Comparative study of ideal and inadequate coarse aggregate on the mechanical properties of concrete

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Abstract—The purpose of this study was to produce concrete with ideal coarse aggregate and compare it to concrete made with inadequate aggregate. Assess the influence of inappropriate aggregate on concrete properties. The concretes produced with Blade aggregate presented an elasticity modulus superior to the concrete with cubic aggregate, demonstrating greater elasticity in the concrete and, in the tensile strength, they presented better performance in the first ages. For fresh concrete and compressive strength, the cubic shape performed better. The cubic shape, considered ideal, has length/thickness <18 mm and width/thickness <18 mm; the blade shape, considered inadequate, has length/thickness >30 mm and width/thickness >30 mm. The physical properties of ideal coarse aggregate and inadequate aggregate were compared after separation and classification for concrete production and subsequent analysis of workability, compressive strength, tensile strength and modulus of elasticity of the resulting concrete. The goal was to assess the influence of ideal and inadequate coarse aggregate in different situations: dry material content, binder content, w/c ratio and concrete strength.

Keywords—Coarse aggregate; Ideal aggregate; Inadequate aggregate; Concrete performance.

I. INTRODUCTION

The study of aggregate shape for concrete asphalt and concrete hydraulic is an area already explored by researchers such as [1–3], who were the first to propose an aggregate shape classification method. Currently, there is a great amount of research on the classification of coarse aggregate shape for concrete, such as [4–10], and regulatory norms such as [11–16] that refer to the ideal coarse aggregate shape for concrete. The crushing mechanism is one of the main factors that influences the characteristics of natural stone aggregate, such as particle size distribution, shape, texture, size, specific mass and unit mass. Crushers produce aggregates of various sizes and shapes that can perform positively or negatively in the production of concrete.

Aggregate shape affects concrete behavior, both in the fresh and hardened states, because it influences workability, internal friction angle and compactability, among other factors dependent on kneading water amount[9]. Cubical aggregate presents better performance than those with elongated, discoid and laminar shapes [17].

According to studies done by [17,18], cubical aggregates are generally preferable to flat or elongated aggregate for use in concrete, since they have lower surface area per volume unit and normally lead to better aggregate packing. Laminar aggregates produce mixtures with low workability for a given amount of water, which leads to poor compaction and high void content, resulting in low resistance and durability.

Laminar aggregates, when compared to cubical aggregates, tend to break along the particle axis due to their slenderness. Thus, aggregate shape affects concrete strength and life span [19].

According to Isabel [20], the determination of the ratio between the largest and smallest size of the aggregate in her experimental results indicate that, when most particles have a ratio lower than 3:1, aggregate shape will have little influence on the quality of concrete. However, when more
than 50% of particles have a ratio of 5:1, concrete strength will be affected.

II. METHODOLOGY

Aggregate shape refers to its three-dimensional geometry, but as it is difficult to represent irregular three-dimensional bodies, it is more convenient to define certain geometric characteristics of these bodies, such as elongation, flatness, cubicity, sphericity and angularity [6].

According to studies by [2,21–23], commonly employed methods to determine aggregate shape are based in the measuring of fragment dimensions through projection lines that define length, width and thickness.

Considering the ideal shape in the crushing process and exact dimensions (imagining a perfect shape), the shape of coarse aggregate can be classified according to its length/thickness and width/thickness ratios.

For the analysis of a given aggregate, its axes are defined according to [11], in which the greatest dimension obtained is referred to as length; the intermediate dimension as width, and the smallest dimension as thickness. Classification of crushed coarse aggregate is derived from the degree of particle cubicity, and, according to Silva and Geyer [10], coarse aggregate shape can be classified as cubical, elongated, rod or blade.

Table 1 Shape index determination[10]

| Shape  | Ratio    | Index  |
|--------|----------|--------|
| Cubical| l/t< and w/t< | 18 mm  |
| Elongated| l/t> and w/t< | 18 mm  |
| Rod    | l/t> and w/t>  | 24 mm  |
| Blade  | l/t> and w/t>  | 30 mm  |

According to the analysis in [9], aggregate of cubical shape is considered ideal, aggregates of elongated and rod shape are considered acceptable and aggregate of blade shape is considered inadequate for concrete production.
### III. EXPERIMENTAL PROGRAM

#### 3.1 Aggregate selection

The coarse aggregate selected for the experimental program was granulite from the Anápolis – Goiás quarry, due to its crushing process, rock origin and technical specifications, in line with [24]. This rock is of metamorphic origin and presents a high degree of metamorphism, granoblastic texture and gneissic structure, resembling granite (an igneous rock rich in quartz, feldspar and mica) due to its mineralogy and texture. Aggregate within an interval between 19 mm and 25 mm was used, which best fits the experiment due to its ease of handling.

#### 3.2 Extraction and crushing of coarse aggregate

Extraction of the rock is achieved by open pit blasting. Afterwards, it is transported by trucks over a distance of 500 m to the primary crusher (jaw crusher), and after the primary crushing, it is transported by conveyors to the secondary crusher (cone crusher). The rock is kept in the secondary crushing process until it acquires the desired particle size distribution. Then, it is transported by conveyors to the tertiary crusher (cone crusher) and, when the required grain size is obtained, it is transported by trucks to the end consumer.

#### 3.3 Coarse aggregate analysis

The tests for characterization of particle size distribution, specific mass, unit mass and shape index of the coarse aggregate used in the experiment were done in the Laboratório de Materiais da Escola EEC/UFG (Materials Laboratory of the Civil Engineering School of the Federal University of Goiás), with the following results in regards to particle composition [25–27].
3.4 Coarse aggregate shape classification

Ten samples of 10 kg of coarse aggregate each were prepared and the following sequence was observed: characterization, cataloging and sample separation. Sample characterization was undertaken according to Table 1, followed by cataloging and separation of the aggregate between cubical, elongated, rod and blade shapes, according to [10].

Table 5 presents the classification and separation of the particles between cubical, elongated, rod and blade shapes, based on their dimensions and according to Table 1.

For the first analysis, classification was done according to shape, quantification and weighing of each particle and subsequent measuring of total weight for each shape, with the goal of determining the exact representation of each shape in a 10 kg sample. From the second analysis onward individual weighing of particles was not undertaken.

Table 6 presents the result of aggregate analyses 1 through 5, and Table 7 presents the results of analyses 6 through 10. All analyses consisted of 10 kilograms of the selected aggregate.

Table 5 Characterization of Sample 1 (10 Kg)

| Shape    | Number of aggregates | Index | Weight (kg) | %    |
|----------|----------------------|-------|-------------|------|
| Cubical  | 331                  | 15 mm | 3.35        | 33.50% |
| Elongated| 363                  | 21 mm | 3.11        | 31.10% |
| Rod      | 204                  | 27 mm | 1.61        | 16.10% |
| Blade    | 365                  | 60 mm | 1.93        | 19.30% |
| TOTAL    | 1,263 (aggregates)   | 32 mm | 10.00       | 100.00% |

Table 6 Comparison of coarse aggregate samples 1 through 5 according to shape

| Shape    | Sample 1 (Weight (kg)) | Sample 2 (Weight (kg)) | Sample 3 (Weight (kg)) | Sample 4 (Weight (kg)) | Sample 5 (Weight (kg)) |
|----------|------------------------|------------------------|------------------------|------------------------|------------------------|
| Cubical  | 3.35                   | 3.29                   | 3.1                    | 3.09                   | 3.20                   |
| Elongated| 3.11                   | 3.19                   | 3.21                   | 3.19                   | 3.21                   |
| Rod      | 1.61                   | 1.70                   | 1.95                   | 1.79                   | 1.65                   |
| Blade    | 1.93                   | 1.81                   | 1.72                   | 1.93                   | 1.94                   |
### IV. CONCRETE PRODUCTION

The chosen aggregates for concrete production were the one with cubical shape, considered ideal, with shape index length/thickness and width/thickness of 15 mm, and the one with blade shape, considered inadequate, with shape index length/thickness and width/thickness of 60 mm.

IPT’s (Institute of Technological Research) dosing method was used for concrete production and subsequent analysis of mixes with respect to compressive strength of 10x20 cm specimens at 7, 14 and 28 days, diametral compressive strength of 10x20 cm specimens at 28 days, and modulus of elasticity of a 15x30 cm specimen at 28 days.

| Shape    | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|----------|----------|----------|----------|----------|-----------|
| Cubical  | 3.30     | 3.25     | 3.10     | 3.09     | 3.35      |
| Elongated| 3.12     | 3.03     | 3.25     | 3.50     | 3.14      |
| Rod      | 1.80     | 1.76     | 1.69     | 1.55     | 1.80      |
| Blade    | 1.78     | 1.96     | 1.96     | 1.86     | 1.71      |

Fig. 6: Images of particles according to their classification – cubical shape (Index 1,52:1)

Fig. 7: Images of particles according to their classification – blade shape (Index 6,7:1)

4.1 Concrete dosing

Three different concrete mixes were produced for each aggregate shape: a 1:3,5 mix with high cement consumption, a 1:5 mix with moderate cement consumption, and a 1:6,5 mix with low cement consumption. The goal was to assess the influence of aggregate in different situations: dry material content, binder content, w/c ratio and concrete strength.

Mortar content for the cubical shape aggregate was determined in laboratory (alpha at 0,52). As aggregate shape index increases, so does the irregularity of coarse aggregate; thus, the value of alpha was changed in +0,03 for the blade shape (alpha at 0,55). This procedure was necessary to maintain the same finish in concrete with different aggregate irregularity indices. Table 8 Dry material amount – Cubical aggregate mixes and Table 9 Dry material amount – Blade-shaped aggregate mixes present the dry material amounts for the cubical and blade-shaped aggregate mixes.
Table 8 Dry material amount – Cubical aggregate mixes

| Mix  | cement | coarse sand | gravel 1 | Cement (kg/m³) |
|------|--------|-------------|----------|---------------|
| 1:3.5 | 1      | 1.34        | 2.16     | 473.7         |
| 1:5   | 1      | 2.12        | 2.88     | 355.8         |
| 1:6.5 | 1      | 2.90        | 3.6      | 285.3         |

Table 9 Dry material amount – Blade-shaped aggregate mixes

| Mix  | cement | coarse sand | gravel 1 | Cement (kg/m³) |
|------|--------|-------------|----------|---------------|
| 1:3.5 | 1      | 1.47        | 2.025    | 464.0         |
| 1:5   | 1      | 2.30        | 2.70     | 348.8         |
| 1:6.5 | 1      | 3.12        | 3.37     | 274.9         |

Fresh concrete tests followed the standards of [28] for determination of consistency by slump test. Results of the conic frustum slump were obtained by dosing the concrete without additives. Only water was used to adjust the workability of the concrete, until it led to a slump of the conic frustum of 10 ± 2 cm. Table 10 and Table 11 present the w/c ratio and slump test result for the cubical and blade shapes.

Table 10 w/c ratio and slump test – cubical shape

| Mix  | w/c  | Slump test |
|------|------|------------|
| 1:3.5| 0.426| 10 cm      |
| 1:5  | 0.544| 10 cm      |
| 1:6.5| 0.657| 9 cm       |

Table 11 w/c ratio and slump test – blade shape

| Mix  | w/c  | Slump test |
|------|------|------------|
| 1:3.5| 0.468| 10 cm      |
| 1:5  | 0.598| 10 cm      |
| 1:6.5| 0.785| 9 cm       |

V. COMpressive strength results

To assess the compressive strength of the concrete, compression tests were done according to [29], in order to determine concrete performance at 7, 14 and 28 days of age of 10x20 cm cylindrical specimens. A sulfur surface capping was used in order to regularize the surface of the cylindrical specimen for breaking in the press. Table 12 and

Table 12 Concrete compressive strength – cubical shape

| Mix  | 7 days | 14 days | 28 days |
|------|--------|---------|---------|
| 1:3.5| 26.04 MPa | 31.71 MPa | 36.35 MPa |
| 1:5  | 21.46 MPa | 25.41 MPa | 26.23 MPa |
| 1:6.5| 15.09 MPa | 17.38 MPa | 18.72 MPa |

Table 13 show the result of concrete compression with cubical and blade-shaped aggregate.

Table 13 Concrete compressive strength – blade shape

| Mix  | 7 days | 14 days | 28 days |
|------|--------|---------|---------|
| 1:3.5| 25 MPa | 26 MPa  | 31.2 MPa|
| 1:5  | 15.8 MPa | 17.7 MPa | 20.1 MPa|
| 1:6.5| 9.1 MPa | 11.1 MPa | 16.9 MPa|

VI. TENSILE STRENGTH BY DIAMETRAL COMPRESSION RESULTS

Tensile strength by diametral compression tests of 10x20 cm cylindrical specimens at 28 days were undertaken according to the norm [30]. Table 14 Results of tensile strength by diametral compression tests at 28 days presents the response of the concrete to diametral compression at 28 days for the cubical and blade shapes.

Table 14 Results of tensile strength by diametral compression tests at 28 days

| Mix  | Cubical Shape | Blade Shape |
|------|---------------|-------------|
| 1:3.5| 12.5 MPa      | 12.9 MPa    |
| 1:5  | 10.9 MPa      | 9.5 MPa     |
| 1:6.5| 8.0 MPa       | 5.9 MPa     |

VII. MODULUS OF ELASTICITY RESULTS

Modulus of elasticity tests of cylindrical specimens at 28 days were done with respect to procedures established by the norm [31]. A sulfur surface capping was used in order to regularize the surface of the cylindrical specimen for breaking in the press. Table 15 and Table 16 present the modulus of elasticity results for cubical and blade shapes.

Table 15 Modulus of elasticity results for cubical shape

| Mix  | MPa   | GPa  |
|------|-------|------|
| 1:3.5| 34.6  | 23.3 |
| 1:5  | 25.3  | 18.2 |
| 1:6.5| 18.2  | 7.5  |
VIII. ANALYSES AND DISCUSSION OF RESULTS

8.1 Analysis of cubical shape and blade shape aggregates

Based on the results, the smaller the particle size, the greater its irregularity. Therefore, for an aggregate with particle size between 19 mm and 25 mm to be classified as a good quality aggregate, with continuous and well graded particle size distribution, a certain quantity of particles of decreasing order is required in order to fit the ideal particle size distribution curve.

Table 17 and Graph 2 present the particle size distribution test results for cubical aggregate, which approached the ideal particle size distribution, with 99% of particles retained in sieves with openings of 25, 19, 12.5 and 9.5 mm.

Table 16 Modulus of elasticity results for blade shape

| Mix  | MPa  | GPa |
|------|------|-----|
| 1:3.5| 27.6 | 19.7|
| 1:5  | 19.6 | 32.8|
| 1:6.5| 12.2 | 44.3|

Table 17 Particle size distribution results for cubical shape

| Opening | Sieves | Weight retained (g) | % retained |
|---------|--------|---------------------|------------|
|         | Simple | Cumulative          |            |
| 75      | 0      | 0                   | 0          |
| 63      | 0      | 0                   | 0          |
| 50      | 0      | 0                   | 0          |
| 37.5    | 0      | 0                   | 0          |
| 31.5    | 0      | 0                   | 0          |
| 25      | 0      | 0                   | 0          |
| 19      | 4456   | 45                  | 45         |
| 12.5    | 5450   | 55                  | 99         |
| 9.5     | 87     | 1                   | 100        |
| 6.3     | 4      | 0                   | 100        |
| 4.75    | 1      | 0                   | 100        |
| 2.36    | 0      | 0                   | 100        |
| Pan     | 2      | 0                   | 100        |
| TOTALS | 10000  | 100                 | -          |

Graph 2 Cubical aggregate particle size distribution

Table 18 and Graph 3 present the particle size distribution test results for blade-shaped aggregate, which differed from the ideal particle size distribution, with 98% of particles retained in sieves with openings of 19, 12.5 and 9.5 mm.
Table 18 Particle size distribution results for blade shape

| Opening | Retained weight (g) | % retained |
|---------|---------------------|------------|
| Sieves (mm) | Simple | Cumulative | Simple | Cumulative |
| 75 | 0 | 0 | 0 |
| 63 | 0 | 0 | 0 |
| 50 | 0 | 0 | 0 |
| 37.5 | 0 | 0 | 0 |
| 31.5 | 0 | 0 | 0 |
| 25 | 0 | 0 | 0 |
| 19 | 1244 | 12 | 12 |
| 12.5 | 7654 | 77 | 89 |
| 9.5 | 879 | 9 | 98 |
| 6.3 | 200 | 2 | 100 |
| 4.75 | 12 | 0 | 100 |
| 2.36 | 3 | 0 | 100 |
| Pan | 8 | 0 | 100 |
| TOTALS | 10000 | 100 | - |

Graph 3 Blade-shaped aggregate particle size distribution

Table 19 Characterization results of cubical and blade shapes presents the test results for cubical and blade-shaped aggregates used for concrete production.

Table 19 Characterization results of cubical and blade shapes

| Test | Cubical | Blade | Norm |
|------|---------|-------|------|
| Fineness modulus | 7.58 | 7.10 | NBR NM 248 (ABNT, 2003) |
| Maximum characteristic size (mm) | 25 | 25 | NBR NM 248 (ABNT, 2003) |
| Unit mass (kg/dm³) | 1.413 | 1.279 | NBR 7251 (ABNT, 1982) |
| Specific mass (kg/dm³) | 2.57 | 2.72 | NBR NM 53 (ABNT, 2003) |
| Aggregate shape index (mm) | 15 | 60 | NBR 7809 (ABNT, 2008) |
It can be observed that the crushing process significantly influences the physical properties of the crushed aggregate, such as specific mass, unit mass, fineness module and shape index.

It is important to note that coarse aggregates with blade shape or inadequate particle size distribution do not fit the dosing methods, which are based, for instance, on ideal particle size distribution curves, and influence the properties of concrete and its cement consumption [7].

8.2 Fresh concrete

As the amount of mortar in a mix increases, it is necessary to increase the water/binder ratio in order to maintain the same workability. Concrete with blade-shaped aggregate presented higher water consumption when compared to concrete with cubical aggregate, to maintain the desired workability. Graph 4, Graph 5 and Graph 6 present the w/c ratio of concrete mixes produced with cubical and blade-shaped aggregates.

8.3 Compressive strength

Concretes with ideal (cubical) shape used for the experimental program have 100% of particles with an average ratio of 1.5:1. Concretes with inadequate (blade) shape, in contrast, have 100% of particles with an average ratio of 6:1. Graph 7, Graph 8 and Graph 9 present the compressive strength results for the 1:3.5 1:5 and 1:6.5 mixes.
The 1:5 and 1:6.5 mixes with ideal (cubical) aggregate showed the best results for all ages. However, both aggregate shapes presented a similar strength projection.

The 1:3.5 mix with cubical aggregate presented an increase in strength, from 7 to 28 days of age, of 9.2 MPa, followed by the 1:5 mix with an increase of 3.49 MPa and the 1:6.5 mix with the smallest increase of 3.14 MPa. For the compressive strength of blade-shaped aggregate concrete, the 1:5 mix showed an increase in strength, from 7 to 28 days of age, of 1.6 MPa, followed by the 1:3.5 mix with an increase of 1.34 MPa and the 1:6.5 mix with the smallest increase of 1.12 MPa.

Compressive strength of ideally shaped (cubical) aggregate presented better performance due to the compaction index of the aggregate, which, in general, has continuous particle size distribution, thus favoring the concrete and making it denser and less porous.

Graph 10 and Graph 11 present the Abrams curve for w/c ratio of the 1:3.5, 1:5 and 1:6.5 mixes at 7, 14 and 28 days old, for cubical and blade-shaped aggregates.
Cubical aggregate presents better characteristics for use in concrete when compared to blade-shaped aggregate. Cubical aggregate is denser, stronger and shows better performance than inadequate aggregates, making the mortar more fragile than the aggregate, and, due to these properties, fractures or cracks start in the transition zone between mortar and aggregate when the concrete is submitted to stress. The inadequate aggregate shape is highly flat, causing a build-up of voids in the concrete microstructure, making it fragile and brittle, ultimately weakening its microstructure.

Studies done by [32] indicate that the influence of aggregate properties on workability and mechanical strength decreases with the increase of cement amount, and according to studies proposed by [9], which consider cubical aggregate as ideal coarse aggregate and blade-shaped aggregate as inadequate for concrete production, and its influence on the mechanical properties of concrete, there is a loss of concrete properties with the increase of inadequate aggregate amount. However, some researchers such as [20] suggest that concrete strength is affected if more than 50% of the aggregate has a 5:1 shape index (blade shape), which can lead to low compaction and high void rate, resulting in low strength and lower durability concrete. [9], in contrast, reports that a proportion higher than 20% of inadequate (blade-shaped) aggregate affects concrete performance with respect to compressive strength, tensile strength and modulus of elasticity.

8.3 Tensile strength by diametral compression
For the tensile strength by diametral compression tests, the 1:3,5 concrete mix with inadequate (blade) shape aggregate showed better performance than the concrete with ideal (cubical) aggregate. However, there was a sharper decrease in the concrete with inadequate (blade) shape for mixes with lower cement amount. Concrete with ideal (cubical) aggregate presented better performance for mixes with moderate (1:5) and low (1:3,5) cement consumption. Graph 12 and Graph 13 present the tensile strength test results for the 1:3,5, 1:5 and 1:6,5 mixes.

The negative influence of the physical characteristics of inadequate aggregate is greater than that of the cement. The inadequate particle’s shape is fragile and when submitted to stress it tends to rupture as a fixed beam, making the coarse aggregate the weak point of the concrete microstructure.

With respect to tensile strength by diametral compression, the concrete made with inadequate aggregate showed the best performance, with an Fck of 12.86 MPa for the 1:3,5 mix. This result can be attributed to the greater surface area of inadequate aggregate, which leads to higher adherence between the aggregate and the mortar.

Due to the greater surface area of the inadequate (blade-shaped) aggregate, a better contact region between mortar and coarse aggregate is achieved. Inadequate aggregates, for being slimmer and flatter, function as anchoring areas in the microstructure of concrete when submitted to stress. This effect occurs in mixes with high cement consumption.

8.4 Elasticity modulus
For the concrete made with cubical and blade-shaped aggregates, it was observed that with the increase of w/c ratio there was an increase in the concretes’ modulus of elasticity and a decrease in the compressive strength. Graph 14 and Graph 15 show that a higher w/c ratio results in a lower compressive strength and a higher modulus of elasticity. This is attributed to the high amount of pores caused by high water consumption in the concretes.
Concrete with a high rate of voids in its microstructure can suffer elastic deformations, causing microdeformations in its interior. By using the pore network in the concrete microstructure, it can settle before rupturing. Graph 16 compares the modulus of elasticity of the cubical aggregate concrete and the blade-shaped aggregate concrete at 28 days.

The 1:3.5 mix with cubical aggregate was determined to have a higher modulus of elasticity than the one with blade-shaped aggregate. This result can be attributed to the high cement consumption along with the good performance of the ideal shape, which produces a denser and more compact concrete, allowing it to reach high strengths before rupturing. For the remaining mixes, with moderate and low cement consumption, the concrete with blade-shaped aggregate presented lower compressive strength and higher modulus of elasticity when compared to that with cubical aggregate. According to studies performed by [33–35], this result is due to the influence of inadequate aggregate on the mechanical properties of concrete, such as the increase of porosity that causes greater elastic deformation before the rupture of concrete at low strengths.

IX. CONCLUSION

According to analysis of the concrete, the ideal aggregate with cubical shape has better performance when compared to the blade shape in concrete production, due to aggregate shape and good particle size distribution, which allows good packing of coarse and fine aggregates, eliminating voids in the microstructure of the concrete and improving the properties of both fresh and hardened concrete.

Concrete produced with inadequate aggregate with blade shape produces higher void rates caused by the accumulation of bubbles. These voids provide elasticity to the concrete, functioning as tension concentrators and allowing the concrete to work when subjected to stress. However, it makes the concrete more fragile, causing it to rupture at low resistance.

With data from monitored tests of traction, compression and modulus of elasticity, where there is a record of the deformations presented for each trace of the elongated-lamellar shape. The behavior stops being linear just before the last load. This behavior is due to the progressive microcracking that occurs initially at the coarse aggregate interface and the cement paste, and subsequently spreads throughout the concrete, presenting greater elastic deformations before rupture, in contrast to the cubic shape that presents few elastic deformations before rupture of concrete.

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