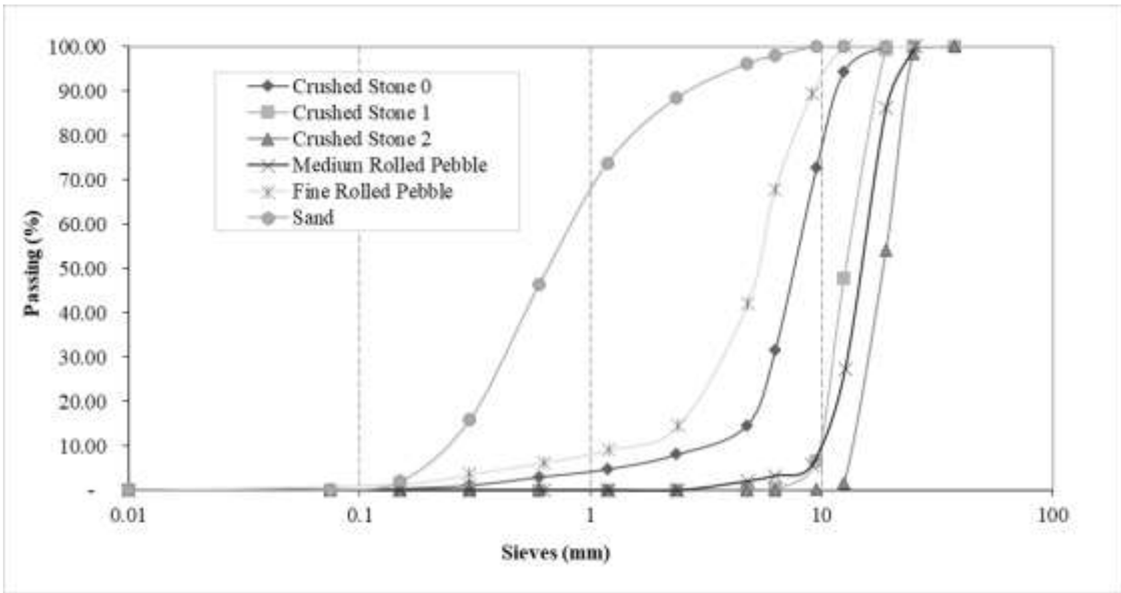
The rolled pebble is considered a very brittle aggregate. However, although studies indicate the negative influence of brittle aggregates in the mechanical resistance of concrete (Ferreira, 1999), this aggregate is largely used in the city of Belém. Regarding the influence of the format and texture, this aggregate has a regular format and smooth texture.

2.2 Methods

2.2.1 Grain size composition

The determination of the grain size composition was performed according to test method NBR NM 248:2003, in which the samples are sieved using a sequence of sieves with meshes ranging from 25.0 to 0.3 mm. Figure 1 shows the grain size distribution of granitic crushed stone, rolled pebbles and sand, from which the differences in grain size can be observed.

Figure 1. Grain size curves of crushed stone 0, 1, 2, medium and fine rolled pebble, and sand.



Source: Authors.

The grain size curves indicate the uniformity of the aggregate fractions used. Most part of crushed stones 0, 1, and 2 is retained in sieves with openings 4.8, 9.5, and 12.5 mm, respectively, whereas for the medium and fine rolled pebble, most part is retained in sieves with openings 9.5 and 4.8 mm, respectively. The grain size curve of the sand indicates a continuous distribution.

2.2.2 Unit weight

The unit weight in the dry state was determined according to test method NBR NM 45:2006. The values obtained were 1,500 kg/m³ for crushed stone 0, 1,460 kg/m³ for crushed stone 1, and 1,420 kg/m³ for crushed stone 2. For rolled pebble, the unit weight was 1,350 kg/m³ for the medium and 1,454 kg/m³ for the fine. The unit weight of sand was 1,440 kg/m³.

2.3 Experimental planning

2.3.1 Preparation of ternary mixtures

The ternary mixtures were composed according to the percentage of material retained in each grain size fraction of the theoretical curves obtained in accordance with the proposed by Furnas (1931) apud Carneiro (1999). For the curves in this work, the number of terms of the GP was adopted as 4. Thus, each class of the crushed stone (0, 1, and 2) represents a term, and the fourth term is the sieve of bigger opening (mm), by which all the grain size fractions pass. Then, by identifying the sieves in which the grain size fractions of each crushed stone were concentrated, the terms of the GP were the sieves with openings: 19.0 mm, as the fourth term by which all the fractions, 12.5, 9.5, and 4.8 mm pass.

The GP ratio defines the profile continuity of the grain size curve. Thus, by attempt and qualitative analysis of the profiles generated, four values were defined for the ratio of the GP, 0.5, 0.6, 0.75, and 0.85. The grain size composition of each theoretical curve is presented in Table 1.

Table 1. Grain size composition of theoretical curves.

Sieves (mm)	Crushed Stone	Curve A – 0.5 (%)	Curve B – 0.6 (%)	Curve C – 0.75 (%)	Curve D – 0.85 (%)
19.0		0	0	0	0
12.5	Crushed Stone 2	53.4	46.0	36.6	31.4
9.5	Crushed Stone 1	26.7	27.6	27.5	26.7
4.8	Crushed Stone 0	13.4	16.5	20.6	22.7
< 4.8		6.5	9.9	15.3	19.2

Source: Authors.

As observed in Table 1, the percentage of crushed stone 2 used in each curve decreases, ranging from 53.4% in curve A to 31.4% in curve D. Thus, curve A presents as the major contribution a coarser fraction of aggregate, which decreases until reaching a balanced proportion for curve D.

The grain size composition was also determined for the ternary mixtures composed with the percentages of each crushed stone to evaluate the difference with the theoretical mixture. Table 2 and Figure 2 present the real values of retained percentages for each ternary mixture and the corresponding grain size curves, respectively.

Table 2. Grain size composition of effective ternary mixtures.

Sieves (mm)	Curve A – 0.5 (% retained)	Curve B – 0.6 (% retained)	Curve C – 0.75 (% retained)	Curve D – 0.85 (% retained)
25.0	0	0	0	0
19.0	31.40	21.86	11.40	17.5
12.5	40.61	43.5	31.8	44.3
9.5	16.50	18.2	22.8	23.0
4.8	10.90	12.85	27.50	15.1
< 4.8	0.59	3.59	6.5	0.1
Bulk density (kg/m^3)	1,699	1,690	1,610	1,500

Source: Authors.

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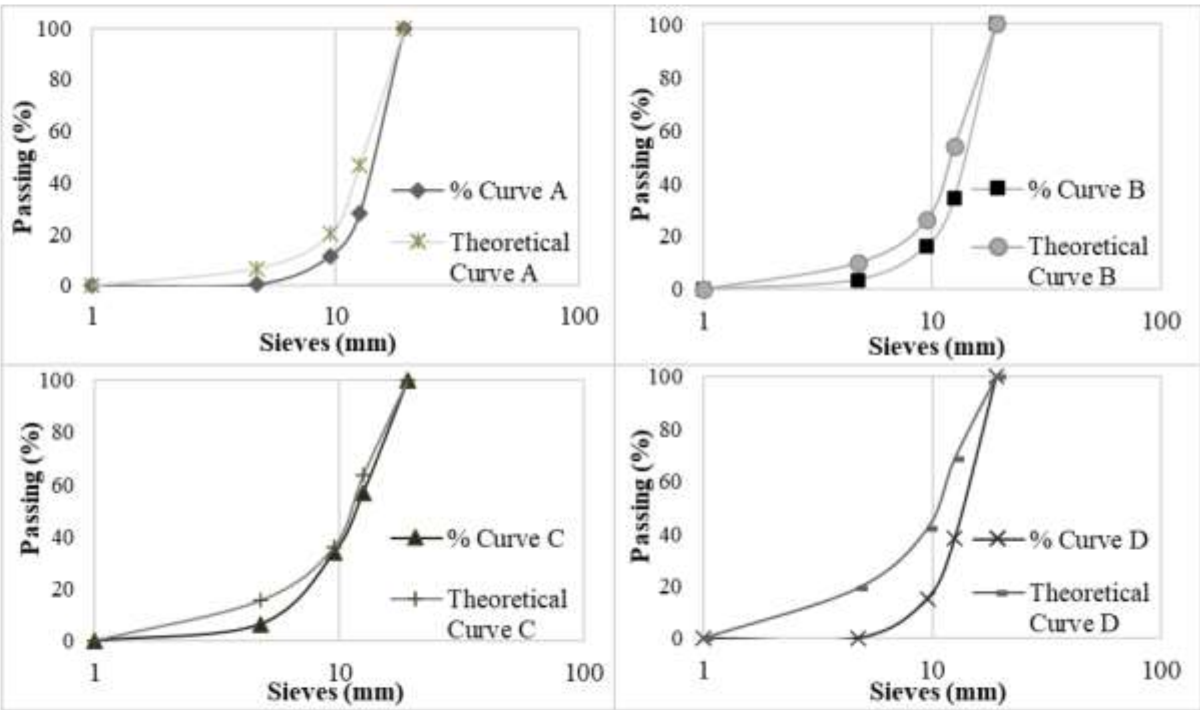
Figure 2. Grain size distribution curves of ternary mixtures with crushed stones.



Source: Authors.

It is observed in Table 2 a difference in the effective and theoretical distributions, illustrated in Figure 2. The theoretical curve considered only fractions retained in sieves with openings of 12.5, 9.5, 4.8, and < 4.8 mm. However, as observed, the effective curves have a considerable contribution of the fraction retained in the sieve with opening of 19.0 mm. Thus, for the effective curves, the coarser fraction is composed of grains retained in the sieves of 19.0 and 12.5 mm, whereas in the theoretical curve this contribution corresponds only to the fraction 12.5 mm. In addition, as observed in Figure 2, there was no superposition of the real and theoretical curves for all the mixtures analyzed, and mixture D was the one more distant from the theoretical profile.

2.3.2 Preparation of binary mixtures

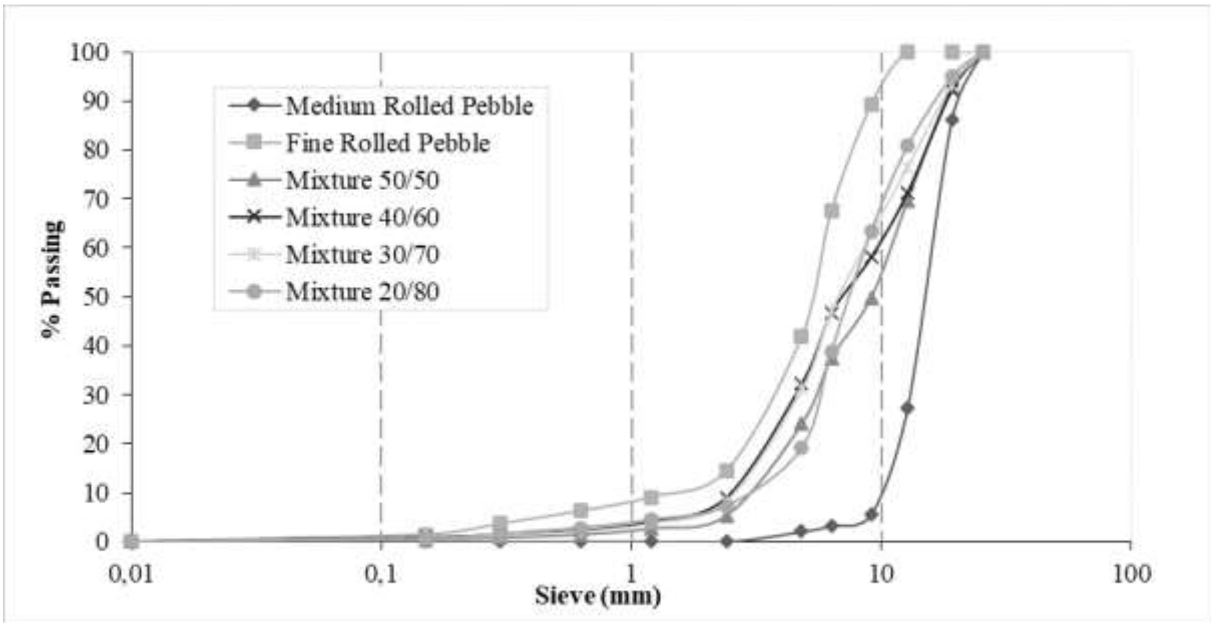
The proportions of the binary mixtures used, prepared with medium and fine rolled pebble, and their unit weight values are detailed in Table 3, and the grain size distribution curves are shown in Figure 3.

Table 3. Characteristics of binary mixtures for concrete dosage.

Mixtures	**Proportions (%)**		**Unit Weight (kg/m³)**
	Medium Rolled Pebble	**Fine Rolled Pebble**	
1	100	0	1,350
2	0	100	1,454
3	50	50	1,373
4	40	60	1,446
5	30	70	1,402
6	20	80	1,368

Source: Authors.

Figure 3. Grain size distribution curves of medium and fine rolled pebble binary mixtures.



Source: Authors.

From Table 3, it is observed that mixtures 1 and 2 use only one fraction of aggregate, 100% medium and 100% fine rolled pebble, respectively. Mixtures 3 to 6 are intermediate mixtures, starting from a balanced composition (50% of each aggregate for mixture 3) and gradually increasing the proportion of fine rolled pebble until reaching a value of 80% in mixture 6. From Figure 3, the medium rolled pebble exhibited a very uniform curve compared to the others, whereas the fine rolled pebble presented higher continuity. The variation of percentages enabled an increase in the compactness of the grain size distribution of the mixtures.

2.3.3 Dosage of concrete

The slump test was used for the characterization of concretes in fresh state, and the value of 80 ± 10 mm was adopted. The dosage followed the IPT/EPUSP procedure, starting with experimental values for the mortar content and water/cement (w/c) ratio and adding more mortar until the desired slump. In this method, three mix designs are considered with cement/aggregate ratios of 1:3.5, 1:5.0, and 1:6.5. This method provides correlations of characteristics such as compressive strength, w/c ratio, mix design, and cement consumption.

After the dosage, cylindrical specimens (30 × 15 cm) were moulded and cured until 28 days in saturated water with hydrated lime. In the hardened state, the compressive strength test was performed, according to NBR 7222:2011, applying sulphur levelling.

2.4 Obtained data

Table 4 presents the mortar content, w/c ratio, compressive strength for each curve family, mix design, and cement consumption, and Table 5 presents the data of mortar content for each binary mixture and the related compressive strength.

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Table 4. Data from concretes dosed with ternary mixtures.

	Mix Design	w/c	Fc (MPa)	Consumption (kg/m³)
A – 0.50 Mortar Content 42%	1:3.5	0.37	42.0	480
	1:5	0.46	35.3	370
	1:6.5	0.55	27.5	290
B – 0.60 Mortar Content 45%	1:3.5	0.37	39.0	430
	1:5	0.50	33.6	360
	1:6.5	0.57	26.5	320
C – 0.75 Mortar Content 58%	1:3.5	0.43	41.6	500
	1:5	0.44	34.4	390
	1:6.5	0.60	19.2	310
D – 0.85 Mortar Content 46%	1:3.5	0.40	31.0	489
	1:5	0.55	27.5	359
	1:6.5	0.63	24.5	298

Source: Authors.

Table 5. Characteristics of produced concretes with binary mixtures.

Mixtures	Proportion (%)		Mortar Content (%)	Compressive Strength (MPa)
	Medium Rolled Pebble	Fine Rolled Pebble		
1	100	0	51	23.40
2	0	100	39	24.30
3	50	50	47	19.40
4	40	60	41	20.30
5	30	70	41	20.60
6	20	80	35	24.10

Source: Authors.

Tables 4 and 5 summarize the values found for each composition of ternary and binary mixtures, respectively. For the binary mixtures, values of compressive strength and mortar content are provided, whereas for ternary mixtures, these values and also cement consumption are presented. Analyses of the values obtained are provided in the next section.

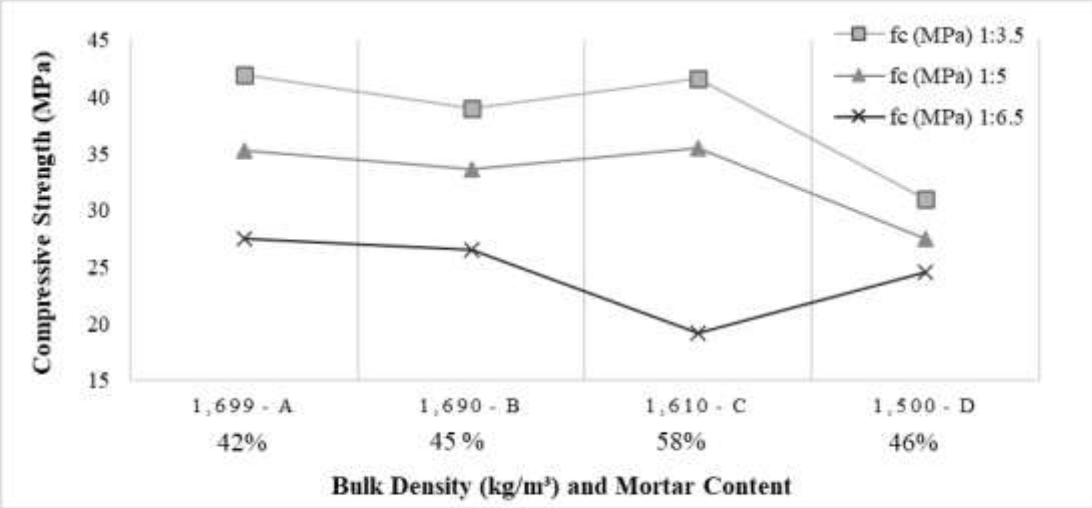
3. Results and Discussion

3.1 Unit weight versus compressive strength

3.1.1 Ternary mixtures

The bulk density of mixtures was correlated with the compressive strength, as seen in Figure 4.

Figure 4. Bulk density (kg/m^3) and mortar content (%) *versus* compressive strength (MPa).



Source: Authors.

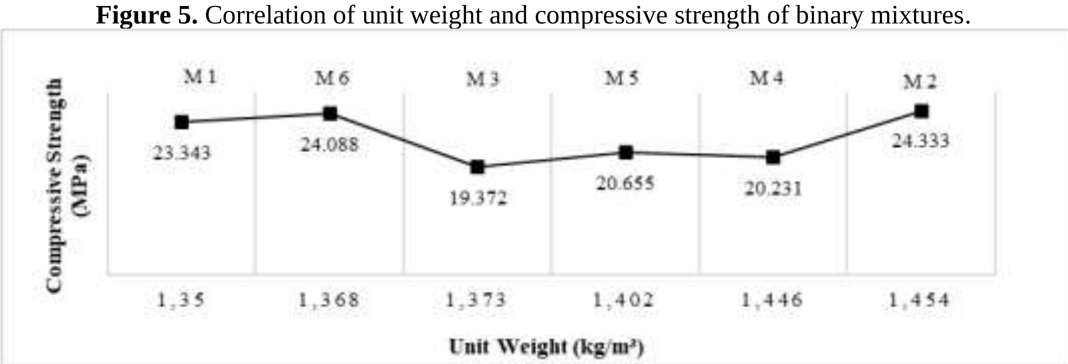
From Figure 4, ternary mixtures with higher bulk density provided higher compressive strengths for the same mix design, only varying the continuity of the mixtures. It is also observed a tendency of reduction in compressive strength with the increase of continuity of the grain size distribution of ternary mixtures, for a same mix design and different ternary mixture.

The conclusions from the graph are contradictory to what is expected for particle size optimization. The proposed explanation for the increase of strengths with the decrease of continuity of the grain size curves of the ternary mixtures is the considerable concentration of aggregates of the same grain size range. In this case, the crushed stone 2 contributes to increase the strength of the concrete, because of its larger dimension. Moreover, the grain size composition of curves A and B in all mix designs provided concretes with higher compressive strength compared to composition D, although concretes from curves A and B had the lowest mortar contents, 42% and 45%, respectively, compared to the concrete produced with composition D, with mortar content of 46%.

3.1.2 Binary mixtures

Figure 5 presents a graph correlating the unit weight and compressive strength of binary mixtures.

Figure 5. Correlation of unit weight and compressive strength of binary mixtures.



Source: Authors.

From Figure 5, the higher compressive strengths were obtained for mixtures M1, M2, and M6, which provided an average value of 24.00 MPa (fc). However, from these mixtures, M6 mixture provided the best overall result, because the concrete produced achieved a high compressive strength value and also required the lowest mortar content for the stipulated workability (35%), although the unit weight was lower compared to the others mixtures (1,368 kg/m³). The concrete produced with the medium rolled pebble had higher strength despite the lower unit weight (1,350 kg/dm³) because of the higher mortar content and low continuity, which results in a higher concentration of aggregate. The strength of the concrete produced with fine rolled pebble is due to its better grain size continuity, which provided a higher compactness of the paste-aggregate system resulting from the better packing of aggregate grains.

The concrete produced with mixtures M3, M5 and M4 had lower strength, despite the high consumption of mortar and larger unit weight in comparison to that produced with mixture M6. This is due to the low compactness obtained with these mixtures by the particle size distribution. The larger unit weight indicates a large concentration of big grains in a size range, causing uniformity of the mixture and compactness of the aggregate-paste system, thus requiring a higher mortar content.

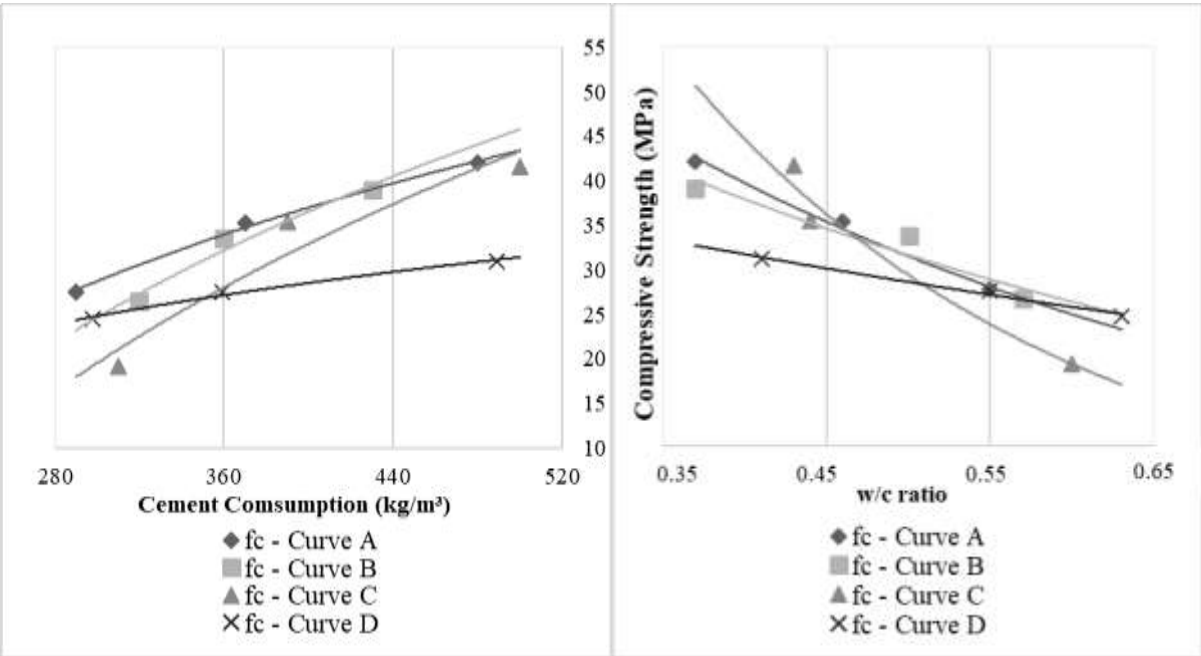
For the binary compositions, no direct relationship was observed between the compactness of mixtures and the compressive strength of the concretes produced. This result may be related to the smooth surface of the rolled pebbles uses as aggregates, which may have interfered in the adherence with the mortar.

3.2 Characteristics of concretes versus compressive strength

3.2.1 Ternary mixtures

Figure 6 presents a graph relating w/c ratio, cement consumption, and compressive strength of concretes produced with ternary mixtures.

Figure 6. W/c ratio and cement consumption (kg/m³) *versus* compressive strength (MPa) of concretes produced with ternary mixtures.



Source: Authors.

From Figure 6, concretes dosed with ternary mixtures A, B, and D presented strength curves with less steepness compared to that of the concrete dosed the mixture C. This tendency indicates that, for a given range of w/c ratio (i.e., from 0.35 to 0.55), the ternary mixtures A, B and D provide concretes with lower compressive strength compared to the concrete dosed with mixture C.

Considering the range of w/c ratio from 0.35 to 0.45, the higher strength is given by mixture C, which can be due to the high content of mortar and also an indication of the good compactness of the system, despite the lower bulk density of this mixture compared to that of mixtures A and B. For the range from 0.35 to 0.45, the compressive strength values are more similar. However, the rate of decrease of the compressive strength for mixture C is higher compared to that of the other mixtures. For the range from 0.55 to 0.65, although the concrete produced with mixture C had a higher mortar content, its compressive strength was lower compared to those of the concretes produced with ternary mixtures A, B and D. It is speculated that the increase in w/c ratio contributed to the reduction of mechanical strength, particularly because of the high mortar content of 58%, as the w/c ratio of 0.6 increased the porosity in the concrete paste. Thus, this effect might have been predominant in relation to the grain system compactness of the ternary mixture.

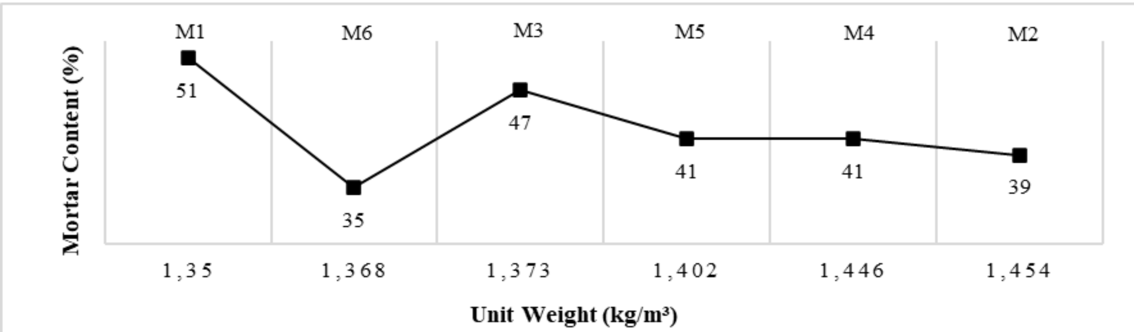
In addition, the strength of the concretes dosed with ternary mixtures increased with the increase in cement consumption, which was expected. The curves relating compressive strength and cement consumption (kg/m³) have different tendencies: the steepness of curves A, B, and C is higher compared to that of curve D. Thus, for a range of cement consumption (i.e., from 360 to 440 kg/m³), the compressive strengths for curves A, C and B are higher than those for curve D.

For a compressive strength of 30 MPa, ternary mixture A provides the lowest consumption of cement (310 kg/m³), followed by mixture B (340 kg/m³), and mixture C (360 kg/m³). The highest consumption is required for mixture D (450 kg/m³). For a cement consumption between 280 and 360 kg/m³, the influence of the distribution curve of ternary mixtures is more significant. For example, for a consumption of 300 kg/m³, the approximate variation of the strengths for each concrete with the respective ternary mixtures are: Curve A with fc = 28 MPa; Curves B and D with fc = 25 MPa; and Curve C with fc = 20 MPa. For a consumption of 350 kg/m³, it is observed the concentration of compressive strengths in two groups, approximately 33 MPa for the concretes dosed with ternary mixtures A and B, and approximately 27 MPa for concretes dosed with C and D mixtures.

3.2.2 Binary mixtures

Figure 7 presents a correlation between the unit weight and mortar content for binary mixtures.

Figure 7. Unit weight and mortar content for binary mixtures.



Source: Authors.

From Figure 7, the unit weight of mixtures M2, M3, M4, M5, and M6 are larger compared to that of mixture M1. Mixture M1 also exhibited the highest mortar consumption due to the high void content and low coefficient of continuity. The mortar content in the concretes produced with mixtures M4, M5, and M6 is in the range of 35 to 40%, indicating good efficiency of these concretes. However, the concrete produced with mixture 2 was also in the range from 35 to 40%, which was probably due to the action of continuous grain size distribution of the fine rolled pebble, which contributed to the workability of the concrete.

Among the optimized mixtures, mixture M3 exhibited the highest mortar consumption, approximately 47%. This mixture required a higher mortar content for the same workability stipulated because it presented a higher proportion of medium rolled pebbles, which had a slightly continuous particle size distribution compared to fine rolled pebbles. In addition, the lower mortar consumption was expected for mixture M6 due to the optimization of its grain size composition, providing a continuous distribution. The continuity was obtained because of the higher proportion of fine rolled pebble.

4. Conclusion

From the analysis of compressive strength of concretes dosed with ternary mixtures, the optimization of grain size curves of aggregates influenced in the reduction of cement consumption, with no loss of compressive strength.

The compressive strength of concretes produced with binary and ternary mixtures with different particle size distribution, indicates that the optimization of the grain size composition is relevant, as it favours the increase of concrete strength, reduction in mortar consumption and, consequently, binder consumption. The variation of this consumption can reach up to 30% for a desired strength. This can be obtained by modifying the grain size distribution of the coarse aggregate, seeking to increase its continuity.

A directly proportional relation was observed between bulk density and compressive strength of ternary mixtures. Thus, the optimization can be measured by the bulk density of the mixtures.

The optimization of binary mixtures can be achieved with higher compactness and continuity of mixtures. The search for increasing the continuity of a binary mixture should be the main goal to optimize the concrete dosage instead of using only the unit weight value, because there might be cases in which the particle size curve indicates good continuity of the aggregate, but its unit weight is lower than that of another aggregate, with a more uniform grain. It happens because a high unit weight can only indicate a concentration of a single grain range of aggregate. In the study, the binary compositions did not present a direct relation with the increase of compressive strength, probably because of the smooth surface of the rolled pebbles used as aggregates, which interferes in the adherence with the mortar.

Moreover, the procedure to optimize the aggregate's grain size composition allows its rational use and may contribute to reduce the environmental impacts caused by the exploitation of aggregate deposits.

The optimization of grain size curves, performed in this study, provided good results for the ternary mixtures analysed using crushed stone, whereas for the binary mixtures with rolled pebble a good correlation was not observed. Therefore, other aggregates should be analysed to evaluate their behaviour. In addition, other concrete properties should be evaluated in future research to further study the effectiveness of the optimization of grain size curves.

References

Brazilian Association of Technical Standards – ABNT (2015). Portland cement and other powdered materials — Determination of fineness by the air permeability method (Blaine method) (NBR 16372). ABNT.

Brazilian Association of Technical Standards – ABNT (2003). Aggregates - Sieve analysis of fine and coarse aggregates (NBR NM 248). ABNT.

Brazilian Association of Technical Standards – ABNT (2006). Aggregates - Determination of the unit weight and air-void contents (NBR NM 45). ABNT.

Brazilian Association of Technical Standards – ABNT (2011). Concrete and mortar - Determination of the tension strength by diametrical compression of cylindrical test specimens (NBR 7222). ABNT.

Aiqin, W., Chengzhi, Z., & Ningsheng, Z. (1997). Study of the influence of the particle size distribution on the properties of cement. Cement and Concrete Research, 27, 685–695.

Aiqin, W., Chengzhi, Z., & Ningsheng, Z. (1999). The theoretic analysis of the influence of the particle size distribution of cement system on the property of cement, Cement and Concrete Research, 29(11), 1721-1726.

Baghaee Moghaddam, T., & Baaj, H. (2018). Application of compressible packing model for optimization of asphalt concrete mix design. Construction and Building Materials, 159, 530–539. doi:10.1016/j.conbuildmat.2017.11.004

Bonen, D., & Sarkar, S. L. (1995). The superplasticizer adsorption capacity of cement pastes, pore solution composition, and parameters affecting flow loss, Cement and Concrete Research, 25(7), 1423–1434.

Campos, H. F., Klein, N. S., & Marques Filho, J. (2020). Proposed mix design method for sustainable high-strength concrete using particle packing optimization. Journal of Cleaner Production, 121907. doi:10.1016/j.jclepro.2020.121907

Carneiro, A. M. P & Cincotto, M. A. (1999). Dosagem de argamassas através de curvas granulométricas. Boletim Técnico da Escola Politécnica da USP (n. 237), São Paulo.

Castro, A. L., & Pandolfelli, V. C. (2009). Revisão: Conceitos de dispersão e empacotamento de partículas para a produção de concretos especiais aplicados na construção civil. Cerâmica, 55, 18–32.

Damineli, B. L. (2013). Conceitos para formulação de concretos com baixo consumo de ligantes: concretos reológico, empacotamento e dispersão de partículas. Doctoral dissertation. Universidade de São Paulo.

Larrard, F. & Sedran, T. (1994). Optimization of ultra-high-performance concrete by the use of a packing model, Cement and Concrete Research, 24(6), 997–1009.

Ferreira, A. P. (1999). Ensaios não destrutivos: resistência ao esmagamento do agregado graúdo como variável para avaliação da resistência do concreto. Master's dissertation. Universidade Federal Fluminense.

Fuller, W. B. & Thompson, S.E. (1907). The laws of proportioning concrete. Proceedings of American Society of Civil Engineers, N. 3. Vol XXXIII, 223–298.

Furnas, C. C. (1931). Grading aggregates, I- Mathematical relations for beds of broken solids of maximum density. Industrial and Engineering Chemistry, 23(9), 1052–1058.

Lenz, L.A. (2016). Avaliação da influência do empacotamento do esqueleto granular no módulo de elasticidade de concretos convencionais. Master's dissertation. Universidade Federal do Paraná.

Londero, C., Lenz, L. A., Santos, I. M. R., & Klein, N. S. (2017). Determinação da densidade de empacotamento de sistemas granulares compostos a partir da areia normal do IPT: comparação entre modelos de otimização de distribuição granulométrica e composições aleatórias. Cerâmica, 63, 22–33.

Alexander, M. & Mindess, S. (2005). Aggregates in Concrete. New York: Taylor & Francis.

Metha, P. K. & Monteiro, P.J.M. (1994). Concreto: estrutura, propriedades e materiais. São Paulo: PINI.

Pileggi, R. G. (2001). Ferramentas para o estudo e desenvolvimento de concretos refratários. Doctoral dissertation. Universidade Federal de São Carlos, São Carlos.

Robalo, K., Soldado, E., Costa, H., do Carmo, R., Alves, H., & Júlio, E. (2021). Efficiency of cement content and of compactness on mechanical performance of low cement concrete designed with packing optimization. Construction and Building Materials, 266, 121077. doi:10.1016/j.conbuildmat.2020.121077

Salvador Filho, J.A.A. (2007). Blocos de concreto para alvenaria em construções industrializadas. Doctoral dissertation. Universidade de São Paulo.

Silva, A. F. P., Andrade, D. T. M., Rios, N. A. B., & Nascimento, L. G. (2020). Concrete performance with addition of bamboo ash. Research, Society and Development, 9(9), e309996755. https://doi.org/10.33448/rsd-v9i9.6755

Weidmann, D. F. (2008). Contribuição ao estudo da influência da forma e da composição granulométrica de agregados miúdos de britagem nas propriedades do concreto de cimento Portland. Master's dissertation. Universidade Federal de Santa Catarina.

Wong, V., Chan, K. W., & Kwan, A. K. H. (2013). Applying theories of particle packing and rheology to concrete for sustainable development. Organization, Technology and Management in Construction, 5, 844–851.