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Evaluation and Analysis of the Influence of Aggregate Type on Selected Concrete Properties

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Abstract

The main objective of the study was to determine the impact of the use of various types of aggregates for C40/50 class concretes used in construction. As part of the research, concrete mixtures containing natural, artificial and recycled aggregates (dolomite, recycled aggregate, lightweight aggregate, basalt) were designed, as well as a reference mix. Selected characteristics of the mixtures were determined – consistency, viscosity, air content, density, as well as strength properties of concrete and frost resistance. Endurance tests were carried out after 2 and 28 days of maturation. Tests of water absorption and depth of penetration of water under pressure were also carried out. Based on the tests carried out, it was found that concrete mixes with a density close to 2321 kg/m³ and an air content of about 2.5% can be optimal in terms of compressive strength. Mixtures with a higher air content, on the other hand, can be beneficial in conditions that require high frost resistance.

Keywords: concrete mix, additives, aggregate, concrete strength

1 Introduction

Concrete as a building material not only plays a key role in contemporary architecture and infrastructure, but is also becoming the subject of intensive research on sustainable development. Referred to as the "stone of modernity", it is unquestionably the most widely used man-made composite and the second most widely used material in the world after water. Without concrete, modern construction could not exist. Concrete is an ecological composite, often produced from locally available raw materials, such as aggregate, cement, water, admixtures and mineral additives. The popularity of this building material is due to many factors, which undoubtedly include:

a) the possibility of erecting various building structures,

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b) full automation of the production process,
c) flexibility in shaping the spatial forms of buildings,
d) high resistance to aggressive environmental factors and high temperatures,
e) susceptibility to modifications allowing to obtain specific material properties [1].

Human activity affects the environment to varying degrees, and understanding these impacts and implementing appropriate environmental protection measures allows for the rational use and proper management of its resources. Social awareness of the need to protect the natural environment is growing and covers more and more areas of life. In the face of changes in environmental regulations, the energy sector is facing the challenge of meeting increasingly stringent emission standards. From 1 January 2016, with the entry into force of the Industrial Emissions Directive, the limits for emissions of nitrogen oxides, sulphur and dust oxides have been tightened. In the construction industry, the key issue is to strive to make concrete an even more ecological and environmentally friendly material. It is necessary to look for solutions in the field of designing the composition of the concrete mix, because its two main components – cement and aggregate – have a significant impact on the environment already at the stage of their extraction and production. Opponents of concrete point to the high energy consumption in its production and the negative impact on the natural environment, m.in. through the exploitation of natural resources in the form of aggregates. Since 2011, record aggregate extraction in Poland has been recorded, estimated at 220-230 million tonnes. There are already areas where obtaining good quality aggregates becomes difficult [2-4]. In addition, there are already areas in Poland and around the world where access to high-quality raw materials for the production of concrete and cement is limited. In addition, the global economy requires more and more cement to produce concrete every year, and so far no suitable replacement has been found. Another problem is that the production of one ton of cement produces between 0.5 and 1 ton of greenhouse gases, which according to various data accounts for 6-8% of total greenhouse gas emissions generated by humans [5-7].

Globally, we are seeing an upward trend in aggregate consumption, which is currently around 40 billion tonnes per year. This is directly related to the dynamic development of transport infrastructure and the residential sector. Aggregates are particularly in demand for linear construction, where they are used in different layers of the structure to ensure the durability and safety of road infrastructure. At the same time, the demand for aggregates in cubature construction, where they are used in the production of concrete, mortars and in some earthworks, is increasing.

In Poland, the resources of natural aggregates, both fine and coarse, are not evenly distributed. As much as 90% of coarse aggregate resources are located in the south of the country, while in the north there are only 4%. This disparity leads to increased transportation costs. The high rate of exploitation causes the quality of the extracted gravel and sand aggregate deposits to deteriorate, which results in an increase in production costs. The structure of raw material extraction is also changing: the share of gravel fell from 8.8% to 2.3%, and sand and gravel deposits decreased from 65.5% to 57.4%, while the extraction of sands increased from about 26% to 40%. The increase in the depth of exploitation and the need to process harder-to-cut aggregates forces manufacturers to change the extraction technology, which leads to increased costs. In the case of crushed aggregates, deeper mining often requires dewatering of the deposit, which also increases operating costs.

The European Union produces over 3 billion tons of natural aggregates annually, and 4-4.5 tons in Poland. Although the current situation seems stable, such intensive exploitation can lead to the depletion of resources. Mining restrictions may appear in the next few years, which will increase aggregate prices and increase interest in alternative materials.

Growing environmental awareness is driving the construction sector to look for innovative solutions, such as recycling and reusing materials. This is due to the increasing amount of construction waste and the high production of concrete. The Raw Materials Initiative strategy, adopted by the European Commission in 2008, aims to secure the supply of raw materials necessary for the functioning of the economy and to promote recycling as an element of closing the raw material cycle [8].

The aim of the study was to assess the possibility of using various types of aggregate in concrete technology, and thus to determine their impact on selected properties of concrete mix and mature concrete.

2 Concrete design with various kinds of additives

2.1 Concrete mix

In order to determine the effect of the type of aggregate on the selected properties of the concrete mix and mature concrete, two types of samples were prepared:

- ZW – ordinary reference concrete mixture,
- DO, KR, KL, BA – mixtures based on various aggregates (dolomite, recycled aggregate, light aggregate, basalt).

The recipe of the C40/50 class ordinary concrete mix with SF2 consistency was developed by an empirical and experimental method. The proportions of aggregates 50% - 30% - 20% were experimentally selected to the correct, consistent "appearance" of the concrete mix in order to meet the condition of tightness.

$$\frac{C}{\rho c}+\frac{K}{\rho k} + W = 980$$

where:

C,K,W – amount of cement, aggregate and water per 1m^3 of concrete [kg].

$\rho c, \rho k$ - density of cement and aggregate [$\frac{kg}{m3}$]

Procedures included in the applicable EU regulations and standards were used to perform the experimental studies. Selected ingredients were used to prepare the concrete mix, the properties of which have been tested in the laboratory. According to the information obtained from the producers, the bulk density of aggregates was determined by pycnometric method in accordance with EN 1097-6:2003-11 [9]. The density for cement was 3.10 g/cm3, for limestone powder 2.67 g/cm3, sand 2.65 g/cm3, dolomite 2.71 g/cm3, gravel 2.71 g/cm3, recycled aggregate 2.67 g/cm3, basalt 2.98 g/cm3. Table 1 shows the composition of individual concrete mixtures. The SIKA 99pol Superplasticizer was added to each concrete mix in the amount of 3.0 kg/m3.

Table 1. Weight proportions of the concrete mix.

Mix Type	Components of the concrete mix [kg]					
ZW	**cement**	**limestone flour**	**sand 0/2 [mm]**	**gravel 2/8 [mm]**	**gravel 8/16 [mm]**	**water**
	300	190	840	504	336	175
INTO	**cement**	**limestone flour**	**sand 0/2 [mm]**	**Dolomite 2/8 [mm]**	**Dolomite 8/16 [mm]**	**water**
	300	190	860	516	344	175
KR	**cement**	**limestone flour**	**sand 0/2 [mm]**	**recycled aggregate 2/12 [mm]**		**water**
	300	190	800	800		175
KL	**cement**	**limestone flour**	**sand 0/2 [mm]**	**lightweight aggregate LSA 4/16 [mm]**		**water**
	300	190	850	310		175
BA	**cement**	**limestone flour**	**sand 0/2 [mm]**	**Basalt 2/8 [mm]**	**Basalt 8/16 [mm]**	**water**
	300	190	904	542	362	175

2.2 Cement and aggregate

Samples for experimental tests were made on the basis of CEM I 52.5 R cement (Górażdże cement, Chorula branch, Heidelberg Materials Polska) compliant with EN 197-1:2012 and drinking water – tap water in accordance with EN 1008:2004 [10,11]. This cement is characterized by high early strength (after 2 days > 30.0MPa). In addition, it exhibits a high heat of hydration, which allows for significant reduction or elimination of concrete heat treatment.

2.3 Research

On the concrete mix, the following were checked:

- consistency according to EN 12350-8:2019-08 according to Table 2 by the cone reflow method [12].

Table 2. Consistency Grades: Cone Flow Method

Classes	Cone reflow [mm]	Tolerance [mm]
SF1	550-650	+/- 50
SF2	660-750	
SF3	760-850	

- viscosity measurement according to EN 12350-8:2019-08 [12] according to Table 3 of the T500 timing method.

Table 3. Viscosity classes of concrete mix

Class	T500.
VS1	< 2.0
VS2	≥ 2.0

- air content according to EN 12350-7:2019-08 [13],
- density according to EN 12350-6:2019-08 [14].

On mature concrete, the following were checked:

- density according to EN 12390-7:2019-08 [15],
- compressive strength after 2 and 28 days according to EN 12390-3:2019-07 [16],
- frost hardiness according to PN-B-06265:2022-08 [17],
- water absorption according to EN 206+A2:2021-08 [18],
- depth of water penetration according to EN 12390-8:2019-08 [19].

The frost resistance test was performed after 28 days of concrete curing for 150 freeze-thaw cycles. Three criteria were adopted to assess the degree of frost resistance, the fulfillment of which determines the degree of frost resistance achieved:

- No cracking on the specimens after all freeze-thaw cycles
- not exceeding the value of 5% difference in the weight of samples soaked in water before and after the frost resistance test,
- A decrease in compressive strength between witness and frozen samples of not more than 20%.

The research was carried out in the Construction Laboratory at the Faculty of Civil Engineering and Civil Engineering, in the Laboratory of Physical Processes at the Water Centre of the Warsaw University of Life Sciences.

3 Results and their analysis

3.1 Concrete mix

Table 4 presents the results of tests of concrete mixtures.

Table 4. Concrete Mix Test Results

Property/Type of mixture	ZW	INTO	KR	KL	BA
Reflow diameter [mm]	655	655	545	605	635
Consistency class	SF2	SF2	SF1	SF1	SF1
Viscosity [s]	1.5	1.3	4.2	3.7	3.2
Viscosity Grade	VS1	VS1	VS2	VS2	VS2
Density [kg/m3]	2236	2321	2178	2011	2346
Air content [%]	3.4	2.5	4.5	4.3	3.8

On the basis of laboratory tests, it was found that the consistency of mixtures produced on the basis of artificial aggregates is lower than the reference mixture. The mixtures with gravel (ZW) and dolomite (DO) have reached the highest flow diameters (655 mm), which classifies them in the SF2 consistency class. This means that they are more fluid and easier to concentrate. The mix with recycled aggregate (KR) has achieved the lowest flow diameter (545 mm), which places it in the SF1 consistency class. This means that the mixture is less fluid and may require more energy to thicken. The lightweight aggregate (KL) and basalt (BA) mixtures have flow diameters of 605 mm and 635 mm respectively, which also places them in SF1 class, but they are more fluid than the recycled aggregate mix.

Gravel (ZW) and dolomite (DO) concrete mixtures exhibit similar properties with high flow diameter and low viscosity. They are easy to thicken and pump, which makes them suitable. Mixtures with gravel (ZW) and dolomite (DO) have the lowest viscosity (1.5 and 1.3 respectively), which classifies them in viscosity class VS1. This means that these mixtures are smoother and easier to pump and pour. Mixtures with recycled aggregate (KR), light aggregate (KL) and basalt (BA) have higher viscosity values (4.2, 3.7 and 3.2 respectively), which classifies them in the viscosity class VS2. These mixtures are more viscous, which means they can be more viscous and harder to pump.

The results of the density of concrete mixtures range from 2011 kg/m3 (KL) to 2346 kg/m3 (BA). Samples with high density can exhibit higher compressive strength, lower porosity, and better durability. The samples with low density obtained a high air content (4.3%), which indicates their higher porosity. This can reduce the density and compressive strength of the concrete and improve the frost resistance.

3.2 Concrete

Table 5 shows the results of the density of mature concrete.

Table 5. Mature concrete density

Mix Type	ZW	INTO	KR	KL	BA
Density [kg/dm3]	2.257	2.342	2.223	2.007	2.367

The density of concrete is an indicator of its compact structure and the number of air voids in the concrete mix. Higher density usually means better strength and durability of concrete. On the basis of the tests carried out, it was found that the highest density was obtained by the BA mixture (2,367 kg/dm³). This means that BA is the densest concrete, suggesting its high compact structure and low amount of air voids. The lowest density is the KL mixture (2,007 kg/dm³). This indicates higher porosity and potentially lower strength.

The figure shows the average values of compressive strength determined in two maturation periods – after 2 and after 28 days determined on 3 samples of 15x15x15 cm.

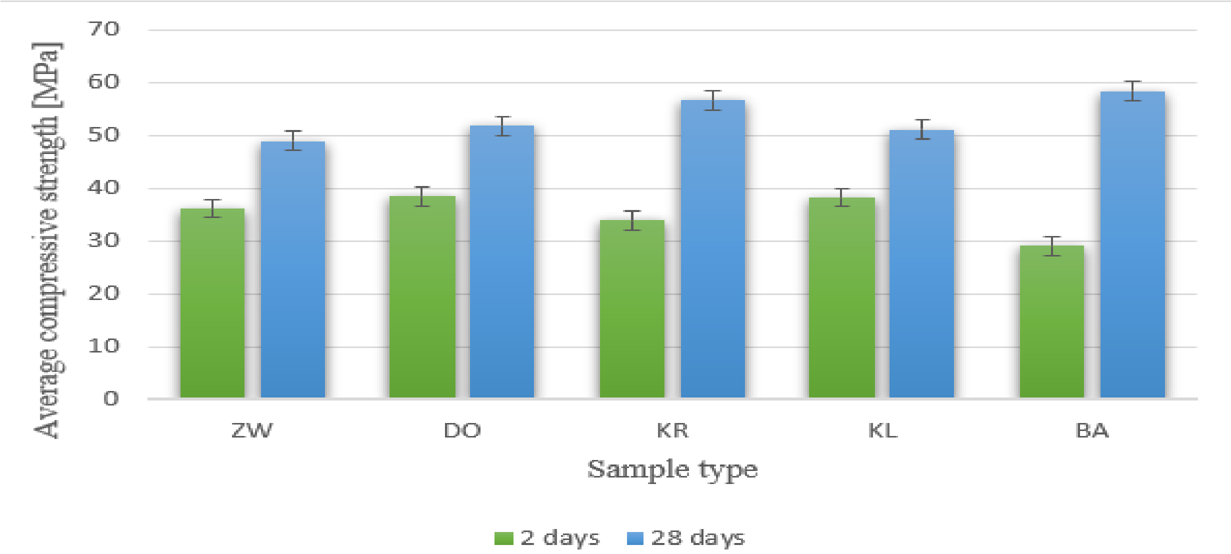

Fig. 1. Average compressive strength after 2 and 28 days of maturation.

Compressive strength is one of the most important parameters of concrete, which determines its ability to withstand loads. After 2 days , the highest compressive strength was obtained by the DO specimens (38.4 MPa), which suggests a rapid increase in strength in the initial period, while thelowest strength of the BA specimen (29.3 MPa). Considering the second maturation period, the highest compressive strength was observed for BA samples (58.4 MPa), which is consistent with its highest density. The lowest ZW sample strength (49.0 MPa), which is an average value compared to the other mixtures.

Table 6 shows the results of water absorption and depth of penetration under pressure.

Table 6. Results of water absorption and depth of penetration under pressure.

Mix Type	ZW	INTO	KR	KL	BA
Water absorption %	6.2	6.1	7.0	7.8	6.2
Water penetration depth [mm]	21	20	23	33	13

The water absorption of concrete determines its ability to absorb water, which is crucial for its durability, especially in freeze-thaw conditions. The lowest water absorption was obtained by DO (6.1%) and BA (6.2%) concrete samples, which indicates lower porosity and better durability in wet conditions. The highest absorbability of the KL sample (7.8%), which can negatively affect its long-term durability.

The depth of water penetration is a measure of the resistance of concrete to the ingress of water under pressure. A lower penetration depth means better concrete tightness. On the basis of the tests carried out, it was found that the lowest depth of water penetration under pressure was shown by BA samples (13 mm), which indicates the best tightness and resistance to water penetration. The KL samples (33 mm) had the highest penetration depth, suggesting higher porosity and lower resistance to water ingress.

The ZW compound presents medium density and water absorption, with low compressive strength after 28 days. It is a less optimal blend compared to others in terms of long-term endurance. BA is the most compact and robust compound, showing excellent resistance to water ingress. It is an ideal mix for structures that require high durability and moisture resistance. The DO compound is very robust and durable, especially in the initial period, making it suitable for structures requiring fast initial strength and good moisture resistance. The KL compound, despite its high compressive strength, has the lowest density and the highest water absorption and depth of penetration, which indicates higher porosity. This can affect its long-term durability, especially in conditions exposed to water and frost. The KR mixture has a high compressive strength after 28 days, but a low initial strength and higher water absorption. High water penetration depth can mean greater durability issues in wet conditions.

Table 7 presents the results of frost resistance after 150 freeze-thaw cycles.

Table 7. Average strength loss and average weight loss of frozen specimens.

Sample	Average Compressive Strength		Average Decrease in Strength of Frozen Samples	Average Weight		Average weight loss
	reference processing	reference sample after 150 freeze-thaw cycles		before freezing	after 150 freeze-thaw cycles	
	[MPa]	[MPa]	[%]	[g]	[g]	[%]
ZW	**55.6**	**50.8**	**-8.6**	**2.305**	**2.285**	**- 0.9**
INTO	52.7	54.8	3.9	2.322	2.310	-0.5
KR	55.1	51.3	-6.8	2.212	2.182	-1.4
KL	51.6	48.1	-6.8	1.993	1.803	-9.5
BA	59.6	57.8	-3.1	2.363	2.340	-1.0

In the case of ZW reference concrete samples, a significant decrease in compressive strength (-8.6%) was observed. The samples showed some signs of degradation after freeze-thaw cycles, suggesting moderate frost hardiness. Concrete samples produced on the basis of dolomite showed an increase in strength (+3.9%). DO samples show remarkable freeze-thaw resistance, even showing improved strength. It is possible that the structure of the concrete has been further compacted. A moderate decrease in strength (-6.8%) was obtained by the KR and KL samples. This shows a similar trend to ZW, with some decrease in endurance, which also suggests moderate frost resistance. The smallest decrease in strength (-3.1%) was obtained by BA samples. BA concrete shows the best frost resistance, retaining a significant part of its strength after freeze-thaw cycles. Taking into account the loss of masses, it was found that the smallest loss (-0.5%) was shown by DO concrete samples. Combined with an increase in strength, it makes this compound highly resistant to freeze-thaw cycles. The largest weight loss (-9.5%) was achieved by KL concrete. This indicates significant physical degradation and potential durability issues in extreme freezing conditions. Concrete is not frost resistant. The remaining samples showed a slight loss of mass (-0.9 ZW, -1.4 KR and -1.0 BA). This suggests good resistance to physical degradation, despite the decrease in endurance.

4 Discussion and conclusions

Choosing the right type of aggregate depends on the specific requirements of your construction project. Natural aggregates such as gravel and dolomite provide better workability, while aggregates such as basalt can offer better strength and durability. Recycled aggregates require extra attention to ensure the quality and properties of the concrete mix.

Correlation of density and air content: Usually, the higher air content of concrete is inversely proportional to its density. Higher air content increases porosity, which can reduce the density of concrete.

Impact on strength: Concrete with a higher density and lower air content (e.g. 2321 kg/m³ and 2.5%) is likely to exhibit higher compressive strength. Concrete with a lower density and higher air content (e.g. 2011 kg/m³ and 4.3%) may be less robust but better able to withstand freeze-thaw cycles.

Optimal air content: The ideal air content in concrete is usually in the range of 3-5% for good frost resistance, while maintaining acceptable compressive strength.

Based on this data, it can be seen that concrete mixes with a density close to 2321 kg/m³ and an air content of about 2.5% can be optimal in terms of compressive strength. Mixtures with a higher air content, on the other hand, can be beneficial in conditions that require high frost resistance.

1. The BA mixture is most optimal when high mechanical parameters and resistance to water are required.

2. The DO compound has a rapid increase in initial strength and good durability, which makes it suitable for structures that require fast initial strength.

3. KL compound, despite good strength, may be less durable in humid conditions due to its high water absorption and depth of penetration.

4. The KR blend shows high strength after 28 days, but with higher porosity, which can affect the durability in the long term.

5. The ZW compound is less optimal in terms of long-term endurance compared to others.

Each of the mixtures has its own specific properties that must be taken into account depending on the design requirements and operating conditions.

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