DOI: 10.7409/rabdim.025.037

ANDRZEJ DUSZYŃSKI [1)]
ORCID: 0000-0002-8842-5630

Evaluation of recycled construction aggregates in terms of strength and durability properties for use in road engineering

Abstract: Recycled construction aggregates represent a wide range of aggregates used in road engineering and are characterised by relatively high variability in the properties tested even within the same type of raw material used for its production. The properties laid down in specific regulations concerning applications do not reflect the specific characteristics of recycled aggregates. Being aggregates that are inherently multi-component or formed by mixing different raw materials and crushable, they require expanded testing and evaluation methods for their classification for road engineering applications. The important strength- and durability-related properties of these aggregates are grading stability, stability of load-bearing capacity, and reinforcement ratio. The basic element of this paper will be the results of aggregate tests and their analysis in terms of the evaluation of properties resulting from the specificity of aggregates as well as the classification of requirements and performance characteristics used in Polish technical documents. The maximum change in grading makes it possible to pre-classify recycled construction aggregates for specific layers in road pavement construction. On the other hand, the stability of load-bearing capacity expressed through the guaranteed bearing capacity index or reinforcement ratio makes it possible to correctly identify changes in load-bearing capacity in an aggregate in terms of minerals, composition, or chemistry.

Keywords: bearing capacity index, maximum change in grading, recycled aggregates, reinforcement ratio, stability of load-bearing capacity.

[1)] Road and Bridge Research Institute, Wrocław Branch, 55-140 Żmigród, Poland; andrzej.duszynski@ibdim.edu.pl

1. RECYCLED CONSTRUCTION AGGREGATES

1.1. COMPONENTS

In Europe, demolished buildings consist mainly of brick and concrete [1], with the percentage of the main materials in demolished buildings being brick 45%, concrete 40%, wood 8%, metals 4%, other 3% [2]. PN-EN 13242+A1:2010 [3] specifies the required coarse component categories (Table 1) for recycled aggregates for unbound and hydraulically bound mixtures used in construction and civil engineering. The specificity of recycled construction aggregates, as opposed to, for example, natural aggregates, lies primarily in the fact that, even as single-component aggregates, they may contain, in a limited proportion, other components listed in Table 1 or, within the basic component, the same component but of different quality. Besides, these components can affect the properties of the aggregate in question in either a positive or a negative way.

Table 1. Component categories of coarse recycled aggregates according to PN-EN 933-11:2009 [4]

Designation of categories	Components of coarse recycled aggregates
Rc	Concrete, concrete products, mortar, concrete brick walls
Ru	Unbound aggregates, natural rocks, hydraulically bound aggregate
Rb	Clay brick walls (i.e., brick and tile), lime-sand brick, non-floating cellular concrete
Ra	Bituminous materials
FL	Free-floating material
X	Other: cohesive (i.e., clay and soil); miscellaneous: metals (ferrous and non-ferrous), non-floating wood, plastic and rubber
Rg	Glass

The following essential characteristics are important at the stage of selecting recycled construction aggregates:

- content of components (parts) in coarse fractions above 4 mm – categories of components (Table 1),
- water-soluble components - required absence of substances harmful to the environment according to separate regulations.

1.2. TYPES

According to the 1994 RILEM Recommendation [5], the following types of recycled construction aggregates are distinguished:

- Type I – material derived from masonry elements.
- Type II – material derived from concrete elements.
- Type III – mixed aggregate consisting of at least 80% natural aggregate and a maximum of 10% Type I aggregate.

RILEM recommendations also define the criteria for accepting recycled concrete aggregate. However, these recommendations do not consider reclaimed asphalt pavement.

Currently, recycled construction aggregates produced worldwide [6], in Europe [1], [2] and in Poland include primarily:

- Recycled concrete aggregate [7-9] obtained from waste concrete that can come from building structures, i.e., from construction and demolition during the construction of new buildings and civil engineering structures and obtained during the renovation or demolition of existing buildings. As well as with engineered facilities covering civil engineering structures, including public facilities such as streets and highways, bridges, utilities, and dams. The waste concrete and aggregates deriving from it should be paid special attention to. The performance of aggregate largely depends on the origin of the raw material, processing, grading, and the amount of mortar [7], [9-10], A peculiar property of recycled concrete aggregates is the possible liberation of non-hydrated portions of cement as a result of crushing the raw concrete material. Storage of recycled concrete aggregates at aggregate plants requires special storage facilities.
- Recycled brick aggregate manufactured from crushed brick walls and bricks, but also from tiles and building ceramic elements.
- Recycled mixed aggregate is formed by combining different types of construction waste, such as concrete, brick, and bituminous components.
- Reclaimed asphalt pavement [7] is produced from bituminous mixtures were referred to in Regulation [11], and as reclaimed asphalt pavement in Regulation [12], which is formed as a result of cold milling of asphalt

layers and crushing slabs cut out from asphalt pavement or lumps obtained from these slabs. As well as from rejects or surpluses generated in the production of bituminous mixture as waste with code 17.03.02 [11]. They may contain tar components, which are subject to separate regulations [12]. In general, reclaimed asphalt pavement is a valuable material for use in unbound mixtures due to its very good strength and durability properties [5].

2. TECHNICAL REGULATIONS

Polish technical regulations for unbound recycled aggregates are based on PN-EN 13242 + A1:2010 [3] for road construction and on PN-EN 13285:2018-08 [13], but specific requirements are specified in Technical Requirements WT-4 2010 [14] I WT-4 2025 [15], and technical specifications (TS). It should be stressed that WT-4 [14-15], apply to the following mixtures: 0/8; 0/11.2; 0/16; 0/22.4; 0/31.5; 0/45; 0/63.

Archival WT-4 2010 [14] opened the possibility of using recycled aggregates to the extent limited by their crushability after 5-fold Proctor compaction, according to PN-EN 13286-2:2010 [16]. According to WT-4 2010 [14], recycled aggregates could be used independently (100%). In addition, when the resistance to freezing and thawing of recycled aggregate is in the range between 10% and 25%, the aggregate could be used as long as its content in the mix did not exceed 50% m/m.

The current WT-4 2025 [15] contains an important provision stating that when one aggregate makes up 100% of the unbound mixture, the requirements for mixtures should be applied while meeting the requirements included for aggregates for mixtures in terms of density and absorbability. Besides, according to Note 3 in Table 1 in WT-4 2025 [15], recycled aggregate can be used in mixtures with natural aggregate, provided that the requirements for aggregates for mixtures are met. The recycled aggregate content in the mixture must not exceed 30% m/m. In the case of recycled concrete aggregate for the improved base and substructure, it is recommended to use aggregate extracted from concrete with specific classes based on compressive strength and tensile strength in splitting tests.

The Road and Bridge Research Institute issues National Technical Assessments for, among other things, recycled construction aggregates in a wide range of materials and applications for unpaved temporary roads, base and subbase, improved subgrade, embankments, and earthworks. The basis for such action is the proper recognition of the quality of recycled construction aggregate, taking into account its specific characteristics. The essential characteristics of these aggregates are crushability and the ability to change (either positively or negatively) the strength characteristics in terms of minerals, composition, or chemistry.

3. SELECTION OF RECYCLED CONSTRUCTION AGGREGATES

Recycled construction aggregates, a list of which is included in Table 2, were selected for the study. The test results of recycled brick aggregates and reclaimed asphalt pavement as single component aggregates are presented for comparison in relation to recycled concrete aggregates, and for this purpose the test results for reclaimed asphalt pavement according to [7] and recycled brick aggregates were used.

Table 2. List of recycled construction aggregates selected for testing

No.	Waste material type	Aggregate type	Aggregate designation
1	Concrete	Recycled concrete aggregate	2, 8, 9, 10, 12, 13
2	Concrete, brick (up to 8%)	Recycled concrete aggregate	4, 11
3	Concrete, aggregate (up to 16%)	Recycled concrete aggregate	6, 7
4	Brick without mortar (mortar 2%)	Recycled brick aggregate	C
5	Brick with mortar 8%	Recycled brick aggregate	Cz
6	Reclaimed asphalt pavement	Reclaimed asphalt pavement	A

4. RESEARCH SCOPE AND METHODOLOGY

4.1. IDENTIFICATION STUDIES

Identification studies are concerned with the basic essential characteristics directly related to the grading of recycled aggregates, which include the stability of these aggregates in terms of grading and composition, as well as substances particularly harmful to the water environment in terms of:

a) grading $f(d_i)$ – according to PN-EN 933-1:2012 [17]; recycled construction aggregates should be prepared in such a way that their characteristics related to binding properties or to the presence of binder in the reclaimed asphalt pavement are not altered. It is best to dry the aggregate under natural or laboratory conditions at an increased room temperature with ensured ventilation. Grading of $f(d_i)$ aggregate should be tested dry on basic sieves according to PN-EN 933-1:2012 [17] plus set 1 according to PN-EN 13242 + A1:2010 [3],

b) content of components after grading testing (see section 2.3.1.a on a fractionated test sample. The content of components should be determined on the spread sample after grading test according to a),

c) grading $f_5(d_i)$ – (after 5-fold Proctor compaction according to PN-EN 13286-2:2010 [16], according to PN-EN 933-1:2012 [17]. After mixing the sample after testing the content of components according to b), dry 5-fold Proctor compaction is carried out according to PN-EN 13286-2:2010 [16], and then the grading $f_5(d_i)$ is determined according to PN-EN 933-1:2012 [17],

d) grading stability [6] – maximum change in grading $Z_{f\,max}$ after 5-fold Proctor compaction according to PN-EN 13286-2:2010 [16]. WT-4 2010 [14] defines the term "maximum grading change" when defining "weak aggregate". Grading change $Z_f(d_i)$ is calculated on each sieve d_i as the difference of grading $f(d_i)$ from grading $f_5(d_i)$ obtained after 5-fold Proctor compaction according to PN-EN 13286-2:2010 [16]. The obtained values of grading change $Z_f(d_i)$ allow to determine grading stability as the maximum change in grading $Z_{f\,max}$,

e) values of impurities in water extract – preparation of water extract according to PN-EN 12457-4:2006 [18]. Table 3 lists the main contaminants, as well as the values of permissible contaminants in the water extract based on the environmental regulations [7] used in the NTA; for pH, the limit values were adapted to recycled concrete aggregates.

4.2. STRENGTH AND DURABILITY TESTS

Strength and durability tests included studies related to the stability of coarse particles and load-bearing capacity under road conditions in:

a) shape index according to PN-EN 933-4:2008 [26],

b) resistance to fragmentation determined by the Los Angeles method according to PN-EN 1097-2:2020-09 [27],

c) resistance to freezing and thawing according to PN-EN 1367-1:2007 [28],

d) resistance to freezing and thawing in the presence of salt (NaCl) according to PN-EN 1367-6:2008 [29],

e) bearing capacity index after Proctor compaction according to PN-EN 13286-2:2010 [16] after 4, 7, 15 and 30 days of water saturation under load according to PN-EN 13286-47:2022-04 [30]. Based on these tests, the following were calculated:

- stability of load-bearing capacity [6] defined as the guaranteed bearing capacity index w_g after soaking under load, constituting an average of bearing capacity index after 4, 7, 15 and 30 days of soaking in water,
- reinforcement ratio $ww = w_g/w_4$.

5. CLASSIFICATION REQUIREMENTS

5.1. IDENTIFICATION REQUIREMENTS

Table 4 shows the identification requirements according to IBDiM National Technical Assessments (NTA) including the ww reinforcement ratio and according to WT-4 2025 [15] for traffic category KR3-KR7.

5.2. STRENGTH AND DURABILITY REQUIREMENTS

Table 5 shows the strength and durability requirements according to NTA including the ww reinforcement ratio and according to WT-4 2025 [15] for traffic category KR3-KR7. The requirements for resistance to freezing and thawing in the presence of salt (NaCl) and for shape have been omitted due to the mild requirements met by all recycled construction aggregates selected according to Section 3.

6. TEST RESULTS AND ANALYSIS

6.1. IDENTIFICATION STUDIES

Table 6 shows the results of the test of recycled construction aggregate components and maximum particle sizes obtained from calculations based on the grading test and grading after 5-fold Proctor compaction.

Table 3. Testing the contaminant values in water extracts

No.	Tested feature	Method	Reference document	Minimum scope *min* mg/dm^3	Admissible value v_i mg/dm^3
1	Chlorides	IC-CD	PN-EN ISO 10304-1:2009 [19]	5.0	1000
2	Sulphates VI	IC-CD		1.0	500
3	Sodium	ICP-OES	PN-EN ISO 11885:2009 [20]	0.23	800
4	Potassium	ICP-OES		0.39	80
5	Zinc	ICP-OES		0.0050	2
6	Cadmium	ICP-OES		0.0005	0.2
7	Copper	ICP-OES		0.0050	0.5
8	Nickel	ICP-OES		0.0050	0.5
9	Lead	ICP-OES		0.0050	0.5
10	Total chromium	ICP-OES		0.0030	0.5
11	Free cyanides	CFA-S	PN-EN ISO 14403-2:2012 [21]	0.0050	0.1
12	Sulphides	(S)	Percentage Bad (Merck Spectroquant 14779) [22]	0.050	0.2
13	pH	(P)	PN-EN ISO 10523:2012 [23]	2.0	13
14	Antimony	ICP-OES	PN-EN ISO 11885:2009 [20]	0.0050	0.3
15	Arsenic	ICP-OES		0.0050	0.1
16	Barium	ICP-OES		0.0050	2
17	Tin	ICP-OES		0.0050	2
18	Cobalt	ICP-OES		0.0030	1
19	Molybdenum	ICP-OES		0.0050	1
20	Iron	ICP-OES		0.0050	10
21	Mercury	AFS	PN-EN ISO 17852:2009 [24]	0.00050	0.03
22	Polycyclic aromatic hydrocarbons	HPLC-FLD	PN-EN ISO 17993:2005 [25]	0.050 µg/dm^3	25 µg/dm3

Test method desingations:
IC-CD – Ion chromatography with conductometric detection; ICP-OES – Plasma emission spectrometry; AFS – Atomic fluorescence spectrometry method; (S) – Spectrophotometric; CFA-S – Continuous flow analysis with spectrophotometric detection; (P) – Potentiometric; HPLC-FLD – SPE extraction, high-performance liquid chromatography with fluorescence detection.

Table 4. Identification requirements according to NTA for recycled construction aggregates and WT-4 2025 [15]

Properties	Marking	Requirements for the type of construction product		
		UP	PP	PZ
Requirements according to NTA in the absence of binding properties $ww \leq 1.2$				
Maximum change in grading (grading stability)	$Z_{f\,max}$	45	25	15
Contaminant values in water extract	–	according to Table 3		
Requirements according to NTA with binding properties or after improvement with cement or road binder with $ww \geq 1.2$				
Maximum change in grading (grading stability)	$Z_{f\,max}$	55	35	20
Contaminant values in water extract	–	according to Table 3		
Requirements according to WT-4 2025 [15] for traffic category KR3-KR7				
Grading requirements – grading curves	0/D	0/11.2-0/63	0/31.5-0/63	0/31.5-0/63
Contaminant values in water extract	–	lack of substances harmful to the environment according to separate regulations		

Table 5. Strength and durability requirements according to NTA for recycled construction aggregates and WT-4 2025 [15]

Key characteristics	Marking	Requirements for the type of construction product		
		UP	PP	PZ
Requirements according to NTA in the absence of binding properties $ww \leq 1.2$				
Resistance to fragmentation	LA	55	40	40
Resistance to freezing and thawing	F	10	7	4
Guaranteed bearing capacity index (stability of load-bearing capacity after Proctor compaction in accordance with PN-EN 13286-2:2010 [16] and after soaking under load)	w_g	40	60	80
Requirements according to NTA with binding properties or after improvement with cement or road binder with $ww \geq 1.2$				
Resistance to fragmentation	LA	–	40	40
Resistance to freezing and thawing	F	20	10	4
Guaranteed bearing capacity index (stability of load-bearing capacity after Proctor compaction in accordance with PN-EN 13286-2:2010 [16] and after soaking under load)	w_g	40	60	80
Requirements according to WT-4 2025 [15] for traffic category KR3-KR7				
Resistance to fragmentation	LA	60	40	35
Resistance to freezing and thawing	F	10	7	4
California bearing ratio (after Proctor compaction in accordance with PN-EN 13286-2:2010 [16] and after 4 days of soaking under load)	w_4 (CBR)	35	60	80

Table 6. Components of recycled construction aggregates and maximum grading obtained from grading test and grading after 5-fold Proctor compaction

Aggregate designation	Maximum particle size		Maximum change in grading	Share of components				
	Grading	Grading after 5-fold Proctor compaction		Reclaimed asphalt pavement	Concrete	Brick	Natural aggregate	Other
	mm	mm	%	%	%	%	%	%
C	31.5	22.4	43	–	–	94.5	–	3.5
Cz	31.5	22.4	33	–	–	90.1	–	1.5
2	100	90	35	–	100	–	–	–
4	80	63	34	–	82.1	8.1	8.2	1.6
6	45	31.5	10	–	84	–	16.1	–
7	80	63	48	–	94	0.5	4.9	0.3
8	90	63	21	–	98	2	–	–
9	90	63	20	–	100.0	–	–	–
10	80	45	16	–	98.7	1.7	–	–
11	31.5	22.4	13	–	95.7	4.3	–	–
12	45	31.5	9	–	99.8	–	–	0.2
13	45	31.5	20	–	100.0	–	–	–
A	–	–	20	100	–	–	–	–

In terms of grading, grading after 5-fold Proctor compaction and coarse component content, the following comments can be given:

- for the aggregate designated as No. 12, the maximum change in grading $Z_{\mathrm{f\,max}} = 9\%$ is less than 12.5%. According to the requirements of the NTA, the effect of 5-fold Proctor compaction on grading can be neglected,
- for each aggregate tested, there is a reduction in the maximum particle size after 5-fold Proctor compaction; in general, with an accuracy of up to 10% of the particle,

- no relationship between the grading of recycled construction aggregates and component shares.

According to the NTA, when the value of a specific contaminant is at most 2 times less than the limit value for that contaminant, it is subject to ongoing laboratory control. Table 7 shows the average test results of contaminant values in the water extract of recycled concrete aggregates for those values for which the factors of the impurity values in the permissible value (according to Table 3) are at most 2, i.e., when the contaminant values are at most 2 times smaller than the permissible values. Table 7 calculates the factor in the limit v_i for the maximum test result $\max_i x_i$ and the mean with 2 times the standard deviation $\overline{x_i} + 2 \cdot \sigma_i$. Other contaminants not included in Table 7 for the recycled aggregates tested have impurity values that correspond to the permissible contaminant values in the water extract in Table 3 and are more than 2 times lower than these permissible values.

In terms of contaminant values in the water extract, the following comments can be provided:

- the calculated factors of the test results of contaminant values in the water extract in relation to the limit values for each contaminant are at least 1. The calculated factors are similar for both the maximum value of impurities and statistically calculated for the mean with 2 times the standard deviation of the tested recycled concrete aggregates,
- the test results of the contaminant values in the water extract of all the recycled concrete aggregates tested meet the requirements for use in road construction.

6.2. STRENGTH AND DURABILITY TESTS

6.2.1. Strength and durability test results – stability of load-bearing capacity

First of all, Table 8 shows the results of strength and durability tests for stability of load-bearing capacity and including bearing capacity index and reinforcement ratios (Fig. 1).

Table 7. Statistical and identification values of contaminants in the water extract for recycled concrete aggregates

Tested feature	Acceptable value	Result			Factor in the limit value	
		Mean	Standard deviation	Maximum	Maximum	Average with 2 times the standard deviation
i	v_i	$\overline{x_i}$	σ_i	$\max_i x_i$	$v_i / \max_i x_i$	$v_i / \overline{x_i} + 2 \cdot \sigma_i$
–	mg/dm^3				–	–
Sulphates VI	500	71.1	127.0	369.0	1.4	1.5
Potassium	80	21.5	11.0	40.2	2.0	1.8
Free cyanides	0.1	0.034	0.022	0.050	2.0	1.3
pH	13	11.9	0.3	12.0	1.1	1.0

Table 8. Strength and durability test results – stability of load-bearing capacity

Aggregate type	Aggregate designation	Test results			
		Bearing capacity index after Proctor compaction [%]			Reinforcement ratio [%]
		immediate	after 4 days of soaking	guaranteed	
		w_b	w_4	w_g	ww
Recycled brick aggregate	C	51	50	45	0.90
	Cz	60	90	63	1.05
Recycled concrete aggregate	2	100	99	131	1.33
	4	33	26	30	1.15
	6	51	102	78	0.77
	7	45	61	79	1.29
	8	25	64	64	1.00
	9	101	118	124	1.05
	10	55	72	70	1.00
	11	84	98	85	0.87
	12	20	106	109	1.02
	13	17	60	60	1.02
Reclaimed asphalt pavement	A	–	19	19	0.97

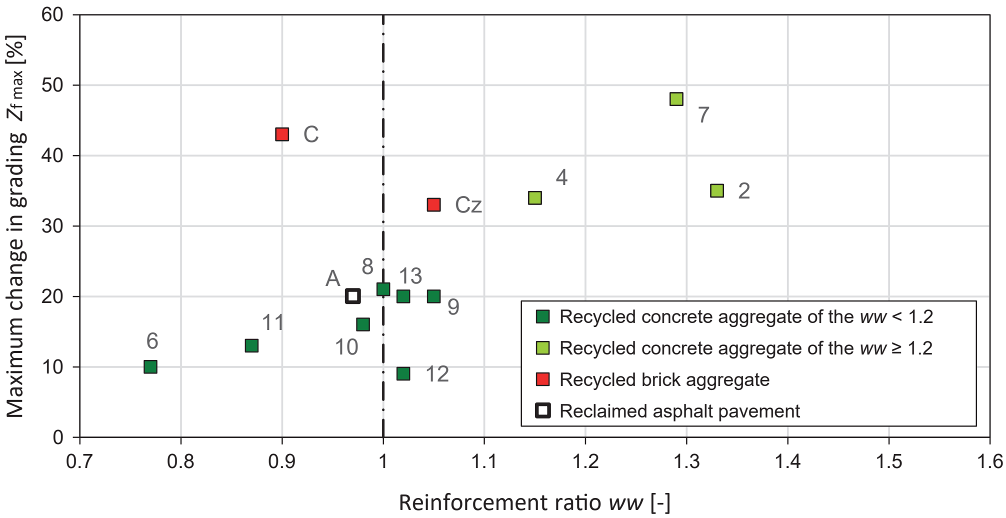

Fig. 1. Relationship between the maximum change in grading $Z_{f\ max}$ and the reinforcement ratio *ww* of the tested aggregates

In terms of strength and durability, the essential identifying property of recycled construction aggregates is the change in bearing capacity index determined over 4 days of soaking, manifested as an increase or a decrease in bearing capacity over time. The change in bearing capacity index is particularly important for recycled aggregates. For full classification, the binding properties of these aggregates, related to the release during compaction from the non-hydrated portions of cement contained in the concrete, must also be taken into account. To this end, Fig. 1 shows the maximum change in grading $Z_{f\ max}$ after 5-fold Proctor compaction according to PN-EN 13286-2:2010 [16] from the reinforcement ratio ww of the aggregates tested.

In terms of stability of load-bearing capacity, the following comments can be provided:

- it can be noted that the increase in bearing capacity index, as defined by a reinforcement ratio of at least 1.2, occurs only for recycled concrete aggregates characterised by a maximum change in grading of more than about 30%, i.e. aggregates that undergo significant grinding,
- the reinforcement ratio provides a good representation of the potential for reinforcement or weakening of the bearing capacity index for recycled aggregates over time,
- the range of the reinforcement ratio $ww = 1.0 \pm 0.1$ can be considered neutral in terms of the change in the bearing capacity index,
- a certain peculiarity is the aggregate designated as No. 6 with a low maximum grading change of 10%, which is characterised by a 23% decrease in the reinforcement ratio ww, and in terms of the bearing capacity index after 4 days of soaking from a value of 102% to a guaranteed bearing capacity index of 78%,
- for the aggregate designated as No. 2, there is an increase of 33% in the reinforcement ratio, which indicates the binding properties.

6.2.2. Results of strength and durability tests of w_g, *LA*, *F* and F_{NaCl}

The results of the *SI*, *LA*, *F* and F_{NaCl} tests are included in Table 9 and the results of the tests w_g, *LA*, *F* and F_{NaCl} are shown in Fig. 2 for the possibility of recognising recycled concrete aggregates in terms of applications.

In terms of strength and durability testing of coarse fractions, the following comments can be provided:

- resistance to fragmentation *LA* is an essential test that includes aggregate crushing. Results of tests for resistance to fragmentation using the Los Angeles method are contained in the range between 24% and 80%. The highest values of resistance to fragmentation *LA* occur for aggregates from recycled bricks and for aggregates from recycled bricks with mortar,
- aggregate designated as No. 11 with resistance to fragmentation of 39% according to WT-4 2025 [15] can be classified as an subbase due to the requirement for a base below 35%,

- the results of *SI* shape index tests for all tested aggregates meet the requirements for use in road construction,
- the results of resistance to freezing and thawing in the presence of salt (NaCl) F_{NaCl} are included in this study, although they are not required for the evaluation of bases and improved subgrade. It is worth noting that these requirements are met for brick, brick with mortar, and reclaimed asphalt pavement aggregates.

Table 9. Results of strength and durability tests for coarse fractions

Aggregate designation	Test results			
	Shape index [%]	Resistance to fragmentation [%]	Resistance to freezing and thawing [%]	Resistance to freezing and thawing in the presence of salt (NaCl) [%]
	SI	*LA*	*F*	F_{NaCl}
C	18	80	5.6	7.6
Cz	12	77	6.4	8.7
2	20	48	6.0	54.0
4	13	38	14.7	40.3
6	4	30	3.0	32.7
7	5	49	11.5	32.2
8	10	32	2.3	35.3
9	15	28	7.1	43.7
10	2	36	26.4	39.1
11	8	39	3.3	39.3
12	3	45	1.8	28.1
13	6	43	2.1	38.3
A	5	24	1.3	3.1

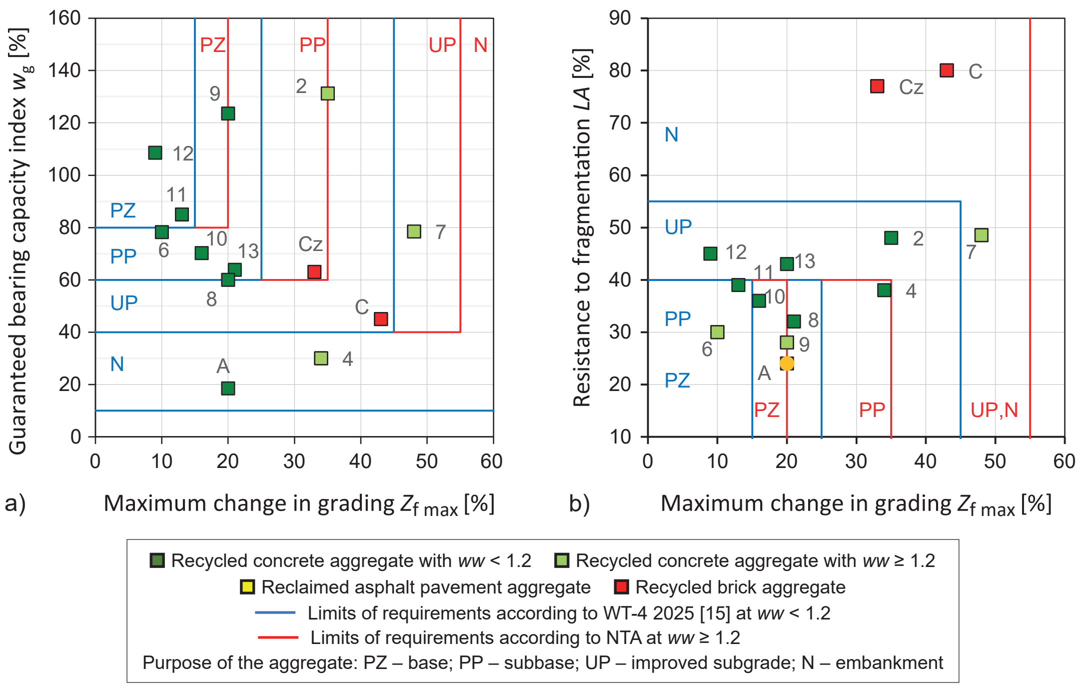

Fig. 2. Relationship between: a) guaranteed bearing capacity index w_g and the maximum change in grading $Z_{f\ max}$; b) resistance to fragmentation *LA* and the maximum change in grading $Z_{f\ max}$; including the limits of aggregate requirements according to the National Technical Assessments and WT-4:2025 [15] →

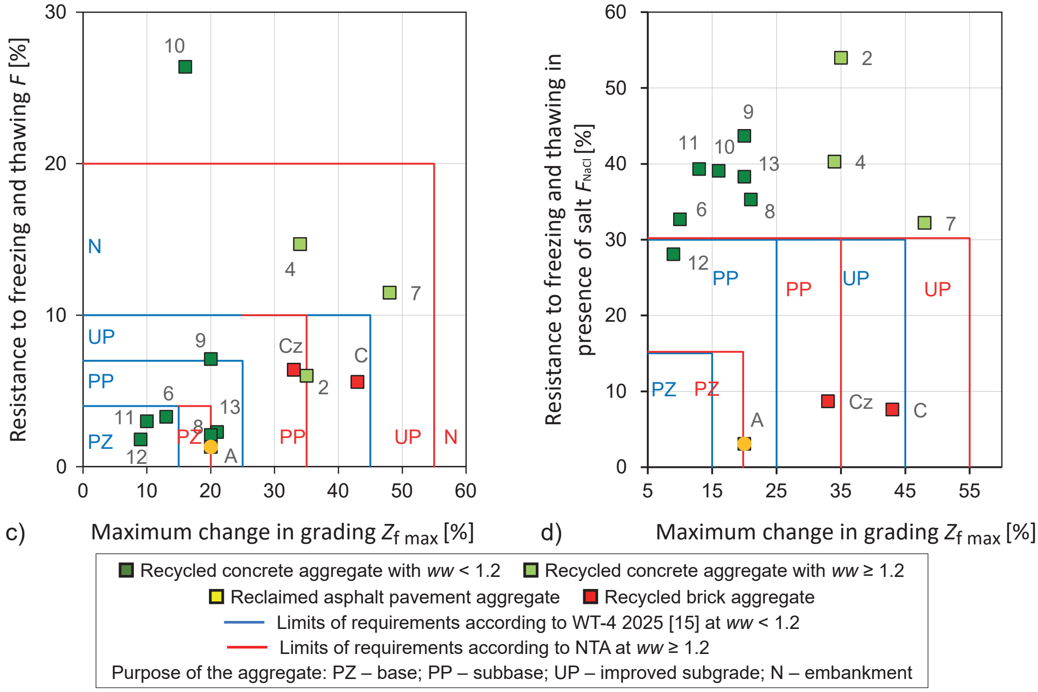

Fig. 2. Relationship between: c) resistance to freezing and thawing F and the maximum change in grading $Z_{\text{f max}}$; d) resistance to freezing and thawing in the presence of salt F_{NaCl} and the maximum change in grading $Z_{\text{f max}}$; including the limits of aggregate requirements according to the National Technical Assessments and WT-4:2025 [15]

7. CLASSIFICATION OF TEST RESULTS

Based on the test results obtained, the classification of the results labelled $Z_{\text{f max}}$, LA, F, w_g was carried out according to the requirements of the National Technical Assessments (NTAs) including the ww reinforcement ratio and the results labelled LA, F, w_4 according to WT-4 2025 [15]. The results of the classification are included in Table 10 and shown in Fig. 3 for specific layers in the road structure: base (PZ), subbase (PP), improved subgrade (UP) and beyond these layers (N). In the latter case, application to the layers of the embankment can be assumed.

For the aggregate designated as No. 6, the guaranteed bearing capacity index after Proctor compaction $w_g = 78\%$ compared to the bearing capacity index after 4 days of soaking $w_4 = 102\%$ is characterised by a 24% decrease in the bearing capacity index. Consequently, the requirements according to WT-4 2025 [15] allow this aggregate to be classified as a base (PZ), and the requirements according to NTA as a subbase (PP). The requirements according to NTA take into account the possibility of adverse changes in the aggregate in terms of bearing capacity.

For the aggregates designated as No. 2, No. 4, and No. 7, which are subject to the reinforcement ratio $ww \geq 1.2$, only aggregate No. 7 leads to a change in application to the improved subgrade (UP) layer.

Table 10. Classification of test results according to NTA requirements with *ww* reinforcement ratio and acc. to WT-4 2025 [15]

Aggregate designation	Classification according to requirements		
	of the National Technical Assessments at		WT-4 2025 [15]
	$ww < 1.2$	$ww \geq 1.2$	
C	N	–	N
Cz	N	–	N
2	UP	UP	UP
4	N	N	N
6	PP	–	PZ
7	N	UP	N
8	PP	–	PP
9	UP	–	UP
10	N	–	N
11	PZ	–	PP
12	UP	–	UP
13	UP	–	UP
A	N	–	N

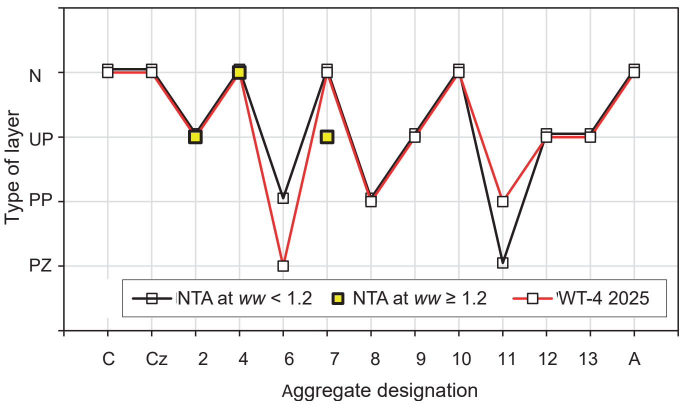

Fig. 3. Classification of recycled aggregates in terms of $Z_{f\,max}$, *LA*, *F* and w_g according to the National Technical Assessments (NTAs) and in terms of *LA*, *F* and w_4 according to WT-4 2025 [15]

8. CONCLUSIONS

The NTA requirements for recycled construction aggregates consider the following essential characteristics as relevant for unbound and multi-component aggregates: maximum change in grading determining the grading stability, as well as stability of load-bearing capacity determined by the guaranteed bearing capacity index after Proctor compaction after 4, 7, 15 and 30 days of soaking. For recycled construction aggregates, in addition to those included in PN-EN 13242 + A1:2010 [3], they are essential for classifying these aggregates in terms of strength and durability. Namely:

1. The maximum change in grading makes it possible to pre-classify recycled construction aggregates as unbound aggregates for specific layers in road pavement construction.
2. The guaranteed bearing capacity index ratio after Proctor compaction allows for proper identification of recycled aggregates, taking into account the possibility of changes in bearing capacity in the aggregate in terms of minerals, composition, or chemistry. In this aspect, using the reinforcement ratio, it is possible to determine the potential of binding or destructive properties of unbound aggregates related to the essential requirement which is bearing capacity.
3. The requirements of WT-4 2010 [14] for recycled concrete aggregates and construction aggregates in general should be supplemented with essential characteristics based on the specifics of these aggregates. Some of them, such as maximum change in grading, require changes in terms of procedure and classification. The reason is the bonding properties associated with the non-hydrated portions of cement present in recycled concrete aggregates after grinding. Similarly, other ingredients such as brick, asphalt waste and plastics present in recycled aggregates have a significant impact on the properties of these aggregates.

REFERENCES

[1] *Pereira P.M.*, *Vieira C.S.*: A literature review on the use of recycled construction and demolition materials in unbound pavement applications. Sustainability, **14**, 21, 2022, Article ID: 13918, DOI: 10.3390/su142113918

[2] *Kijowski G.*: Kruszywo z betonu. Budownictwo, Technologie, Architektura, **2**, 34, 2006, 46-47, https://www.bta-czasopismo.pl/archiwum/wydanie-234-2006 (available in Polish: 24.11.2025)

[3] PN-EN 13242+A1:2010 Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction

[4] PN-EN 933-11:2009 Tests for geometrical properties of aggregates – Part 11: Classification test for the constituents of coarse recycled aggregate

[5] RILEM Recommendation. Specifications for concrete with recycled aggregates. Materials and Structures, **27**, 1994, 557-559, https://link.springer.com/article/10.1007/BF02473217 (available 24.11.2025)

[6] *Tam V.W.Y.*, *Soomro M.*, *Evangelista A.C.J.*: A review of recycled aggregate in concrete applications (2000-2017). Construction and Building Materials, **172**, 2018, 272-292, DOI: 10.1016/j.conbuildmat.2018.03.240

[7] *Duszyński A.*, *Bańkowski W.*, *Horodecka R.*: Wykorzystanie kruszywa z recyklingu betonowego i destruktu asfaltowego w podbudowie i dolnych warstwach konstrukcyjnych nawierzchni drogowych oraz w ulepszonym podłożu. IBDiM, Studia i Materiały „S” 98, Warszawa, 2025 (in Polish)

[8] *Duszyński A.*, *Jasiński W.*, *Gut R.*: The effect of compaction of typical recycled concrete aggregates on meeting WT-4 requirements. Materiały Budowlane, **632**, 4, 2025, 8-14, DOI: 10.15199/33.2025.04.02

[9] *Junior G.A.F.*, *Leite J.C.T.*, *Mendez G.P.*, *Haddad A.N.*, *Silva J.A.F.*, *da Costa B.B.F.*: A review of the characteristics of recycled aggregates and the mechanical properties of concrete produced by replacing natural coarse aggregates with recycled ones – fostering resilient and sustainable infrastructures. Infrastructures, **10**, 8, 2025, Article ID: 213, DOI: 10.3390/infrastructures10080213

[10] *Kalinowska-Wichrowska K.*, *Pawluczuk E.*, *Bołtryk M.*: Waste-free technology for recycling concrete rubble. Construction and Building Materials, **234**, 2020, Article ID: 117407, DOI: 10.1016/j.conbuildmat.2019.117407

[11] Rozporządzenie Ministra Klimatu z dnia 2 stycznia 2020 r. w sprawie katalogu odpadów. Dz. U. z dnia 3 stycznia 2020 r. poz. 10

[12] Rozporządzenie Ministra Klimatu i Środowiska z dnia 23 grudnia 2021 r. w sprawie określenia szczegółowych warunków utraty statusu odpadów dla odpadów destruktu asfaltowego, Dz.U. 2021, poz. 2468

[13] PN-EN 13285:2018-08 Unbound mixtures. Specifications

[14] WT-4 2010 Mieszanki niezwiązane do dróg krajowych. Wymagania Techniczne. Załącznik Nr 3 do Zarządzenia Nr 102, GDDKiA, 2010 (in Polish)

[15] WT-4 2025 Mieszanki niezwiązane do dróg krajowych. Wymagania Techniczne, GDDKiA, 2025 (in Polish)

[16] PN-EN 13286-2:2010 Unbound and hydraulically bound mixtures. Part 2: Test methods for laboratory reference density and water content – Proctor compaction

[17] PN-EN 933-1:2012 Testing of geometrical properties of aggregates – Part 1: Determination of particle size distribution – Sieving method

[18] PN-EN 12457-4:2006 Characterisation of waste – Leaching – Compliance test for leaching of granular waste materials and sludges – Part 4: One stage batch test at a liquid to solid ratio of 10 l/kg for materials with particle size below 10 mm (without or with size reduction)

[19] PN-EN ISO 10304-1:2009 Water quality – Determination of dissolved anions by liquid chromatography of ions – Part 1: Determination of bromide, chloride, fluoride, nitrate, nitrite, phosphate and sulphate

[20] PN-EN ISO 11885:2009 Water quality – Determination of selected elements by inductively coupled plasma optical emission spectrometry (ICP-OES)

[21] PN-EN ISO 14403-2:2012 Water quality – Determination of total cyanide and free cyanide using flow analysis (FIA and CFA) – Part 2: Method using continuous flow analysis (CFA)

[22] Test Procedure (Merck Spectroquant 14779) – Sulfide test. Merck KGaA, Darmstadt, Germany, 2021, https://www.sigmaaldrich.com/PL/pl/product/mm/114779?utm_source=-chatgpt.com(available (available: 24.11.2025)

[23] PN-EN ISO 10523:2012 Water quality – Determination of pH

[24] PN-EN ISO 17852:2009 Water quality – Determination of mercury – Method using atomic fluorescence spectrometry

[25] PN-EN ISO 17993:2005 Water quality – Determination of 15 polycyclic aromatic hydrocarbons (PAH) in water by HPLC with fluorescence detection after liquid-liquid extraction

[26] PN-EN 933-4:2008 Tests for geometrical properties of aggregates – Part 4: Determination of particle shape – Shape index

[27] PN-EN 1097-2:2020-09 Tests for mechanical and physical properties of aggregates – Part 2: Methods for determination of the resistance to fragmentation

[28] PN-EN 1367-1:2007 Testing thermal properties and resistance of aggregates to the elements – Part 1: Determination and resistance to freezing and thawing

[29] PN-EN 1367-6:2008 Tests for thermal and weathering properties of aggregates – Part 6: Determination of resistance to freezing and thawing in the presence of salt (NaCl)

[30] PN-EN 13286-47:2022-04 Unbound and hydraulically bound mixtures – Part 47: Test method for the determination of California bearing ratio, immediate bearing index and linear swelling

Ocena kruszyw z recyklingu budowlanego pod względem właściwości wytrzymałościowo-trwałościowych do stosowania w budownictwie komunikacyjnym

Streszczenie: Kruszywa pochodzące z recyklingu budowlanego stanowią znaczący udział wśród materiałów stosowanych w budownictwie komunikacyjnym i charakteryzują się stosunkowo dużą zmiennością badanych właściwości, nawet w obrębie tego samego rodzaju surowca wykorzystanego do ich produkcji. Właściwości określone w przepisach szczegółowych dotyczących zastosowań nie odzwierciedlają specyficznych cech kruszyw z recyklingu. Jako kruszywa z natury wieloskładnikowe lub powstające w wyniku mieszania składników o zróżnicowanym pochodzeniu surowcowym oraz charakteryzujące się obniżoną odpornością na kruszenie wymagają one rozszerzenia zakresu metod badawczych i ustalenia kryteriów oceny na potrzeby ich klasyfikacji do zastosowań w budownictwie komunikacyjnym. Istotnymi właściwościami wytrzymałościowo-trwałościowych tych kruszyw są stabilność uziarnienia, stabilność nośności i wskaźnik wzmocnienia. Podstawowym jednak elementem niniejszego artykułu są wyniki badań kruszyw oraz ich analiza w kontekście oceny właściwości wynikających ze specyfiki kruszyw, a także klasyfikacji wymagań i właściwości użytkowych określonych w polskich dokumentach technicznych. Maksymalna zmiana uziarnienia umożliwia wstępną klasyfikację kruszyw pochodzących z recyklingu budowlanego do odpowiednich warstw konstrukcji nawierzchni drogowej. Z kolei stabilność nośności, wyrażona za pomocą gwarantowanego wskaźnika nośności lub wskaźnika wzmocnienia, pozwala na właściwą identyfikację zmian nośności kruszywa wynikających z jego składu mineralnego, struktury oraz właściwości chemicznych.

Słowa kluczowe: kruszywa z recyklingu, maksymalna zmiana uziarnienia, stabilność nośności, wskaźnik nośności, wskaźnik wzmocnienia.