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Original Research Article

INVESTIGATION OF THE PROPERTIES OF CONCRETES PRODUCED USING RECYCLED AMPHIBOLITE AGGREGATES

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A b s t r a c t

The article presents the results of laboratory studies on the impact of replacing part of the cement and natural aggregate with amphibolite dust and aggregate on the properties of concrete. The dust and amphibolite aggregates used in the research are by-products generated during the industrial processing of amphibolite rock. The study included a sieve analysis of the applied aggregates, the design of concrete mix formulas, determination of their consistency, as well as an examination of concrete shrinkage, assessment of specimen absorbability, and evaluation of compressive, flexural, and splitting tensile strength in accordance with relevant standards. The research results enabled an assessment of the impact of recycled amphibolite additives on the mechanical and physical properties of concrete, which is significant for optimizing concrete mix compositions.

Keywords: concrete, amphibolite aggregates, laboratory test

1. INTRODUCTION

In recent years, increasing attention in the construction industry has been devoted to issues related to circular waste management and sustainable production of building materials. This trend stems from growing environmental awareness, stricter legal requirements concerning environmental protection, and the depletion of natural aggregate resources. Additionally, rising extraction and transportation costs of natural raw materials encourage the search for alternative solutions in obtaining building materials. In this context, the rational use of waste and alternative raw materials, which can replace or supplement traditional sources, becomes particularly important. Concrete, as one of the most widely used construction materials, plays a key role in these considerations, as its production involves high consumption of mineral aggregates and a significant carbon footprint. The production process of cement, one of the main components of concrete, is a major source of carbon dioxide emissions, further emphasizing the need to implement more environmentally friendly practices in construction [1-3]. Moreover, the growing popularity of the concept of sustainable construction necessitates greater

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involvement in research on the use of secondary raw materials and the development of technologies that enable their optimal application in concrete mixes [2, 4].

In the context of dynamic changes in the construction industry and the necessity of implementing solutions aligned with the concept of sustainable development, increasing attention is being paid to the potential use of recycled aggregates with suitable physicochemical and mechanical properties. Rock waste, in particular, has garnered significant interest, as its rich mineral content with beneficial properties can, in many cases, not only match but even surpass the characteristics of traditional natural aggregates used in structural concrete production. A notable example of such materials is amphibolite waste, which is distinguished by exceptionally high strength, hardness, and chemical resistance due to the presence of minerals from the amphibole group [5, 6]. Proper processing of this waste, including selective crushing and cleaning processes, enables its effective use as a high-quality substitute or additive to traditional gravel and granite aggregates [4]. This approach not only supports the conservation of natural resources but also contributes to reducing the amount of generated waste and lowering the costs associated with its disposal [6, 7].

However, the potential application of recycled amphibolite aggregates in concrete production requires extensive research to determine their impact on the strength, durability, and other key properties of both the concrete mix and the hardened concrete [4]. It is particularly important to examine how mechanical properties, such as compressive, flexural, and tensile strength, change as a result of incorporating amphibolite aggregate with different grain sizes [3]. In addition to fundamental physico-mechanical aspects, microstructural evaluation is also crucial, as it reveals how the introduction of amphibolite aggregate influences the interfacial transition zone between the aggregate particles and the cement matrix. The use of scanning electron microscopy (SEM) and chemical composition analysis in this field allows for the identification of changes in the transition structure, which in turn enables a more precise characterization of the mechanisms responsible for improving or deteriorating strength parameters. Furthermore, studies on water absorption, resistance to freeze-thaw cycles, and volumetric changes resulting from chemical processes such as carbonation help to better assess the potential application of these materials under various operational conditions [5, 8]. This allows for a better understanding of the mechanisms responsible for potential improvements or deteriorations in strength and physical parameters, which is crucial for implementing such solutions in engineering practice [7, 8].

The aim of this study is to present the results of research on the properties of concrete incorporating recycled amphibolite aggregates and to analyze the potential for their broader application in engineering practice. The study will include the results of strength tests and the evaluation of selected physical parameters. In the context of the dynamic development of concrete technology and the diverse requirements currently imposed on building materials, this research represents an important step toward the effective and environmentally friendly use of recycled materials [6, 9].

Further research should consider advanced analysis of fracture surfaces, such as the Entire fracture surface method proposed by Macek [10] and the Fracture surface topography analysis (FRASTA) by Kobayashi [11, 12], which allow for a more detailed identification of dominant failure mechanisms based on surface topography parameters.

2. NOMENCLATURE

Abbreviations:

NA – natural aggregate

A02 – amphibolite aggregate fraction 0–2 mm

A05 – amphibolite aggregate fraction 0–5 mm

ASC – amphibolite substitution of cement
AS02A – amphibolite substitution of aggregate 0–2 mm
AS05A – amphibolite substitution of aggregate 0–5 mm
RS – reference specimen
$f_{ct,f}$ – flexural tensile strength
$f_{ct,sp}$ – splitting tensile strength

3. MATERIALS AND METHODS

3.1 Aggregate

In the research for preparing the concrete mix, natural aggregate was used, composed of two fractions: fine (0–2 mm) and medium (2–8 mm). Additionally, recycled amphibolite aggregate (Fig. 1) was used in various proportions, with fractions of 0–2 mm and 0–5 mm replacing part of the natural aggregate. To further modify the concrete composition, amphibolite dust was introduced as a partial substitute for cement. The aggregates used, as well as the amphibolite dust, originated from the industrial processing of amphibolite and are considered post-production waste. Amphibolite is a metamorphic rock whose main components are amphiboles, along with biotite, quartz, titanite, pyroxenes, epidote, and ilmenite. It is commonly used as crushed aggregate in infrastructure construction, such as for building railway lines and roads, as well as an ornamental stone in landscape design. The sandy fractions of amphibolite are relatively easy to sell, whereas the dust fraction poses a problem due to storage costs.

Fig. 1. Recycled amphibolite aggregate: a) dust fraction, b) 0–2 mm fraction, c) 0–5 mm fraction,

To determine the granulometric composition of the aggregates used, a sieve analysis was carried out in accordance with the standard [13]. Figure 2 presents the obtained grading curves.

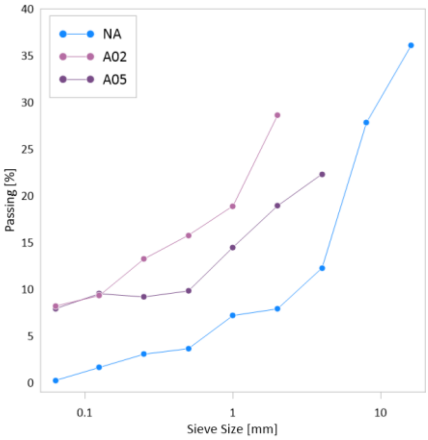

Fig. 2. Grading curves: NA – natural aggregate, A02 – amphibolite aggregate fraction 0–2 mm, A05 – amphibolite aggregate fraction 0–5 mm

3.2 Specimen designations

For the purposes of the research, various concrete mix formulations were developed. The goal was to determine the optimal proportions for replacing cement and natural aggregate with amphibolite materials while maintaining or improving the desired concrete properties. Specimens were molded in steel forms with the following dimensions: cubes (100 mm × 100 mm × 100 mm), beams (40 mm × 40 mm × 160 mm), and cylinders with a diameter of 150 mm and a height of 300 mm (Fig. 3).

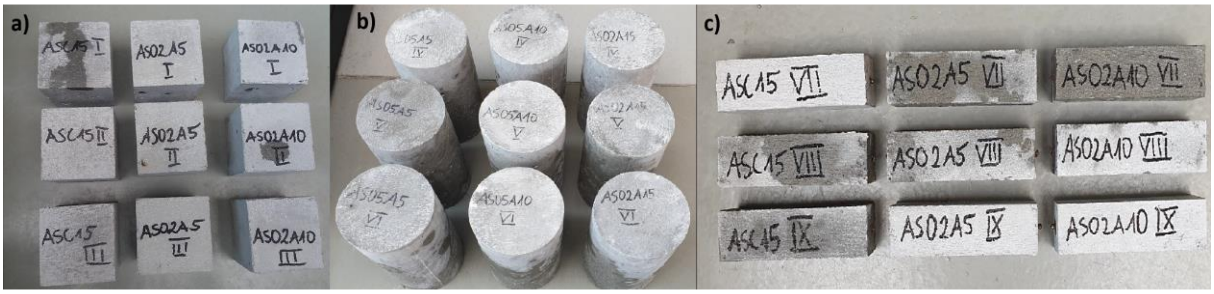

Fig. 3. Test specimens: a) cubes 100x100x100 mm, b) cylinders 150/300 mm, c) beams 40x40x160 mm

Reference specimens (RS) - were made from traditional materials without amphibolite additives, with parameters corresponding to C25/30 class concrete.

Specimens with cement modification (ASC) - partial replacement of cement with amphibolite dust in the following proportions:

- ASC5: 5% of the cement was replaced with amphibolite dust,
- ASC10: 10% of the cement was replaced with amphibolite dust,
- ASC15: 15% of the cement was replaced with amphibolite dust.

Specimens with aggregate modification (AS02A) - partial replacement of natural aggregate with amphibolite aggregate of 0–2 mm fraction in the following proportions:

- AS02A5: 5% of the natural aggregate was replaced with amphibolite aggregate 0–2 mm,
- AS02A10: 10% of the natural aggregate was replaced with amphibolite aggregate 0–2 mm,
- AS02A15: 15% of the natural aggregate was replaced with amphibolite aggregate 0–2 mm.

Specimens with aggregate modification (AS05A) - partial replacement of natural aggregate with amphibolite aggregate of 0–5 mm fraction in the following proportions:

- AS05A5: 5% of the natural aggregate was replaced with amphibolite aggregate 0–5 mm,
- AS05A10: 10% of the natural aggregate was replaced with amphibolite aggregate 0–5 mm,
- AS05A15: 15% of the natural aggregate was replaced with amphibolite aggregate 0–5 mm.

The curing process of the concrete specimens was carried out in accordance with the standard [14]. After molding, the specimens were left in the forms for at least 16 hours, protected from shocks, vibrations, and water loss, at a temperature of 20°C ± 5°C. Then, after demolding, the specimens were placed in water at a temperature of 20°C ± 2°C, where they were stored until testing. This curing method ensured proper concrete maturation conditions, minimizing the risk of drying out or other adverse environmental effects, which is crucial for obtaining reliable strength test results.

3.3 Concrete mix recipes

For the preparation of concrete mixes, CEM I 42.5 class cement and tap water meeting the requirements of the standard were used [15]. The proportions of ingredients for the individual concrete mixes are shown in Table 1.

Table 1. Concrete mix recipes

Specimen designation	**Water [l/m^3]**	**Cement [kg/m^3]**	**Natural aggregate NA [kg/m^3]**	**Amphibolite dust [kg/m^3]**	**Amphibolite aggregate A02 [kg/m3]**	**Amphibolite aggregate A05 [kg/m3]**
RS	223	558	1979	-	-	-
ASC5	223	530	1979	28	-	-
ASC10	223	502	1979	56	-	-
ASC15	223	474	1979	84	-	-
AS02A5	223	558	1880	-	99	-
AS02A10	223	558	1781	-	198	-
AS02A15	223	558	1682	-	297	-
AS05A5	223	558	1880	-	-	99
AS05A10	223	558	1781	-	-	198
AS05A15	223	558	1682	-	-	297

The process of preparing the concrete mix included several key stages to ensure uniformity and the desired properties of the mix. The dry ingredients were mixed in a slow-speed concrete mixer for 5 minutes to achieve a homogeneous blend. Then, the measured amount of water was gradually added while continuing mixing until a uniform concrete mix consistency was obtained. After mixing was completed, the consistency of the concrete mix was tested using the slump test method, in accordance with the standard [15]. The prepared concrete mix was placed into pre-prepared and greased molds of appropriate dimensions and then compacted on a vibrating table for 0.5 minutes to remove any air bubbles and ensure the proper density of the concrete. This mixing and molding process ensured that the specimens achieved the desired mechanical and physical properties, which was crucial for further research on the impact of amphibolite additives on concrete parameters.

4. TEST RESULTS AND DISCUSSION

All tests were conducted in accordance with the applicable standards [15, 16]. The obtained results were thoroughly compiled in tables and charts, allowing for the analysis of the impact of concrete composition modifications on its properties.

4.1 Testing the consistency of concrete mix

The consistency of the concrete mix has a significant impact on the quality of construction and the durability of the concrete. Mixes with too low a consistency may require excessive compaction, leading to a non-homogeneous structure, segregation of components, and the formation of air voids. On the other hand, mixes with excessively high consistency may be more prone to segregation and bleeding of the cement paste. Testing the consistency of the concrete mix is an essential step in quality control during concrete production. Proper classification of workability allows for the optimal selection of technological parameters, ensuring the durability and uniform structure of the hardened concrete. The most commonly used laboratory method for testing the consistency of a concrete mix is the slump test, which was applied in this study. The classification of the consistency of individual mixes, according to standard [15], is shown in Table 2.

Table 2. Classification of the consistency of the tested concrete mixes according to [15]

Mix designation	Slump [mm]	Consistency class
RS	7	S1
ASC5	3	S1
ASC10	7	S1
ASC15	12	S2
AS02A5	13	S2
AS02A10	13	S2
AS02A15	17	S2
AS05A5	14	S2
AS05A10	15	S2
AS05A15	21	S2

The slump test of the concrete mix revealed that its workability depends on the composition, particularly the content of amphibolite dust and aggregate. The slump in the tested specimens ranged from 3 mm to 21 mm, classifying the mixes into consistency classes S1 and S2 according to standard [15]. The reference mix exhibited the lowest slump (7 mm), indicating its stiffness and the need for more intensive compaction. The introduction of amphibolite into the mix resulted in increased fluidity, leading to a higher slump of up to 21 mm. This suggests improved workability, which can be beneficial for concretes requiring easy placement; however, excessive fluidity may cause segregation of components. The results indicate that an appropriate amount of amphibolite dust and aggregate can enhance the workability of the concrete mix. However, composition optimization is necessary to avoid adverse effects associated with excessive fluidization.

4.2 Concrete shrinkage testing

Concrete shrinkage is the process of volume reduction, primarily due to the evaporation of mixing water and ongoing cement hydration reactions. This phenomenon plays a significant role in assessing the durability of concrete structures, as it can lead to the formation of cracks, especially in massive elements and concrete with a high water content. The magnitude of shrinkage is influenced by numerous factors, such as the water-cement or water-binder ratio, the type of cement, the mix composition, and environmental conditions, including temperature and humidity. Initial shrinkage occurs within the first few days of curing and can reach up to 50% of the final value within 28 days. However, full deformations may continue to develop over several years. Concrete shrinkage testing helps assess potential risks associated with its long-term performance and allows for the optimization of mix composition to minimize the risk of shrinkage cracks. This is particularly crucial in structures exposed to atmospheric conditions and prefabricated elements, where controlling deformations is essential for durability and safety.

The shrinkage test was conducted on beams measuring 40 mm × 40 mm × 160 mm using a Graf-Kaufman apparatus. Length measurements were taken at different curing periods: 3, 7, 14, and 28 days. During testing, the specimens were kept in stable thermal-humidity conditions, with temperatures maintained between 19°C and 21°C and air humidity between 40% and 47%. The measurement results are shown in Figure 4.

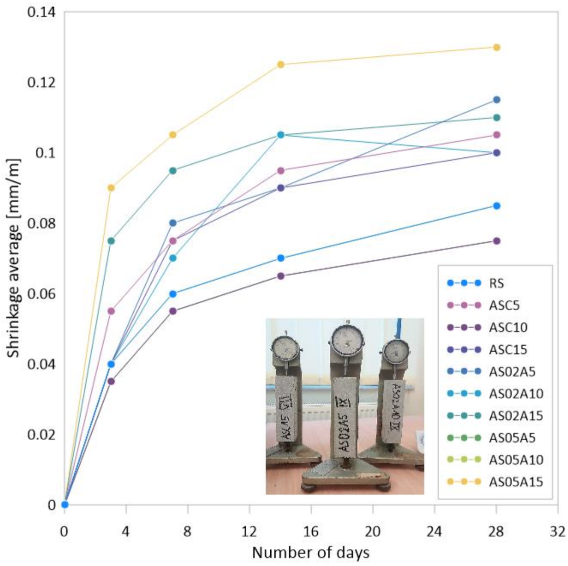

Fig. 4. Shrinkage test results

The concrete shrinkage test revealed that the volumetric changes of the specimens depend on the mix composition, particularly the content of amphibolite dust and aggregate. The highest shrinkage values were observed in the AS05A15 mix, suggesting that a high amphibolite content increases the susceptibility of concrete to deformation. In contrast, the reference mix RS and the AS05A5 and AS05A10 specimens exhibited lower shrinkage values, indicating that a moderate amount of amphibolite can be beneficial and does not lead to excessive volumetric changes.

The obtained results confirm that replacing part of the natural aggregate and cement with amphibolite affects concrete shrinkage, with excessive amounts potentially increasing the risk of shrinkage cracks. Proper selection of mix proportions helps mitigate the negative effects of shrinkage, which is crucial for the durability and resistance of concrete structures.

4.3 Testing the water absorption of concrete

Concrete absorbability is one of the key parameters determining its durability and resistance to external factors, particularly water, frost, and chemically aggressive substances. High absorbability can lead to structural weakening, an increased risk of reinforcement corrosion, and reduced frost resistance. The test results are influenced by factors such as concrete porosity, the water-binder ratio, the type and amount of cement, and aggregate composition. Concretes with a lower water-binder ratio exhibit lower absorbability, which enhances their resistance to environmental factors. Testing concrete absorbability provides valuable insights into its impermeability and durability. High absorbability may indicate an overly porous structure, which, in construction practice, necessitates the use of sealing additives or adjustments to the mix composition to improve the concrete's resistance to water and frost.

The concrete absorbability test was conducted on 100 mm × 100 mm × 100 mm cubes that had cured in water conditions for 28 days. After the curing period, the specimens were weighed in a saturated state and then dried at 105°C for 7 days, with additional mass measurements taken after 1, 3, 5, and 7 days of drying. The measurement results are shown in Figure 5.

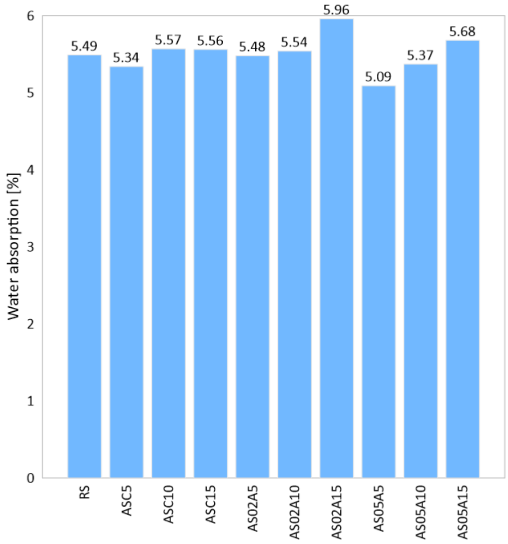

Fig. 5. Water absorption

The analysis of concrete absorbability measurements indicates that the weight-based absorbability values for different mixes range from 5.09% to 5.96%. The reference mix (RS) achieved an absorbability of 5.49%, serving as a benchmark for the other specimens. Mixes containing amphibolite exhibited variations in absorbability depending on its amount. The lowest absorbability was recorded for AS05A5 at 5.09%, suggesting that a small amount of amphibolite may improve concrete impermeability. In contrast, the highest absorbability was observed for AS02A15 at 5.96%, indicating that a higher amphibolite content increases porosity and water absorption capacity. Mixes with amphibolite dust (ASC) showed absorbability values between 5.34% and 5.57%, which do not significantly differ from the reference concrete. This suggests that replacing part of the cement with amphibolite dust does not substantially affect the concrete's absorption properties.

In summary, a small addition of amphibolite does not increase concrete absorbability and, in some cases, may even reduce it. However, at higher amphibolite contents, absorbability increases, which could negatively impact the concrete's resistance to moisture. Mixes with amphibolite dust exhibit absorbability comparable to the reference concrete, suggesting that their structure does not undergo significant weakening. Ultimately, controlling the amount of amphibolite in the mix is crucial, as a moderate addition can be beneficial, while excessive amounts lead to increased water absorption and potential deterioration of concrete durability.

4.4 Testing the compressive strength of concrete

Compressive strength is the primary strength parameter determining the quality and durability of concrete. It plays a fundamental role in the design of engineering structures, as it allows for the assessment of concrete's ability to bear loads and its resistance to degradation processes. Concrete strength is influenced by various factors, including the water-binder ratio, mix composition, curing conditions, and the presence of additives and admixtures. This test provides valuable insights into concrete quality and enables mix optimization to achieve the desired mechanical properties.

The compressive strength test was conducted on 100 mm × 100 mm × 100 mm concrete cubes that had cured for 28 days under controlled conditions. The tests were performed in accordance with standard [17], using an INSTRON 8804 testing machine to gradually increase the load until the specimen failed. The measurement results are shown in Figure 6.

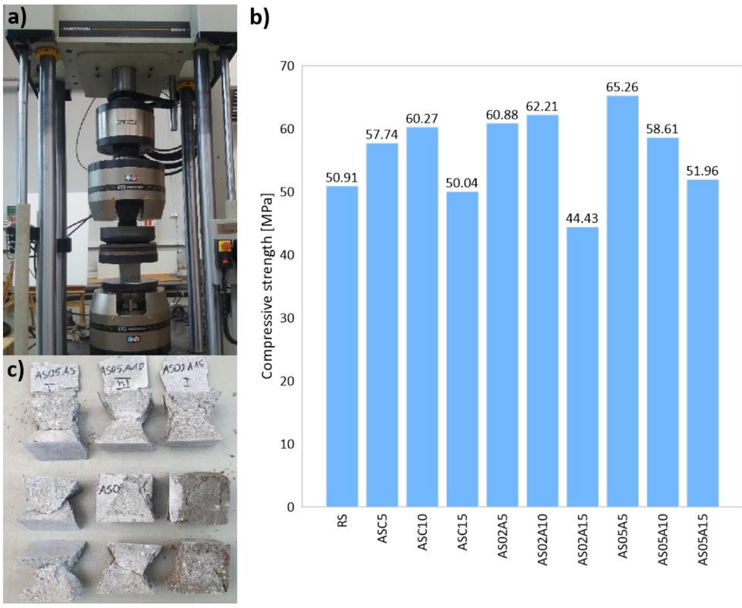

Fig. 6. Compressive strength test: a) specimen during testing, b) average strength of tested specimens, c) specimens after failure

Analyzing the compressive strength test results, it can be observed that the values for the tested concrete mixes range from 44.43 MPa to 65.26 MPa. The reference mix RS achieved a strength of 50.91 MPa, serving as a benchmark for the other specimens.

For mixes with amphibolite dust ASC, compressive strength varied depending on its content. The ASC5 and ASC10 specimens achieved strengths of 57.74 MPa and 60.27 MPa, respectively, indicating an improvement compared to the reference concrete. However, with an increased amphibolite dust content of 15% ASC15, the strength dropped to 50.04 MPa, suggesting that an excessive amount of this additive negatively affects the mechanical properties of concrete.

Mixes containing amphibolite as a replacement for aggregate showed significant variability in results. The highest strength was achieved by the AS05A10 specimens at 65.26 MPa, indicating a positive effect of a moderate amount of amphibolite on concrete strength. In contrast, the AS02A15 mix recorded the lowest strength at 44.43 MPa, suggesting that excessive amphibolite weakens the concrete structure.

In summary, the results indicate that a moderate addition of amphibolite can enhance the compressive strength of concrete, while excessive amounts lead to structural weakening. Mixes with amphibolite dust exhibit strength comparable to or higher than the reference concrete, provided that the additive does not exceed 10% of the cement volume. Similar improvements can be achieved by replacing part of the natural aggregate with recycled amphibolite aggregate. However, the best increase in compressive strength was obtained by replacing 5% of the natural aggregate with amphibolite aggregate.

4.5 Testing the flexural strength of concrete

The next test conducted was the concrete flexural strength test. It was performed on 40 mm × 40 mm × 160 mm beams in accordance with standard [18]. The specimens underwent a three-point bending test using the INSTRON 8804 testing machine. The static diagram of a simply supported beam subjected to a concentrated load at the center, with a support span of 100 mm. The load was applied at a constant rate to induce failure within 30 – 90 seconds. The flexural tensile strength $f_{ct,f}$ was calculated from the maximum load using the following expression:

$$f_{ct,f} = \frac{3Fl}{2bd^2} \tag{4.1}$$

where:

F – is the maximum applied load [N],

l – is the span length [mm],

b – is the width of the specimen [mm],

d – is the height of the specimen [mm].

The measurement results are shown in Figure 7.

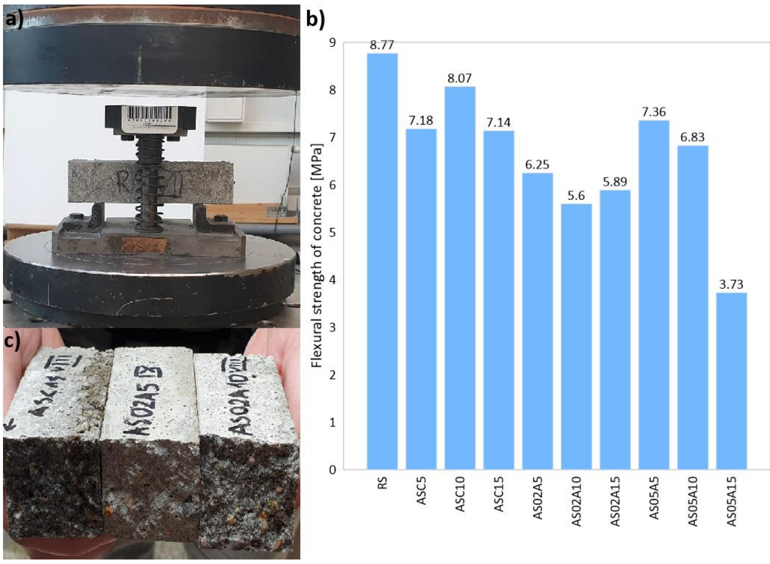

Fig. 7. Flexural strength test: a) specimen during testing, b) average strength of tested specimens, c) specimens after failure

Based on the analysis of the obtained results, it can be concluded that the addition of amphibolite in any form leads to a reduction in flexural strength compared to the reference concrete RS. The RS mix achieved the highest flexural strength at 8.77 MPa. Mixes with amphibolite dust ASC showed a moderate decrease in strength compared to RS. The best result in this group was obtained by the ASC10 mix, with a strength of 8.07 MPa, while ASC5 and ASC15 had lower values of 7.18 MPa and 7.14 MPa, respectively. These results indicate that a small amount of amphibolite dust does not significantly degrade flexural strength while positively influencing other concrete properties, as demonstrated in previous tests.

A more pronounced decrease in flexural strength was observed in mixes where amphibolite replaced aggregate. These values were significantly lower than the reference concrete and systematically decreased with increasing amphibolite content. The best result in this group was achieved by the AS05A5 specimens at 7.36 MPa, suggesting that a small amount of amphibolite does not yet cause significant weakening of the concrete. However, for AS02A10 and AS02A15, strength dropped to 5.60 MPa and 5.89 MPa, respectively, while the lowest value was recorded for AS05A15 at 3.73 MPa - 57% lower than RS.

4.6 Testing the tensile strength by splitting

The last strength test conducted was the tensile strength test of concrete during the splitting test, also known as the Brazilian test. This test was carried out on cylindrical specimens with a diameter of 150 mm and a height of 300 mm, in accordance with the requirements of standard [19]. After 28 days of curing under controlled conditions (temperature 20 ± 2°C, relative humidity >95%), the specimens were subjected to diametrical compression along two opposite faces using a testing machine with a load rate of 0.05 MPa/s. The splitting tensile strength $f_{ct,sp}$ was calculated according to the following formula:

$$f_{ct,sp} = \frac{2F}{\pi l d} \tag{4.2}$$

where:
F – is the maximum applied load [N],
l – is the length of the specimen [mm],
d – is the diameter [mm].

The test results, as well as the appearance of the specimens, are shown in Figure 8.

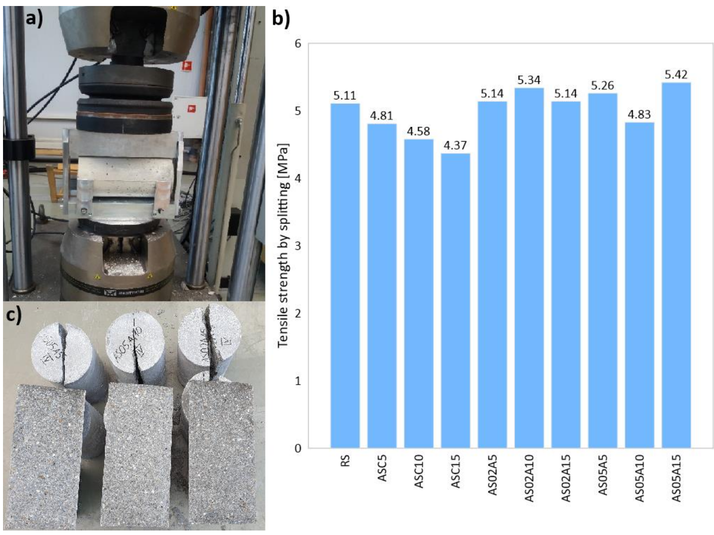

Fig. 8. Tensile strength test by splitting: a) specimen during testing, b) average strength of tested specimens, c) specimens after failure

The analysis of the tensile strength test results by splitting indicates that the addition of amphibolite affects the mechanical properties of concrete in different ways, depending on whether it replaces cement or aggregate. The reference mix RS achieved a strength of 5.11 MPa, serving as a benchmark for the other specimens.

In the case of mixtures containing amphibolite dust ASC, a systematic decrease in strength was observed as its content increased. The ASC5 mixture achieved a strength of 4.81 MPa, while ASC10 and ASC15 reached 4.58 MPa and 4.37 MPa, respectively. This indicates that replacing cement with amphibolite dust weakens the concrete structure and its ability to withstand tensile stresses. This effect may result from increased porosity of the cement matrix and a reduction in its cohesion.

In contrast, for mixtures in which amphibolite replaced part of the aggregate, the results were more varied. However, in most cases, the strength was higher than in ASC mixtures and the reference concrete RS. The best result was achieved by the AS05A15 specimens, with a strength of 5.42 MPa, while a slightly lower value of 5.34 MPa was recorded for AS02A10. In the AS02A5 and AS02A15 mixtures, the values were 5.14 MPa, indicating that they were comparable to RS.

In summary, the use of amphibolite dust in concrete leads to a reduction in tensile strength, whereas replacing natural aggregate with recycled amphibolite aggregate may be acceptable or even beneficial if its quantity is appropriately selected.

It can also be observed that there is some discrepancy between the results of the flexural strength test and the tensile strength test by splitting. This is due to differences in the stress transfer mechanisms in both tests. In the three-point bending test, the concrete specimen is subjected to a load that causes tension in the lower zone and compression in the upper zone. As a brittle material, concrete has low tensile strength, so tensile stresses in the lower zone lead to the formation of cracks and eventual failure of the specimen. In the splitting test, the cylindrical specimen is subjected to compressive loading, but due to the splitting mechanism, tensile stresses dominate in the vertical plane. The results of this test are more uniform because the forces are distributed more evenly. When analyzing the tensile strength of concrete, both tests should be considered complementary. The Brazilian test, or splitting tensile strength test, can be regarded as less sensitive to local weaknesses in the specimen, as the stress state in this test is more homogeneous.

5. CONCLUSIONS

Based on the conducted research, it can be concluded that the addition of amphibolite dust in amounts up to 10% of the cement mass improves the compressive strength of concrete, which in some cases increases by as much as 10–20% compared to reference specimens. However, exceeding this threshold (e.g., at 15% of the cement mass) results in a decrease in compressive strength to values similar to the reference concrete, while parameters such as tensile and flexural strength deteriorate significantly.

In the case of recycled amphibolite aggregate, its introduction in moderate amounts (5–10% instead of natural aggregate) significantly increased the compressive strength of concrete, sometimes reaching up to 65 MPa after 28 days. However, with higher doses of amphibolite, an increase in shrinkage and a decrease in flexural strength were observed, which may ultimately limit the use of such concrete in certain types of structures.

It was also determined that a small proportion of both amphibolite dust and aggregate did not increase water absorption and, in some cases, even reduced it. However, excessive amounts of amphibolite increased the concrete’s susceptibility to cracking due to intensified shrinkage, which may affect the durability of structural elements in the long-term service life.

In conclusion, the obtained results indicate the need for moderation in the amount of added amphibolite to achieve a favorable balance between compressive strength and other mechanical and physical properties. It is optimally recommended to replace up to 10% of the cement mass with amphibolite dust and introduce recycled amphibolite aggregate in the range of 5–10% of natural aggregate. Such a modification not only improves selected concrete parameters but also supports the ecological utilization of industrial by-products generated during amphibolite rock processing.

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17. PKN 2019. PN-EN 12390-3:2019-07 Badania betonu – Część 3: Wytrzymałość na ściskanie próbek do badań [Testing hardened concrete – Part 3: Compressive strength of test specimens].
18. PKN 2019. PN-EN 12390-5:2019-08 Badania betonu – Część 5: Wytrzymałość na zginanie próbek do badań [Testing hardened concrete – Part 5: Flexural strength of test specimens].

19. PKN 2024. PN-EN 12390-6:2024-04 Badania betonu – Część 6: Wytrzymałość na rozciąganie przy rozłupywaniu próbek do badań [Testing hardened concrete – Part 6: Tensile splitting strength of test specimens].