Article

Influence of Maximum Aggregate Grain Size on the Strength Properties and Modulus of Elasticity of Concrete

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Abstract: Depending on the dimensions of concrete elements, aggregates of different grain sizes are used for the building structures. Taking this fact into account, the authors of the paper have undertaken in their work an issue concerning the analysis of the influence of maximum aggregate grain size on the strength properties and modulus of elasticity of concrete. This is also due to the fact that few published research results are available in this area. In this paper, the influence of the maximum grain size on the basic strength and deformation properties of concrete is discussed. The research concerns both concretes and gravel aggregates used for their construction with maximum grain sizes of 8 mm, 16 mm and 31.5 mm. The values of the compressive and splitting tensile strength, brittleness and modulus of elasticity of concretes with \( \frac{w}{c} = 0.45 \) were analysed. The analysis showed that the strength properties are proportional not only to the maximum size of aggregate grain, but also to the crushing strength of the aggregate. There were no analogous relations found with respect to the modulus of elasticity of the tested concretes. Tensile strength was particularly susceptible to the observed changes.

Keywords: the maximum aggregate grain size; modulus of elasticity; compressive and tensile strength of concrete; aggregate crushing value; gravel aggregate; interfacial transition zone

1. Introduction

Concrete is a multi-phase and heterogeneous composite whose behaviour varies according to the load applied [1]. It consists of the cement matrix, aggregates and mineral and chemical admixtures. Many factors are responsible for its durability and safety of concrete and reinforced concrete structures, including compression strength, tensile strength, modulus of elasticity and brittleness of concrete [2–4]. This feature is particularly important if concrete structures with minor defects in their structure are taken into account. If the construction has such defects in its structure, it may contribute to localised damage caused by loading with local discontinuities and sudden differences in the mechanical properties of the material. Within the micro-cracks or discontinuities of the crystal lattice, local stress concentrations may occur, which may contribute to the development of localised damage and, consequently, even to the failure of the structural component [1]. The most sensitive area is the transition zone of cement paste-coarse aggregates. The increased porosity of the area should also be emphasised [5] and the fact that sedimentation pores may form underneath the coarse aggregate grains. The formation of these pores is encouraged by the size of the coarse aggregate grains.

Damage to the structure of cement composites is a complex phenomenon, as it is very difficult to predict the stages of this process that may contribute to the destruction of the concrete element. The internal structure of the cement composite, which includes, among other things, aggregates,
their distribution and diameter, is the basic factor that can cause an increase in damage [6]. In addition, about 75% of the concrete content is occupied by aggregates [7]. Most of which are coarse aggregates around 60–70% by volume.

The connection between the matrix and the coarse or fine aggregate in the concrete is the so-called interfacial transition zone (ITZ) [5]. According to many researchers, the mechanical properties and compressive strength of concrete are influenced by different sizes and types of aggregates [1,7,8]. Ferdous et al. [9] provided the existing models for compressive strength and elastic modulus. In paper [10], it is shown, among other things, that the tensile strength is influenced by the grain size of the aggregate used for concrete production. Piasta et al. [11] found that the type of coarse aggregate, as well as the aggregate shape, surface texture, porosity, ITZ size, and chemical bonding between the cement and the aggregate, affects the test subject deformation characteristics of ordinary concrete. The research has clearly shown that the worst deformation properties were obtained in case of concretes with granite aggregates. In the case of concretes with basalt, granite and pebble aggregates, a significant overestimation of normal modulus of elasticity values was found. Mahmoud et al. [12] determined the effect of the grain size of the aggregate used in concrete on the mass attenuation coefficient. It was specified that with the increase in grain size, the coefficient decreased by 4%. Neville [13] found that the larger the size of the aggregate, the less water is needed for the concrete mixture. As a result, the water-cement ratio is lowered and the strength of the concrete increases. However, in his work, he did not investigate what will happen if the same volume of cement paste is kept. Additionally, it is important to consider the water absorption capacity of the aggregates because highly absorptive aggregates can drastically affect water demand. Khotbehsara et al. [14] showed that the aggregate size has an impact on the mechanical properties.

The modulus of elasticity of concrete is directly related to structural deformations and may be defined on the basis of ASTM C469 standard [15]. These deformations can contribute to excessive deformations, which are a direct cause of cracks in concrete composites. The modulus of elasticity, which indicates the stiffness of the material and is associated with its strength, is one of the most important properties of concrete [6]. Determining the modulus of elasticity of concrete is not an easy task as the material is not completely flexible. Although its behaviour is flexible with low loads ranging from 30% to 40% of its final load capacity. Due to the non-linear behaviour of the stress-strain curve ($\sigma$-$\varepsilon$) of concrete, it is difficult to determine exactly the specific value of the static modulus of elasticity [16]. Since concrete is quasi-brittle, the stress-strain behaviour starts to be non–linear after 50–70% of the peak load.

The parameters affecting the modulus of elasticity of concrete depend on the characteristics of the aggregate matrix, cement paste, testing parameters and transition zone. According to [17], the weakest concrete components are hardened cement paste and the transition zone between cement paste and coarse aggregate, not the coarse aggregate itself. The study [18] examined the effect of four types of coarse aggregates—dolomitic and quartzitic limestone, steel slag and calcareous limestone—on the compressive strength and modulus of elasticity of high strength concrete. The influence of the type of coarse aggregate has more effect on the modulus of elasticity than on compression strength.

Based on the research, it was observed that the mineralogical composition of coarse aggregate strongly influences the modulus of elasticity of concrete. Indeed, the modulus of elasticity can be up to 30% different, depending on the type of aggregate and concrete composition. According to the data contained in the paper [19], the modulus of elasticity of concrete increases with its curing. The modulus of elasticity increases faster than the concrete’s compressive strength, due to the higher density of the interfacial transition zone. The porosity of the matrix affects the individual strength of the cement paste, which results in a change in the modulus of elasticity [20].

The greatest difficulty in using theoretical models to determine the modulus of elasticity of concrete is that they require prior knowledge of the modulus of elasticity of cement paste and aggregates. Therefore, to solve this problem, normative empirical methods have been developed, which estimate the modulus of elasticity value based on the concrete’s compressive strength [20].
To the best of our knowledge, in the literature, there are only a few examples of research evaluating the influence of maximum aggregate grain size on the strength properties and modulus of elasticity. Therefore, this study focuses on the assessment of the above correlations.

2. Materials and Methods

2.1. Materials

The concrete was prepared using CEM I 42.5 R Portland cement. The technical parameters of applied Portland cement are presented in Table 1. The cement used in the tests meets the requirements set out in the EN 197-1 [21] standard.

| Parameters                        | Unit         | Value |
|-----------------------------------|--------------|-------|
| Specific surface                  | (cm²·g⁻¹)    | 4124  |
| Initial setting time              | (min)        | 184   |
| Loss on ignition                  | (%)          | 3.33  |
| Compressive strength              | (MPa)        | 30.1  |
| after 2 days                      |              | 60.2  |
| Density                           | (g·cm⁻³)     | 3.08  |
| Volume stability                  | (mm)         | 1.00  |
| SO₃ content                       | (%)          | 2.95  |
| Cl content                        | (%)          | 0.089 |
| Insoluble residue                 | (%)          | 0.57  |

Washed natural quartz sand (QS) (0 ÷ 2 mm) and gravel (2 ÷ 31.5 mm) was used to prepare concrete samples.

QS density was 2.65 g·cm⁻³, while the properties of gravel aggregate were included in Tables 2 and 3 show sieve analysis of the fine and coarse aggregates.

| Fraction | Specific Density (kg dm⁻³) | Bulk Density (kg dm⁻³) | Porosity (%) | Aggregate Crushing Value (ACV, %) | Content of Irregular Grains (Zni, %) | Content of Mineral Dusts (Zpi, %) |
|----------|-----------------------------|------------------------|--------------|----------------------------------|-------------------------------------|----------------------------------|
| 2 ÷ 8    | 2.72                        | 2.64                   | 7.9          | 0.7                              | 0.22                                | 0.22                             |
| 8 ÷ 16   | 2.72                        | 2.64                   | 2.90         | 10.3                             | 4.1                                 | 0.20                             |
| 16 ÷ 31.5| 2.72                        | 2.64                   | 12.9         | 3.9                              | 0.13                                |                                  |

Table 2. Tests results of gravel properties.

| Sieve Size mm | Sand | Gravel Aggregate |
|---------------|------|------------------|
|               | 2 ÷ 8 mm | 2 ÷ 16 mm | 2 ÷ 31.5 mm |
| 31.5          | 100    | 100       | 100       |
| 16            | 100    | 100       | 40        |
| 8             | 100    | 100       | 20        |
| 4             | 100    | 40        | 10        |
| 2             | 100    | 0         | 0         |
| 1             | 94     | -         | -         |
| 0.5           | 55     | -         | -         |
| 0.25          | 13     | -         | -         |
| 0.125         | 2      | -         | -         |
Three concrete mixtures were prepared with the composition presented in Table 4. The quantities of concrete mixture components were determined experimentally, with the assumption of a \( \frac{w}{c} \) value of 0.45 (minimum permissible maximum value regardless of the exposure class according to EN 206 [22]) and a slump class S1/S2, according to EN 206 [22]. The sand point of the crumble stack determined experimentally was 37.3% by weight. As shown in Table 4, the concrete made differed in the quantities and fractions of gravel aggregates used in their manufacture. Depending on the concrete used, the crossbow fractions of the samples were described as follows: fraction \( 2 \div 8 \) mm–GC2/8, fraction \( 2 \div 16 \) mm–GC2/16 and fraction \( 2 \div 31.5 \) mm GC2/31.5. A superplasticizer based on polycarboxylic ether combined with calcium lignosulfonate has also been added to all earnings.

Table 4. Composition of concrete mixtures.

| Components            | Unit   | GC2/8 | GC2/16 | ACV 1 | GC2/31.5 | ACV 1 |
|-----------------------|--------|-------|--------|-------|----------|-------|
| CEM I 42.5R cement    | (kg·m\(^{-3}\)) | 364   | 364    | 364   |          |       |
| Quartz sand (0 \( \div 2 \) mm) | (kg·m\(^{-3}\)) | 708   | 708    | 708   |          |       |
| Gravel (2 \( \div 4 \) mm) | (kg·m\(^{-3}\)) | 476   | 119    | 60    |          |       |
| Gravel (4 \( \div 8 \) mm) | (kg·m\(^{-3}\)) | 714   | 7.9    | 357   | 178      |       |
| Gravel (8 \( \div 16 \) mm) | (kg·m\(^{-3}\)) | -     | -      | 714   | 9.5      | 238   |
| Gravel (16 \( \div 31.5 \) mm) | (kg·m\(^{-3}\)) | -     | -      | -     | -        | 714   |
| Superplasticizer      | (kg·m\(^{-3}\)) | 2.548 | 1.49   | 1.048 |          |       |
| Water                 | (kg·m\(^{-3}\)) | 165   | 165    | 165   |          |       |

1 ACV—aggregate crushing value for aggregates with grain diameters over 4 mm.

2.2. Methods

For each fraction of aggregates, the crushing strength, the content of irregular grains and mineral dust, as well as the bulk and specific density from which the total porosity was calculated were determined.

The crushing strength of aggregates was determined using the so-called aggregate crushing value (ACV) according to the PN-B-06714-40 standard [23], similarly as in the BS 812 standard [24]. An aggregate sample in a steel cylinder with an inside diameter of 150 mm was loaded with a force of 200 kN. The test is carried out on \( 2 \div 8 \) mm, \( 8 \div 16 \) mm and \( 16 \div 31.5 \) mm fractions. The aggregate crushing value is defined as the percentage of grains crushed into grains smaller than \( \frac{1}{4} \) of the lower sieve size of a given fraction. The ACV can be used to classify the aggregate and assess its suitability for the proper concrete.

The content of irregular grains, i.e., flat and elongated grains (with the proportion of the smallest to the largest grain size exceeding 1:3) was determined according to the PN-B-06714-16 standard [25].

The mineral dusts content (percentage of the aggregate of grains smaller than 0.063 mm i.e., clays, clayey particles, etc.) was determined according to the PN-B-06714-13 standard [26].

The specific density was tested using the pycnometric method, after grinding the aggregate to dimensions smaller than 0.08 mm. The air contained between the grains of powdered material was removed by inserting a pycnometer in a vacuum chamber, and reducing the pressure to 2.33 kPa.

The apparent density was tested on the basis of the EN 1097-6 standard [27]. The total porosity was calculated from the value of apparent density and specific density.

The air content of the fresh concrete mix has been determined for each concrete, using the pressure method based on the EN 12350-7 standard [28]. The consistency was tested according to the EN 12350-2 [29] standard.

To determine the compressive strength and splitting tensile strength after 28 days of curing, 36 cubic samples with the edge length of 150 (6 for each concrete) [30,31]. Cylindrical specimens with a diameter of 150 mm and a height of 300 mm were used to determine the elastic modulus (18 specimens, 6 for each concrete) [32].
According to the EN 12390-3 [30] standard, the compressive strength test was carried out on cubic samples with an edge length of 150 mm. The values of elastic modulus were determined on the basis of the EN 12390-13 [32] standard (Figure 1). The splitting tensile strength was determined in accordance with the EN 12390-6 [31] standard on concrete blocks with an edge length of 150 mm.

![Figure 1. The test stand for testing the static modulus of elasticity.](image)

The concrete brittleness (K) can be calculated from the following formula:

\[ K = \frac{f_{ct,ax}}{f_c}, \tag{1} \]

where: \( f_c \) — compressive strength (MPa), \( f_{ct,ax} \) — axial tensile strength (MPa).

The splitting tensile strength was determined in the presented tests. For the formula to find its application, the values of splitting tensile strength should be recalculated according to the below formula [33]:

\[ f_{ct,ax} = 0.9 \cdot f_{ct,sp}, \tag{2} \]

where: \( f_{ct,ax} \) — axial tensile strength (MPa), \( f_{ct,sp} \) — splitting tensile strength (MPa).

3. Results and Discussion

Generally, when assessing the quality of the aggregate used in concrete, the requirements of the PN-B-06712 [34] standard can be referred to. It should be noted that the requirements contained in this standard have been developed by the Polish Committee for Standardization on the basis of several dozen years of testing experience and are still used by bridge or road construction. According to this standard, the basic property classifying the quality of aggregate is its crushing strength, which is measured by the so-called aggregate crushing value (ACV). On the basis of its value, classification is made into the so-called aggregate brand, on which, in turn, the limit requirements relating to the remaining properties of the aggregate, such as the content of irregular grains or content of mineral dusts, depend. Taking into account the average ACV values of the gravel aggregate used for the tested concretes (Table 4), it is classified to the highest brand 30 (ACV value < 12%), according to the PN-B-06712 [34] standard. The other results of the properties, which can directly affect both the strength properties of concrete and the adhesion of cement paste to aggregate grains, should be considered as very good, the content of irregular grains is significantly lower than the 20% limit and the content of mineral dusts is lower than the 1.5% limit (Table 2).
Table 5 shows the physical properties of gravel concrete, while, in Table 6, the mechanical properties are shown. The obtained results were compared to the values quoted on the basis of the EN 1992 standard [33] (Table 6).

When assessing the air content in the tested mixtures, slight differences were found, which did not exceed 0.3%, and it was considered that they do not affect the mechanical properties of the tested concrete. Similarly, for concrete mixture consistency, the differences did not exceed 1.0 cm (Table 5).

**Table 5. Properties of gravel concrete.**

| Type of Concrete | Air Content (%) | Slump Test (cm) |
|------------------|-----------------|-----------------|
| GC2/8            | 2.40            | 5.0             |
| GC2/16           | 2.60            | 4.0             |
| GC2/31.5         | 2.70            | 4.0             |

The concrete strength classes determined from the results of the compressive strength tests are the same, and correspond to the same class C40/50 (Table 6). The difference between extreme \( f_{cm} \) values is 2.1 MPa, and no statistically significant differences in compression strength results were also confirmed by ANOVA test results (\( p = 0.22 > p = 0.05 \)).

Different relations were found between splitting tensile strengths—the greater the maximum size of aggregate grain (\( D_{\text{max}} \)) the lower the value of \( f_{ctm,sp} \) of concrete. The difference between the extreme values of \( f_{ctm,sp} \) is 1.73 MPa and the GC2/31.5 concrete splitting tensile strength is 34.5% lower than the GC2/8 concrete strength. The significant differences in splitting tensile strength values were confirmed by ANOVA test results. The value of \( p = 5.6 \times 10^{-9} \) is significantly lower than \( p = 0.05 \), which clearly and strongly confirms the statistically significant differences between the concrete tensile strength results. The least significant difference (LSD) test showed that each pair of averages differs significantly from each other (differences are statistically significant).

**Table 6. Mechanical properties of the concretes.**

| Type of Concrete/Descriptive Statistics | Compressive Strength \( f_{cm} \) (MPa) | Strength Class | Splitting Tensile Strength \( f_{ctm,sp} \) (\( f_{ctm,ax} \)) (MPa) | EN 1992 [33] | Elastic Modulus \( E_{cm} \) (GPa) | EN 1992 [33] | K (-) |
|----------------------------------------|----------------------------------------|----------------|-------------------------------------------------|----------------|---------------------------------|----------------|------|
| GC2/8                                  | Mean 54.0                              | C40/50         | 5.01 (4.51)                                     | 33.5           | 0.09                            | 67             |      |
|                                        | CV 2.8                                 |                | 7.2                                            | 3.5            | 2.6                            | 35             | 0.06 |
|                                        | SD 1.52                                |                | 0.36                                          | 3.5            | 0.86                           | 35             | 0.5  |
| GC2/16                                 | Mean 54.7                              | C40/50         | 3.69 (3.32)                                     | 33.1           | 0.06                            | 5.0            |      |
|                                        | CV 4.8                                 |                | 3.5                                            | 3.5            | 1.8                            | 35             | 0.003|
|                                        | SD 2.61                                |                | 0.13                                          | 3.5            | 0.58                           | 35             | 0.03 |
| GC2/31.5                               | Mean 56.1                              | C40/50         | 3.28 (2.95)                                     | 32.7           | 0.05                            | 6.0            |      |
|                                        | CV 5.0                                 |                | 4.6                                            | 3.5            | 4.0                            | 35             | 0.03 |
|                                        | SD 2.81                                |                | 0.15                                          | 3.5            | 1.30                           | 6.0            |      |

CV—coefficient of variation (%), SD—Standard deviation.

The obtained values of \( f_{ctm,sp} \) were compared with the respective values of \( f_{ctm,sp} \) according to the EN 1992 standard [33] corresponding to specific classes of concrete. It was found that the concretes GC2/16 and GC2/31.5 were characterized by lower values by 5% and 16% respectively, i.e., by one and two classes of concrete strength lower. From a practical point of view, this means that increasing the \( D_{\text{max}} \) of the aggregate can cause higher susceptibility to earlier scratches of the element.

The modulus of elasticity of concretes was practically not susceptible to changes caused by different sizes of coarse aggregate. The difference between the extreme values was 0.8 GPa, with the highest \( E_{cm} \) value for GC2/8 being only 1% higher than the lowest modulus of elasticity for the GC2/31.5 concrete. Therefore, the effect of the maximum grain size of the aggregate on the tested values of modulus of elasticity should be treated as insignificant. This was also confirmed by the ANOVA...
test, which shows that the differences between the values of concrete $E_{cm}$ modules are statistically insignificant ($p = 0.43 > p = 0.05$).

By referring the results of the $E_{cm}$ test to the values according to the EN 1992 standard [33], all the specified modules correspond to class C30/37, i.e., by two concrete strength classes below the specified C40/50. However, it should be noted that the modulus of elasticity of concrete is not only dependent on its compressive strength. The influence of the type of coarse aggregate on the value of modulus of elasticity is very strongly visible, which is reflected not only in the EN 1992 standard [33], and also in the literature [35–38]. In particular, this effect may be difficult to assess in the case of gravel aggregates, which are polyminerals with a mineral composition often very different depending on the origin (location of the mine).

The brittleness, i.e., the ratio of the splitting tensile strength to the compressive strength $f_{ctm}/f_{cm}$, of the tested concretes is also varied. A material is considered brittle when the $f_{ctm}/f_{cm}$ ratio is less than 1/8 (0.125) [39]. The lower the $K$-value, the more brittle the material is. The $K$ value calculated on the basis of the EN 1992 standard [33] is 0.07 for all concretes. In the case of two types of aggregates, it was found that the brittleness of the concrete GC2/16 and GC2/31.5 is higher than the value calculated according to standard values (for a given concrete strength class). Only concrete GC2/8, with a brittleness index equal to 0.09, met the requirements calculated on the basis of the EN 1992 standard [33]—it turned out to be less brittle than other concretes (Table 6). In the case of concrete, the matrix, as well as aggregates, are brittle materials. The higher brittleness of concretes GC2/16 and GC2/31.5 may be caused by concrete defects, such as air voids, cracks, discontinuities in the crystal network that may have formed between aggregates of different sizes. Another reason may be that the aggregate used in their manufacture has lower mechanical resistance (Figure 2) than the aggregate used in GC2/8 concrete. The aggregate with the 2 ÷ 8mm fraction has a lower ACV coefficient by about 23% and 63%, compared to the 8 ÷ 16mm and 16 ÷ 31.5mm aggregates, respectively.

![Figure 2. Correlation between aggregate crushing value and aggregate fraction.](image)

In order to explain the differences found in the properties of concrete, the properties of gravel aggregate examined were analysed. The ACV was considered to be the most variable, and its values depend on the thickness of coarse aggregate grains, and there is a very strong correlation between them (Figure 2), with statistically significant differences ($p = 5.6 \times 10^{-5} < p = 0.05$). It should be noted that the increase in the ACV value of the aggregate corresponds to its lower mechanical resistance (lower crushing strength resistance).

For this reason, the potential for relationships between the properties of the concrete and the corresponding ACV values of the aggregate and how correlated they are was analysed.

The strongest correlation was found between the splitting tensile strength $f_{ctm,sp}$ of concretes and ACV values of aggregates (Figure 3). The correlation coefficient $r = 0.91$ indicates a very strong correlation. The correlation shows that the increase in $D_{max}$ of the aggregate and, at the same time, the
decrease in the mechanical resistance of the aggregate (increase in ACV) corresponds to the decrease in the splitting tensile strength.

There is a strong correlation between the compressive strength and ACV values ($r = 0.84$) (Figure 4). The increase in $D_{\text{max}}$ of the aggregate has corresponded to a slight increase in the compressive strength of the concrete. However, it is surprising that in this case, despite the fact that the mechanical resistance of the aggregate significantly decreases, the compressive strength of the concrete increases slightly.

![Figure 3. Correlation between aggregate crushing value and splitting tensile strength of concrete.](image1)

A very weak correlation was found between aggregate crushing value and elastic modulus of concretes (Figure 5). These parameters do not differ significantly statistically.

Analysing the influence of $D_{\text{max}}$ of aggregate on the values of strength properties of the tested concretes, an opposite relation to the commonly accepted one was found, a slight increase in compression strength (within the same concrete strength class) corresponds to a clear decrease in splitting tensile strength.

![Figure 4. Correlation between aggregate crushing value and compressive strength of concrete.](image2)

The relations described above indicate that the influence of $D_{\text{max}}$ of the aggregate on the values of strength properties is greater and more significant for splitting tensile strength. It is widely recognised that the most significant impact on the mechanical properties of concrete is exerted by the interfacial transition zone (ITZ), where the first micro-cracks form under load. As the load increases, micro-cracks propagate, the increasing scratches start to merge and expand until the concrete is destroyed.

In the splitting test, aggregate grains are very often split (cracked), and also in the case of gravel, especially the weaker ones. Therefore, apart from the area of ITZ with increased porosity [5], which
plays the most important role in the destruction, the share of aggregate grains with lower mechanical resistance (higher ACV) will also be significant.

Figure 3. Correlation between aggregate crushing value and splitting tensile strength of concrete.

Figure 4. Correlation between aggregate crushing value and compressive strength of concrete.

Figure 5. Correlation between aggregate crushing value and elastic modulus E of concrete.

Elsharief et al. demonstrated that the reduction of $D_{\text{max}}$ of the aggregate causes the formation of ITZ, with lower porosity around the grains [40].

This explains the results obtained in the tests. The growth of $D_{\text{max}}$ of the aggregate from 8 mm to 31.5 mm resulted in the formation of a more porous ITZ around the aggregate grains in GC2/31.5 and GC2/16 in comparison to ITZ in GC2/8. Simultaneously, with the growth of $D_{\text{max}}$, the mechanical resistance of the aggregate also deteriorated, and the lowest ACV value was determined for the aggregate in the GC2/31.5 concrete. The overlapping of these two factors caused that, despite the same class of all three concretes and similar values of their compressive strength, there was a clear decrease in the splitting tensile strength as the maximum aggregate grain size increased.

Analogous relations to those obtained in this study were obtained by Akçaoğlu et al. [41], but instead of natural aggregate they used steel balls with diameters of 9, 12, 19, 25 and 32 mm, i.e., with very similar $D_{\text{max}}$ to the gravel used in the concretes studied. Low strength concrete (LSC, 25 MPa) and high strength concrete (HSC, 47 MPa) were tested. They also found a significant decrease in tensile strength (to about 15%) as the aggregate size increased, while the compression strength increased only slightly. The observed decrease in tensile strength along with the increase in grain size in both LSC and HSC was justified by the decrease in bond strength. This is due to the increased volume of the aggregate in relation to the total volume of the composite, which makes the significant difference between the elastic modules of the two phases more pronounced, thus creating an increased stress concentration and more micro-cracks near the aggregate. The negative influence of the smooth texture of the aggregate surface on the binding force due to the increased aggregate surface was also emphasized. The smooth surface texture and high modulus of elasticity of the aggregate result in a greater reduction of tensile strength in composites with a lower w/c ratio ($w/c = 0.42$). According to the authors [41], the interfacial bond was considered decisive in the reduction of tensile strength and played a minor role in the influence on the values of the compressive strength. It was found that the tensile strength decreases as the size of the aggregate increases. The rate of tensile strength reduction with increasing size of a single aggregate becomes higher in HSC [41].

In turn, the results of this study and Akçaoğlu et al. [41] differ significantly from the results of the research on mortars and concretes presented by Reinhardt [10]. The tests carried out in the study by Reinhardt [10] showed that when aggregates from 2 mm to 8 mm were used in concrete production, the tensile strength value increased from 2.35 MPa to 2.7 MPa, respectively. This shows a 15% increase in this value. However, when aggregates with a larger diameter of 8 mm to 32 mm were used, the tensile strength of the concrete remained constant at 2.86 MPa. It was found that there is a systematic difference between the strength of mortar (aggregate size up to 4 mm) and concrete (from
8 mm upwards). As noted, whether this conclusion is valid for all types of concrete and aggregate sizes should be confirmed by experiments and numerical simulations, which have not been conducted so far [10].

Figure 6a shows a mathematical/experimental model of the splitting tensile strength of concretes which depends on two other concrete characteristics: \( x_1 \) — compressive strength and \( x_2 \) — aggregate crushing value. The interaction of compressive strength and aggregate crushing value, as described in the three-dimensional graph, indicates that within the tested ranges a higher compressive strength with a lower aggregate crushing value would significantly increase splitting tensile strength. The statistical analysis carried out in the STATISTICA 12 program (StatSoft, Inc., Tulsa, USA) showed that the whole presented regression model is statistically significant. The dependent variable—splitting tensile strength—is explained in 80% using the above model, although the correlation matrix before the analysis indicated that one of the independent variables is statistically insignificant-compressive strength. As can be seen in Figure 6b, very similar relationships occur between splitting tensile strength, elastic modulus and aggregate crushing value. The dependent variable—splitting tensile strength is expressed by two independent variables: \( x_1 \) — elastic modulus and \( x_2 \) — aggregate crushing value. As in the previous case, as \( E_{cm} \) increases and ACV value decreases, splitting tensile strength increases simultaneously. This model also describes 80% of the dependent variable, although initially, the predictor variable \( E_{cm} \) seems to be statistically insignificant.

\[
y = 7.877 + 0.015 \cdot x_1 - 0.488 \cdot x_2 \\
y = 7.401 + 0.028 \cdot x_1 - 0.450 \cdot x_2
\]

Figure 6. Three-dimensional surface plot: (a) the splitting tensile strength (MPa) against the compressive strength (MPa) and the aggregate crushing value (ACV), (b) the splitting tensile strength (MPa) against the elastic modulus (GPa) and the aggregate crushing value (ACV).

4. Conclusions

The following key conclusions can be drawn from this study:

1. The influence of \( D_{\text{max}} \) of the aggregate on the values of strength properties is greater and more significant for splitting tensile strength. Analysing the obtained results, it was found that, with the increase of \( D_{\text{max}} \), the splitting tensile strength of \( f_{\text{ctm,sp}} \) deteriorated-for concrete GC2/31.5 is 34.5% lower than the strength of concrete GC2/8. An increase in aggregate \( D_{\text{max}} \) with a simultaneous decrease in the mechanical resistance of the aggregate (increase in ACV) significantly reduces the tensile strength.

2. Comparing the obtained results of \( f_{\text{ctm,sp}} \) with standard values, it was found that GC2/16 and GC2/31.5 concretes are characterized by 5% and 16% lower values respectively, i.e., one and two
classes of concrete strength lower. This may indicate that an increase in $D_{\text{max}}$ may make the element more susceptible to earlier scratching.

3. The influence of the maximum size of the aggregate grain on the modulus of elasticity was negligible. The changes in the size of the coarse aggregate did not affect the modulus of elasticity of concrete—the $E_{\text{cm}}$ for GC2/8 was only 1\% higher than the GC2/31.5 concrete module, which was the lowest of all.

4. With the growth of $D_{\text{max}}$ of the aggregate, the brittleness of the tested concretes increases.

5. The opposite to commonly accepted relationships have been observed—despite a decrease in the mechanical resistance of the aggregate, the compressive strength of the concrete has increased slightly, and a slight increase in the compressive strength corresponds to a clear decrease in the splitting tensile strength.

To summarise, the issue of the influence of the maximum size of aggregate grain on the properties of concrete requires further extensive research. As can be seen, the few test results presented are not consistent, and thick aggregates of different fractions are used for structural concretes. Undoubtedly, it is also necessary to analyse what effect on the changes caused by the maximum grain size will be exerted by the use of crushed aggregate, instead of pebbles, with irregular grains and rough texture. Mechanical adhesion of the grout to the aggregate will be improved in this case, but how this will affect the properties of the concrete needs to be explained by means of experiments.

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