

Comparative Analysis of Physical-Mechanical Properties of Natural and Recycled Aggregate Concretes

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ABSTRACT

Research on the use of construction and demolition waste as recycled aggregate for the production of new concrete has confirmed that they are environmentally friendly and constitute an alternative method of waste management. However, contrary to conventional concrete, no large applications of concrete made with recycled concrete have been made and there is still the literature studies of recycled aggregate properties are different, which indicates the need for further research on the properties of cements from waste. This paper presents and compares the results of a laboratory study on the properties of ordinary concrete (BZ), high-strength concrete (BWW), recycled aggregate concrete (REC). The tensile and compressive strength, modulus of elasticity of these concentrates were marked. The research results proved that the compressive strength of the concrete with recycled aggregate, compared with high-performance concrete, is much lower, but only slightly lower than for ordinary concrete. In turn, the tensile strength of the concrete with recycled aggregate is lower than that of high-performance concrete and ordinary concrete. These values, in the case of the compressive strength are as follows: REC – 52MPa; BWW – 68MPa; BZ – 25MPa, whereas for the tensile strength, they reach: REC – 4 MPa, BWW – 6 MPa, BZ – 5.1 MPa. Statistical analysis showed that the given parameters of the analysed concretes are indeed statistically different. Obtained results indicate that recycled aggregate may be aggregate of standard value and good mechanical properties, even better than of ordinary concrete. The application of recycled aggregate is considered to be a new approach in balanced construction and a superb solution to protect the environment.

Keywords: sustainable development, compressive strength, tensile strength, recycled aggregate concretes

INTRODUCTION

Globally, the construction industry has the greatest share in a carbon footprint and is the major consumer of natural resources [1]. Moreover, the aforementioned industry is responsible for approximately 25-30% of global emissions of all waste including concrete, bricks, plaster, timber, glass, metal, plastic, solvents, asbestos, and mined dirt [2]. In 2018, in Poland, there were 3774 thousand tonnes of construction waste produced [3, 4] which extend to increasing prices and the growing dependence on foreign suppliers. The situation is particularly unfavorable in the construction sector, which is

among the most resource- and energy-consuming areas of the economy. This paper juxtaposes the situation of Polish construction industry in the context of the national economy with the context of the evolving EU policies promoting green solutions. The resulting changes in Polish legislation, industry and society are identified. The implementation of selected Circular Economy (CE). Construction waste is considered to be produced not only during the construction of new buildings but also during the demolition or reconstruction of existent buildings. The remaining materials used for the construction are disposed and new materials are obtained, for new construction [5, 6, 7, 8].

A part of that waste is being stored at storage yards, whereas others are placed in large quantities in reservoirs, drainage ditches, and wastelands, located nearby the residential areas. The physical and chemical properties of that waste indicate on its possible hazardous impact on the environment [9, 10]. Besides, accumulated waste block available lands which otherwise might have been used for other purposes.

Effective use in new concrete of recycled aggregate obtained from concrete may contribute to a limitation of storage of waste and concurrently decrease the demand on natural aggregate - both constitute a vital environmental aspect, and should be considered in responsible, balanced management [11]. This would also be an essential contribution to solving one of the major scopes of the UN's 2030 agenda on balanced consumption and production: balanced consumption and production management. The aim is focused on economic growth based on the effective management of resources and low environmental degradation together with an improvement in humans' prosperity. It may be reached by a change in the direction of more balanced consumption of the resources and improved production processes [12].

Furthermore, waste reuse is imposed by the legislation of the European Union. The EU waste directive 2008/98/EC requires member states to recycle 70% of their non-hazardous CDW as raw materials by 2020. However, the current recycling rate reaches only approximately 46% [13, 14, 2].

Annually, the construction industry produces 75 million tonnes of concrete rubble [15], 52% (weight) of that waste is concrete, which may be recycled to the recycled aggregate concrete (REC) used as a substitute for natural aggregate in concrete production [16, 17, 18]. Reusing of aggregate has become a subject of various research as well as using recycled materials has started to be popularised. Nevertheless, current specifications and experience seem to be not enough to support and encourage to recycle of construction and demolition waste in parts of the world [19]. Moreover, there are still technical issues, including for instance shortage of research on the interfacial transition zone between cement mortar and recycled aggregate.

According to the research, the physical properties of recycled aggregates (REC) depend on the quantity and quality of used cement mortar [20, 21]. It is observed that mechanical properties (compressive, fracture, and tensile strengths,

Young's modulus) of the recycled aggregate concrete are decreasing with an increase in the percentage of natural aggregate content (NA) [22, 23]. What is more, mechanical properties of recycled concrete are complex. This is influenced by the geometry and mechanics of aggregate properties, as well as two different interfacial transition zones (one is located between the original natural aggregate and the old mortar, the second one between the old and new mortars). Certainly, it is slightly different in the case of natural aggregate concrete, where only one interfacial transition zone occurs [24].

In the literature has been described consensus on the application of recycling-originating aggregates in concrete production; together with the increase in the level of exchange the compressive strength of concrete decreases. It has been observed [25], that considering practical matter the level of exchange at approximately 30% for coarse recycled aggregate or at 20% for fine aggregate has a marginal impact on the development of the strength of concrete. Nevertheless, the strength is decreasing gradually, together with an increase in the level of recycled aggregate (RA) exchange [20, 26, 27, 28, 29]. As an addition, it has been also noticed that the average strength of concrete consisted of 100% coarse recycled aggregate or 50% fine REC is between 20% to 30% lower than for adequate natural aggregate concrete [23, 27].

Recycled aggregate has different properties than natural aggregates, therefore they behave differently in concrete mixtures [30]. Compressive strength, tensile strength and modulus of elasticity are the most effective properties of concrete affecting its performance properties. The studies of the recycled aggregate properties they are different. The compressive strength of REC is generally 10–30% lower than that of natural aggregate concrete [31, 32, 33]. However, other researchers observed that the compressive strength of the concrete remained unchanged or slightly increased when NA was replaced by REC by up to 25% [6]. There are also known methods of increasing the compressive strength of REC, such as usage of admixtures [34, 35, 36, 37], increasing the cement content [38], use of plasticizers and mixing methods [39] etc. Moving on to literature studies tensile strength of REC shows that tensile strength decreases with increase in recycled aggregate (RA) replacement ratio [34]. Bairagi et al. [40] reported that the tensile strength of REC

was 6%, 10% and 40% lower than normal concrete when REC was made with 25%, 50% and 100% replacement for RA. Other studies showed that the REC tensile strength for an exchange rate of up to 30% is the same or even exceeds the tensile strength of the original concrete [6]. They are similarly described with the values of the modulus of elasticity. The modulus of elasticity has been negatively affected by the inclusion of RA [41, 39, 42, 43]. Kou et al. [42] showed that the modulus of elasticity decreased by 12.6% for the 50% replacement rate and by 25.2% for the 100% replacement rate. However, Pereira et al. [39] observed that the modulus of elasticity was almost unchanged when the replacement ratio increased to 30%. Literature studies indicate that various factors have an impact on the properties of concrete made of recycled aggregate, which indicates the importance of further testing of various proportions of recycled waste additives or mineral additives so that they can be used as required.

Popularisation of the results of research on the application of recycled materials for concrete production and acquaintance with their properties are important. The aim of this paper is to assess the possibilities of using concrete as aggregate in new concrete mixtures. The article has been conducted a comparison of properties of various concretes: natural, with the addition of natural aggregate, and with the addition of recycled aggregate. Statistical analysis has been made to determine the significance of variability of physical-mechanical properties of the analysed concretes.

The article consists of four sections. Section 1 presents analysis of the literature in the area. Section 2 describes the methods used. Section 3 presents the compressive strength, tensile strength, modulus of rigidity and modulus of elasticity tested concentrates: ordinary concrete (BZ), high-strength concrete (BWW), recycled aggregate

concrete (REC). The results were compared with each other. The paper ends with Section 4, which contains final conclusions.

MATERIALS AND METHODS

For mixtures Portland cement CEM I 32,5 R and quartz sand (0-0.025 mm; 0.025-0.5 mm; 0.5-1 mm; 1-2 mm) were used. Technical parameters of used cement are presented in Table 1.

Three concrete mixtures have been prepared: ordinary concrete (BZ), high-strength concrete (BWW), recycled aggregate concrete (REC) which compositions are drawn up in Table 2. As it is presented in Table 2, BWW and REC mixtures vary in the material of coarse aggregate. In the BWW mixture basalt gravel has been used, whereas in the REC coarse aggregate was composed of concrete rubble from the construction elements with the concrete resistance corresponding to C16/20 class. The concrete mix was prepared using the aggregate fractions from the smallest 0-2 mm, through 2-4 mm and 4-8 mm, in order to obtain. C16/20 2/4 is the aggregate fraction with a grain diameter from 2 to 4 mm and C16/20 4/8 is the aggregate fraction with a grain diameter from 4 to 8 mm. The chemical composition of substrates used in mixtures is shown in Table 3.

To concrete mixtures, BWW and REC silica fume and superplasticizer Sika ViscoCrete 20 Gold have been also added. Silica fume is a powdered additive to concrete, in which grains are ultra-fine (0.1 μm). It aims to increase water resistance, pumpability, and resistance of concrete to chemical corrosion. A superplasticizer is an additive aiming at a reduction of water required to prepare concrete. Properties of the superplasticizer are presented in Table 4.

Table 1. Composition of CEM II B-V 32,5R [44]

Properties	Unit	CEM II B-V 32,5R
Specific surface	(cm ² ·g ⁻¹)	4237
Initial setting time	(min)	243
Compressive strength		
• after 2 days	(MPa)	20.3
• after 28 days	(MPa)	45.7
Density	(g·cm ⁻³)	2.83
SO ₃ content	(%)	2.28
Chloride ion content	(%)	0.06
Na ₂ O content	(%)	1.09

Table 2. Composition of concentrate mixtures

Components	Unit	BZ	BWW	REC
Cement CEM II B-V 32,5R	kg · m ⁻³	270	500	500
Water	kg · m ⁻³	178	143	143
Sand 0/2	kg · m ⁻³	788	-	-
Gravel 2/8	kg · m ⁻³	488	-	-
Gravel 8/16	kg · m ⁻³	600	-	-
Superplasticizer	kg · m ⁻³	2.21	7.50	7.50
Fine aggregate:				
– sand 0/0,25	kg · m ⁻³	-	36	36
– sand 0,025/ 0,5	kg · m ⁻³	-	108	108
– sand 0,5/1,0	kg · m ⁻³	-	216	216
– sand 1,0/2,0	kg · m ⁻³	-	240	240
Coarse aggregate:				
– basalt gravel 2/4	kg · m ⁻³	-	530	-
– basalt gravel 4/8	kg · m ⁻³	-	700	-
– concrete rubble C16/20 2/4	kg · m ⁻³	-	-	530
– concrete rubble C16/20 4/8	kg · m ⁻³	-	-	700
Silica fume	kg · m ⁻³		50	50

Table 3. Chemical composition of substrates used in concrete mixtures [45]

Compositions	SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	TiO ₂	K ₂ O	Other alkaline compounds
Basalt	48.5	13.8	10.5	12.2	10	0.9	0.1	4.0
Recycled aggregate	26.60	23.22	2.40	2.49	35.25	0.33	3.21	6.5
Sand	95.2	2.0	0.6		0.45			
Silica fume	90	0.4	0.4		1.6		2.2	1.9

Table 4. Properties of the superplasticizer [46]

Properties	Superplasticizer
Aspect	Light brown liquid
Relative density at 25° (g · cm ⁻³)	1.08
pH	≥6
Chloride ion content (%)	<0.2
Expected water reduction (%)	>20

Test method

The research methodology showed on flow-chart (Figure 1). The properties of concentrates were measured after 7, 14, 28 days. The analyses repeated three times. The samples were cured in a constant temperature chamber (23 ± 2 °C) and relative humidity (95 ± 5%). Table 5 shows the tests performed.

Non-destructive concrete tests were performed using a Schmidt hammer to determine the durability of concrete. Tensile and compressive strength tests were conducted in the Laboratory of PSW in Biala Podlaska (Poland) using computer-controlled press CONTROLS, model 50-C7022. To determine Young’s modulus and shear modulus for concrete CONTROLS C311-R device was used.

Statistical analysis

When processing the results of the iterative tests, the arithmetic means and standard deviations of the means were calculated. Obtained results were then tested for normality using the Shapiro-Wilk test [50].

To assess the significance of differences between average values, statistical analyses based on a multiple comparison Tukey’s test, with a fixed significance level $\alpha = 0.05$. The test facilitated performing a detailed comparative analysis of average values, via isolation of statistically homogeneous average groups (so-called Tukey homogeneous groups) defined by literal indicators. Average values of particular parameters defined for compared data and marked by the same letter indicate their affiliation to a statistically homogeneous group, namely, there is no statistically significant difference between them.

In a course of describing correlations between tested variables, linear correlation matrices between pairs of variables were designated, and their strength is expressed via the value of r–Pearson coefficient. For interpretation of the results of correlation, tests were used criteria of the strength of dependence adopted by Bam et al.

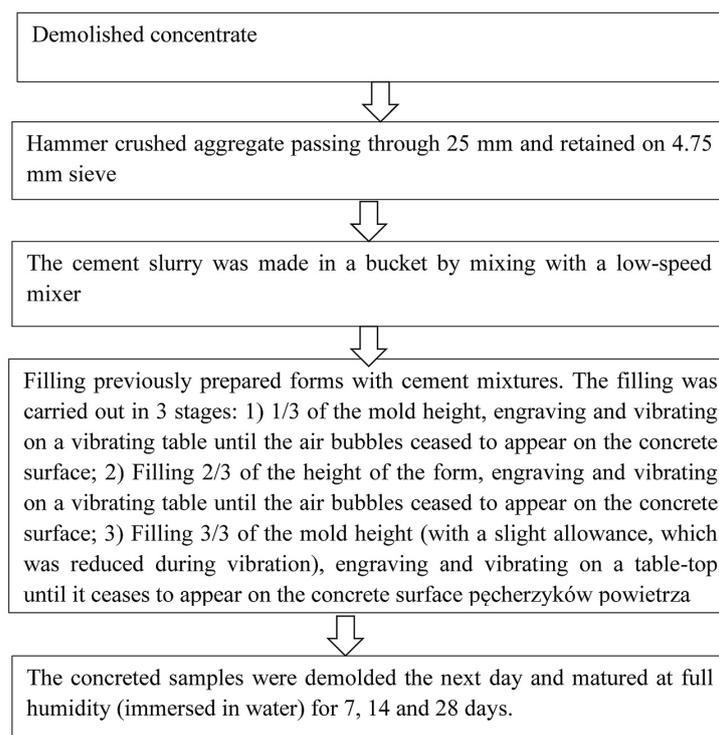


Figure 1. Concrete preparation

Table 5. Tests performed to study the properties of concrete

Test	Standards	Form and Sample Dimensions
Compressive strength	PN-EN 12390-3:2011 (47)	Cuboid: Ø 40 x 40 x 160 mm
Tensile splitting strength	UNE-EN 12390-6:2009 (48)	Cuboid: Ø 40 x 40 x 160 mm
Static modulus of elasticity in compression	UNE 83316:1996 (49)	Cylindrical: Ø 150 x 300 mm

(2011), which assume that correlation coefficient $r > 0,7$ indicate a strong correlation between two parameters, whereas values between 0,5–0,7 indicate moderate correlation [51].

RESULTS AND DISCUSSION

The mean values, the standard error for all analysed concretes on the 28 days concretes are listed in Table 6. Figure 2 and 3 present the photographs of the tested samples during and after testing of the mechanical properties.

Statistical analysis

Values of the Shapiro-Wilk test of normality for tested concretes after 28 days are presented in Table 7. All the variables were observed to have skewness- and kurtosis-to-standard error ratios lying within the -2 to +2 range, indicating no significant deviation from a normal distribution [50]. Normality for all the variables is also confirmed

by obtained Shapiro-Wilk p-values, all of which were over 5%.

Conducted test Tukeya which aims at measuring the impact of tested concretes on properties of concrete has proved that aggregates had a statistically significant influence on the majority of examined variables (p-value <5%).

Compressive strength

The distinctive property of concrete is its compressive strength, other are flexural/tensile strength, durability, permeability, and stiffness. A change in compressive strength usually causes a proportional change in other properties. This also applies to recycled concrete. The compressive strength of each concrete, including recycling-originated, is dependent on multiple factors, especially on the water-binder ratio (w/b), but also on a type of used aggregate, proportion of mixing, properties of used additives, and the age of concrete; for recycled aggregate concretes vital would be also various properties of the material

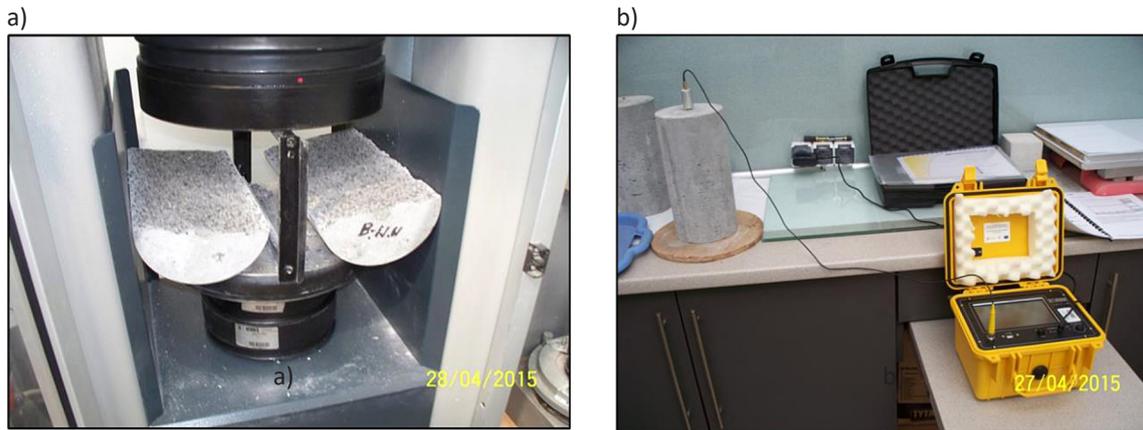


Figure 2. Samples during testing of the (a) dynamic modulus of elasticity with a sensor mounted on a cylindrical specimen; and (b) dynamic modulus of elasticity

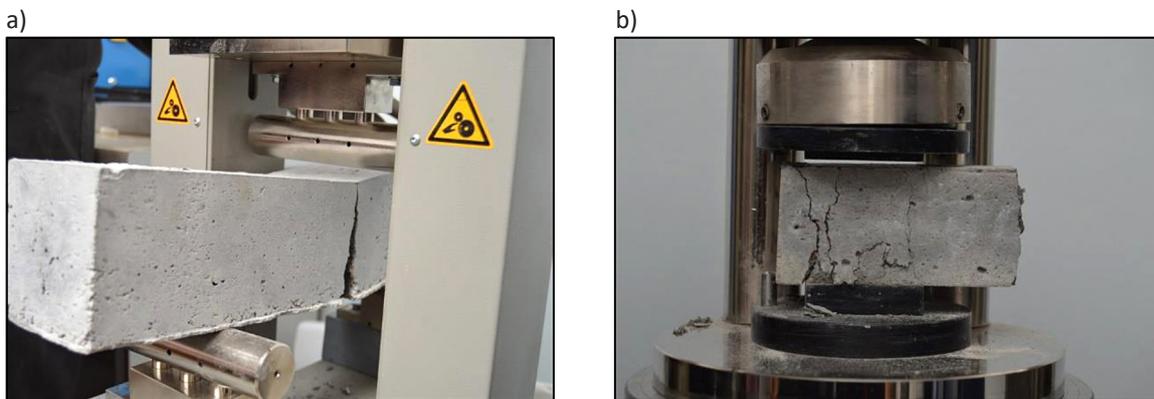


Figure 3. Cubic samples after testing of the (a) tensile strength and (b) compressive strength

Table 6. Compressive, tensile strength, modulus of elasticity for the 28 days concretes (4×4×16 cm), with statistical parameters

Concentrate	Mean	Standard error (%)
<i>Compressive strength (MPa)</i>		
BZ	22	1.28
BWW	69.07	0.77
REC	49.08	1.12
<i>Tensile strength (MPa)</i>		
BZ	3.98	0.07
BWW	5.99	0.23
REC	5.22	0.10
<i>Elastic modulus (GPa)</i>		
BZ	31.77	1.34
BWW	37.27	2.49
REC	31.91	1.98

used to recycle [52]. Compressive strength of aggregate specified for days 7, 14, 28. Results are presented in Figure 4.

As a result of testing 4x4x16cm beams on compressive strength, it was observed that high-strength concrete after 7 days reached 68% higher

strength than concrete with 50% recycled aggregate. After 14 days the difference decreased to 53%, and for the sample tested after 28 days reached 41%. The strength of ordinary concrete in three testing terms oscillates near 45% of concrete with 50% recycled aggregate strength. Previous

Table 7. Shapiro-Wilk normality test

Parameter	Compressive strength (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)
Skewness/standard error	-0.20	-0.37	0.53
Kurtosis/standard error	1.03	-1.49	1.03
Shapiro-Wilk p-value	0.06	0.07	0.10

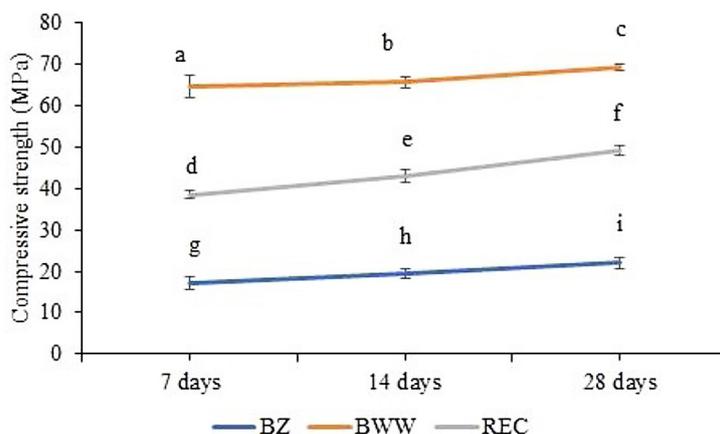


Figure 4. Concrete compressive strength over time. The water-cement ratio for concretes equaled: BZ– 0.47; BWW – 0.29; REC – 0.32.

studies showed that concretes with 100% of recycled aggregate had compressive strength after 7, 14, 28 days lower by 43%, 35%, 43%, respectively, than basalt aggregates (45). Kessal et al. suggested that the decrease of the compressive strength of REC (100% replacement) is about 19% compared to basalt aggregates [53].

Conducted post hoc comparison using Tukey’s significant difference test proved that obtained values of compressive strength for all examined aggregates on each measurement day are significantly different.

A decrease in values of compressive strength of recycled concretes has been also proved in tests of other researchers. Sagoe-Crentsil et al. (2001) have proved that resistance values of concrete with 23% additive of recycled aggregate was 5% lower than in a case of compared natural aggregate concrete [54]. On the other hand, Gomez-Soberón (2002) assumed decreasing by 11% compressive strength between samples made of 100% recycled aggregate only regarding concretes made from the natural aggregate. However, when an exchange of natural aggregate reached 30%, the compressive strength decreased by 5%[55]. Malešev proved that values of compressive strength of natural aggregate concretes with additives of natural coarse and recycled fine aggregates reaching up to 50% is lower than of natural aggregates concrete, which led to the

elimination of such combination from the practical application [56].

Tensile strength

The tensile strength insignificantly relies on the type and quantity of recycled aggregate applied (especially if the mixture contains only coarse recycled aggregate), yet it depends on an aggregate-concrete content ratio. An increase in that ratio may decrease the tensile strength [56].

Figure 5 shows results of the tensile strength of concentrate mixtures after 7, 14, 28 days. As a result of testing 4x4x16cm beams on tensile strength, it was observed that high-strength concrete after 7 days reached 52% higher strength than recycled aggregate concrete. After 14 days, the difference decreased to 28%, and for the sample tested after 28 days reached 15%. The strength of ordinary concrete is as following: after 7 days - 83%, 14 days - 75%, 28 days - 76% of recycled aggregate concrete strength. Tukey’s significant difference test proved that the results of the tensile strength test of all examined mixtures are significantly different.

In the presented results, the tensile strength after 28 days differed insignificantly and reached: for REC 5 MPa, for BWW approximately 6 MPa, and BZ approximately 3.5 MPa. Malsey’s test proved that the addition of only coarse recycled

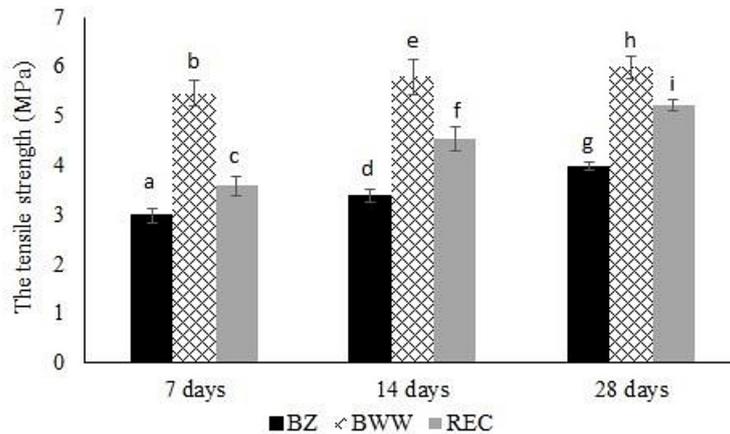


Figure 5. Concrete tensile strength over time

aggregate fraction led to a decrease in the tensile strength up to 10%. It was proved that aggregate containing from 20% to 50% of recycled aggregate has the tensile strength lower by 2% in comparison to concretes from natural aggregate [56]. Etxeberria et al. (2007) attempted to obtain concrete mixtures from recycled aggregate with the same tensile strength as natural aggregate concrete. In mixtures, they replaced natural aggregates in ranges 25%, 50% to 100%. Results revealed that the mixture with 25% had almost the same tensile and compressive strengths as a control sample – non-additives concrete [20].

Table 8 presents the ratio of tensile strength to compressive strength in mixtures tested after 28 days. Calculations showed that the highest value of coefficient has been reached for ordinary concrete and the lowest for recycled aggregate concrete. That might occur because decreasing the tensile strength of recycled concrete is less susceptible than decreasing the compressive strength of natural aggregate concrete [57].

The interrelation between the tensile strength and the compressive strength of concrete is presented in Figure 6. A high rate of the determination being 0.981 indicates that data has been adjusted by the best R-value. The high value of the determination rate suggests that the tensile strength is in a strong interrelation with the compressive strength. The results are distinctly

Table 8. The ratio of the tensile strength to the compressive strength

Mixtures	f _{st} /f _c	f _{st} /f _c (%)
REC	0.10	10.63
BWW	0.08	8.67
BZ	0.18	18.01

grouped, depending on applied concrete. Correlation equation $y=0.04x + 3.13$.

Correlation between modulus of rigidity and modulus of elasticity

As it is presented in Table 6, the greatest value of modulus of rigidity reached natural aggregate concrete, other had approximate values. Statistical analysis proved that values of modulus of rigidity of ordinary and recycled concretes do not statistically differ.

Other researchers' tests show that modulus of elasticity of aggregate from recycled concrete is lower than comparable concrete with natural aggregate, which is a consequence of a considerable amount of old mortar, which has a relatively low level of modulus of elasticity [41, 42]. Researchers suggest that the level of modulus decrease does depend on the type of fine fraction in aggregate mass [52]. In the case of concrete produced entirely from recycled aggregate, the decrease in modulus of elasticity oscillates between 15% to 45% concerning natural aggregate concrete. Modulus of elasticity was reported to be negatively affected by incorporation of REC [6, 41, 56]. Kessal et al. reported that the module of elasticity of REC mixtures is lower in comparison with the normal concrete. The reduction is about 20% with regard to the normal concrete [53].

Figure 7 presents changes of elasticity modulus E of concrete, depending on the type of concrete and the compressive strength after 28 days. A linear trend was characterised by $R = 0.728$. Obtained correlations may be described by an equation: $y = 0.095x + 29.57$.

It is worth noticing that tests proved that the level of difference of elasticity modulus value

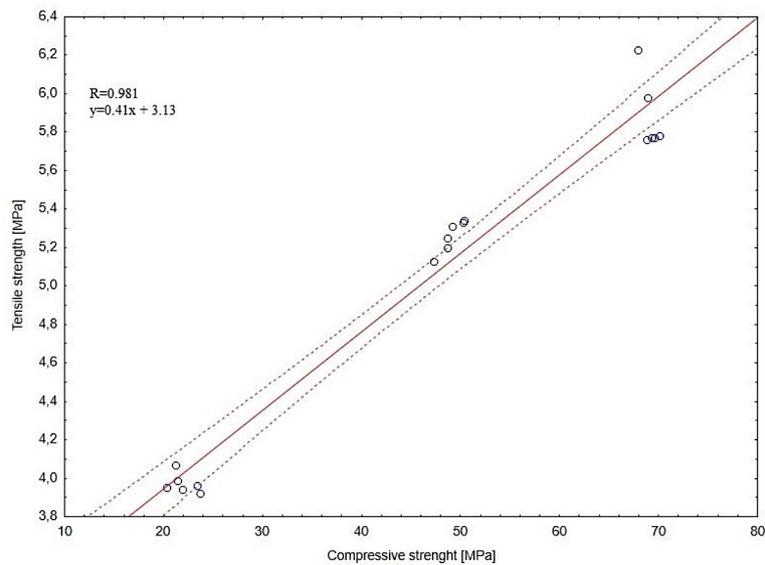


Figure 6. Correlation between tensile strength and compression strength

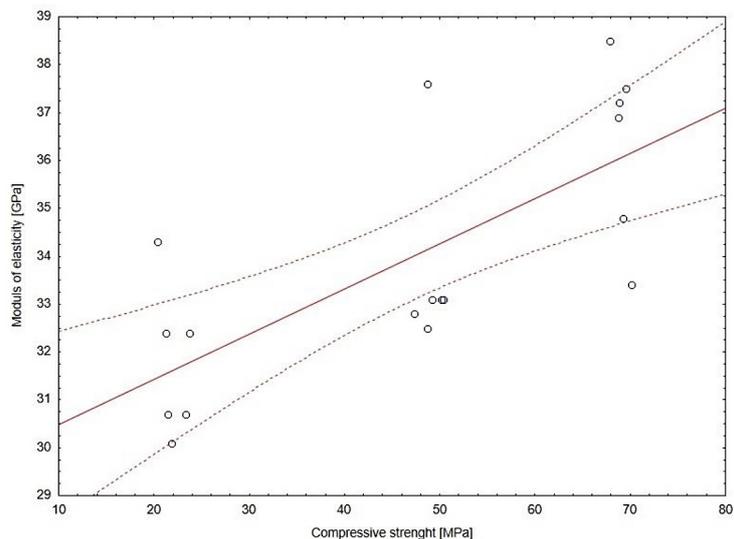


Figure 7. Correlation between compression strength and elastic modulus E of concrete

between recycled concrete and natural aggregate concretes depends also on the compressive strength of tested concretes and for concretes with average values up to 30 MPa the difference of moduli values is almost insignificant, yet with an increase in strength over that values the difference between moduli increases [43]. Table 9 presents values of the ratio of elasticity and rigidity moduli of tested concretes.

The rigidity and elasticity moduli ratio for each tested type of concrete was insignificantly lower than 1%. Tests of dynamic elasticity modulus of concrete proved that both rigidity and elasticity moduli of high-strength concrete are closely approximate and higher approximately 16% than moduli of recycled aggregate

concrete. Rigidity and elasticity moduli of ordinary concrete are lower than REC moduli by 1-2%. The highest value of the ratio of shear strain to the elastic strain of concrete with

Table 9. Correlation rate between elasticity and rigidity moduli

Correlation $B_{i,rigidity}/B_{i,elasticity}$	r	r [%]
BZ_{rg}/BZ_{el}	0.99	99.20
BWW_{rg}/BWW_{el}	0.98	98.04
REC_{rg}/REC_{el}	0.97	97.42
$BWWrg/RECel$	1.16	115.70
$BZrg/RECel$	0.99	99.58
$BWWrg/RECel$	1.15	114.98
$BZrg/RECel$	0.98	97.80

basalt aggregate results from the low elastic strain of that concrete [58].

CONCLUSION

The presented article aimed at the evaluation of mechanics and strength properties of REC and comparison with ordinary concrete, as well as natural aggregate concrete. From the obtained results following conclusions may be drawn:

1. The compressive strength of cubic samples for the concrete with recycled aggregate (REC) was 31% lower than that of BWB, but 50% higher compared to ordinary concrete (BZ).
2. The tensile strength of the concrete with recycled aggregate was 33% lower than that of BWB and 21% lower compared ordinary concrete.
3. Tests of dynamic elasticity modulus of concrete proved that both rigidity and elasticity moduli of high-strength concrete are closely approximate and higher approximately 16% than moduli of REC. Rigidity and elasticity moduli of ordinary concrete are lower than REC moduli by 1-2%;
4. Statistic analyses proved that values of compressive and tensile strengths are statistically different between tested concretes.

The conducted studies indicated that the adopted method of designing the concrete mix with recycled aggregate is correct and yields measurable results. It was proven that recycled aggregate can be successfully used as a concrete ingredient. Those results emphasise the importance of producing mixtures that may facilitate obtaining a structure of concrete, even containing waste, recycled aggregate characterised by various mechanical properties. Recycled aggregate may become an effective mean for decreasing the impact of construction on the environment, even improving their durability. Furthermore, the combined application of recycled aggregate with mineral waste and alternative bio-natural aggregate [59, 60] and structure is an effective approach towards minimalization of the influence of construction on the environment.

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