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Analysis of the feasibility of using shredded waste from group 19 12 10/12 in unbound mixtures for embankment construction

Abstract: The paper investigates the feasibility of incorporating materials obtained from the sorting and mechanical processing of waste into unbound mixtures intended for road embankment construction. The objective of the study was to evaluate the effect of adding shredded waste from groups 19 12 10/12 on the mechanical performance of unbound mixtures designed for road embankments and to determine the maximum waste content that satisfies the applicable technical requirements. The experimental programme comprised laboratory tests to determine compaction characteristics, California Bearing Ratio (*CBR*), coefficient of permeability and internal friction angle of soil/aggregate mixtures containing different proportions of shredded waste. The applicability and limitations of these materials were analysed with reference to current technical specifications and international experience. The results demonstrate that shredded waste from groups 19 12 12/10 can be successfully incorporated into materials used for road embankment construction, providing significant economic, social and environmental benefits.

Keywords: unbound mixtures, road embankment, recycling, shredded waste from groups 19 12 10/12.

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1. INTRODUCTION

This paper continues and extends the research presented in [1-2], which examined the use of waste generated during the mechanical processing and sorting of plastic waste in pavement layers, particularly cement-bound layers. The present study introduces another innovative application of processed waste in road engineering. The proposed solution concerns waste groups 19 12 12 and 19 12 10, which have not yet found large-scale applications in other industrial sectors, while their storage and disposal remain expensive. It should be emphasised that these waste streams cannot be managed solely by municipal waste-to-energy plants because Poland currently has only nine major facilities with a combined treatment capacity of approximately 1.5 million Mg/year, corresponding to only about 10–12% of the total municipal waste generated nationwide [3]. For comparison, Germany operates approximately one hundred waste-to-energy plants with a combined annual capacity of 26-28 million Mg [4-5], representing nearly eight times greater treatment capacity per capita than in Poland. Moreover, attempts to construct new waste-to-energy plants in Poland continue to encounter considerable environmental and social opposition. Consequently, the storage of these waste materials remains an important socio-economic and environmental challenge.

This study evaluates the feasibility of using unbound mixtures composed of soils/aggregates and shredded waste for the construction of road embankments and other linear earth structures. Particular attention is paid to the environmental aspects of the proposed solution.

2. RECYCLED MATERIALS FROM WASTE GROUPS 19 12 12 AND 19 12 10

Materials classified under waste codes 19 12 12 (other mixed materials generated from the mechanical treatment of waste) and 19 12 10 (combustible waste, including mixed materials generated from the mechanical treatment of waste) were used in the experimental programme. The materials originated from the sorting of plastic waste after homogeneous fractions with well-defined physicochemical properties, intended for other industrial applications, had been separated. Representative photographs of the shredded waste are shown in Figs. 1 and 2.

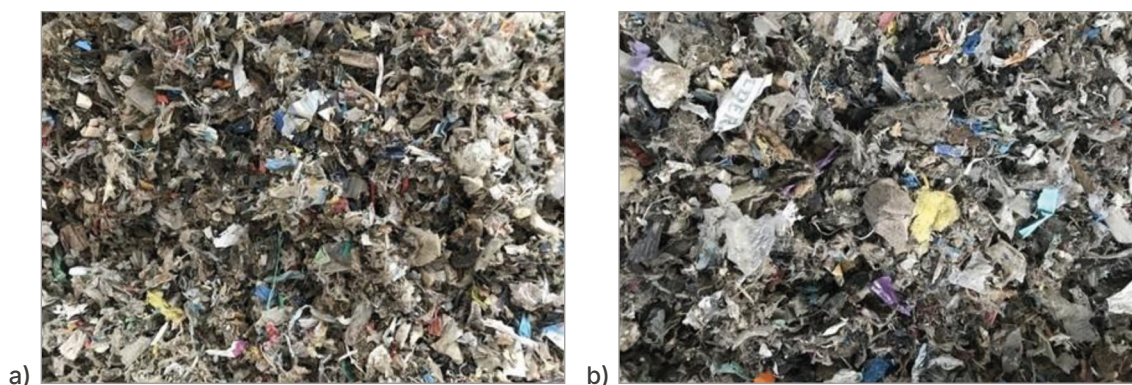


Fig. 1. Shredded waste classified as code: a) 19 12 12, b) 19 12 10



Fig. 2. Materials before adding shredded waste:
a) clay, b) sandy gravel, c) recycled concrete aggregate

It should be noted that the primary use of waste from group 19 12 10 should be as a potential energy source in waste-to-energy facilities. The Authors do not intend to suggest that material recovery in road embankments should replace energy recovery where thermal treatment is technically, environmentally and economically justified. However, the potential use of this waste stream in road embankments was investigated due to the significant lack of suitable waste-to-energy facilities in Poland. The present study should therefore be regarded as an investigation of a potential complementary recovery route rather than as a recommendation to replace waste-to-energy treatment.

Compared with the waste classified as 19 12 12, the 19 12 10 material was characterised by a coarser particle size and greater visual heterogeneity. However, both waste streams exhibited a similar particle density of approximately 1.1 g/cm^3 and a bulk density of approximately 0.11 g/cm^3 . The characteristic particle size of the shredded waste from group 19 12 12 was approximately 10 mm, whereas larger fragments were present in the 19 12 10 material. It should be noted that further shredding to particle sizes below 10 mm is considered excessively energy-intensive and economically unjustified.

3. TECHNICAL REQUIREMENTS

The feasibility of using shredded waste from groups 19 12 12 and 19 12 10 in road embankments was assessed with reference to the still valid and widely applied Polish Standard PN-S-02205 Road Works – Earthworks – Requirements and Testing [6]. It should be noted that the current European standard for earthworks, PN-EN 16907, and in particular PN-EN 16907-2 [7], does not specify limiting values of engineering properties governing the suitability of materials for specific earthwork applications. Therefore, the key acceptance criteria adopted in this study are those specified in PN-S-02205 for unbound embankment materials (Table 1).

Table 1. Selected requirements for embankment materials according to PN-S-02205

Property	Requirement
Maximum dry density $\rho_{d,\max}$ [g/cm^3]	> 1.6
California Bearing Ratio CBR [%]	> 10
Coefficient of permeability k_{10} [m/s]	$> 1 \times 10^{-5}$
Coefficient of permeability k_{10} [m/s] (upper 0.5 m of embankment)	$> 6 \times 10^{-5}$

4. SOILS AND AGGREGATES FOR THE PREPARATION OF MIXTURES CONTAINING SHREDDED WASTE

Three representative materials commonly used in road earthworks were selected for the preparation of mixtures containing shredded waste: clay, sandy gravel, and recycled concrete aggregate (RCA). Photographs of the materials are presented in Fig. 2. The laboratory testing programme included determination of the sand equivalent, capillary rise, grading index, permeability, optimum moisture content, maximum dry density and California Bearing Ratio *CBR* (Table 2).

Table 2. Basic properties of the constituent materials used for preparing mixtures containing shredded waste

Property	Clay	Sand-gravel	Recycled concrete aggregate
Sand equivalent [%]	2	91	42
Capillary rise [m]	>2.0	0.17	0.84
Coefficient of uniformity [-]	10	3	91
Permeability [m/day]	0	3.02	0.02
Optimum moisture content [%]	13	9	7.5
Maximum dry density [g/cm ³]	1.901	1.846	2.215
California Bearing Ratio <i>CBR</i> [%]	2.5	14.7	108.8

The test results demonstrated that all investigated materials are suitable for road embankment construction in accordance with PN-S-02205. Clay may also be used in the upper frost-susceptible zone of an embankment, provided that it is improved with an appropriate hydraulic binder.

5. UNBOUND MIXTURES CONTAINING LIME

The materials listed in Table 2 were subsequently used to prepare unbound mixtures containing shredded waste from group 19 12 12 and lime. The lime content was relatively low (0.5-1.0% by mass of the mixture) and was insufficient to bind the constituent materials. Therefore, any improvement in the mechanical properties resulting from lime addition was considered of secondary importance. The primary purpose of adding lime was environmental, namely to increase the pH and reduce the leachability of contaminants [8-9], particularly trace amounts of heavy metals that may be present in shredded waste from group 19 12 12, as well as to minimise odour emissions. Recommendations concerning the environmental assessment of embankment materials produced from unbound mixtures containing shredded waste from groups 19 12 12 and 19 12 10 are currently being developed by the authors in cooperation with environmental experts and will be presented in a separate publication.

A proprietary additive designated IP10-Ca was prepared by blending 100 kg of lime with 1000 kg of shredded waste from group 19 12 12 (10% lime by mass of shredded waste), producing a material with a uniform appearance. Fig. 3 shows the appearance of the IP10-Ca mixture.



Fig. 3. IP10-Ca mixture composed of lime and shredded waste from group 19 12 12

The shredded waste content of the unbound mixtures was increased by increasing the proportion of the IP10-Ca concentrate rather than by increasing the amount of shredded waste within the concentrate itself. Mixtures containing different proportions of shredded waste from group 19 12 12 were investigated. Clay, sandy gravel and recycled concrete aggregate were blended with 6%, 12% and 18% IP10-Ca (by dry mass). For each mixture, the maximum dry density and optimum moisture content were determined using the Proctor compaction test. The results are presented in Figs. 4 and 5.

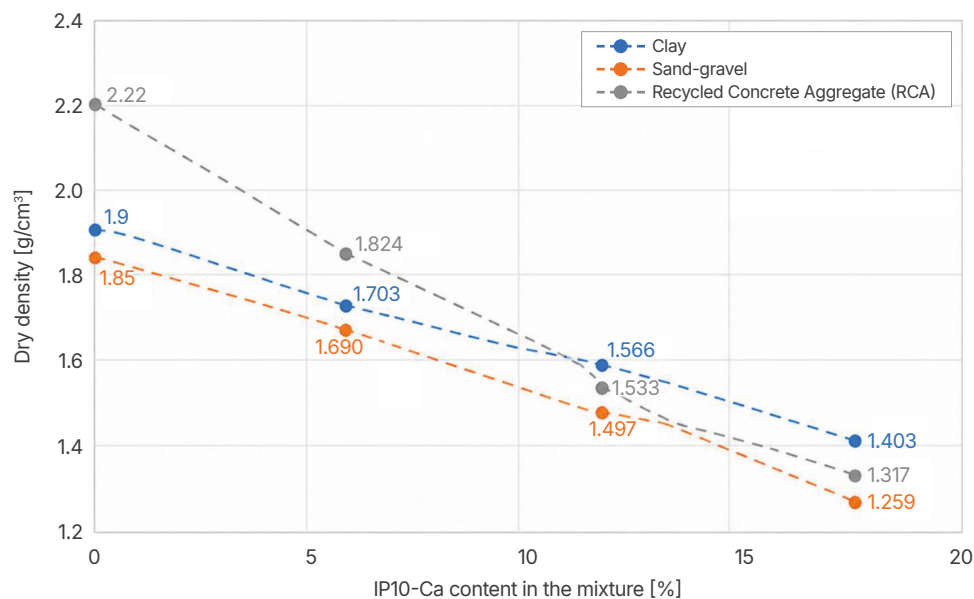


Fig. 4. Maximum dry density versus shredded waste content

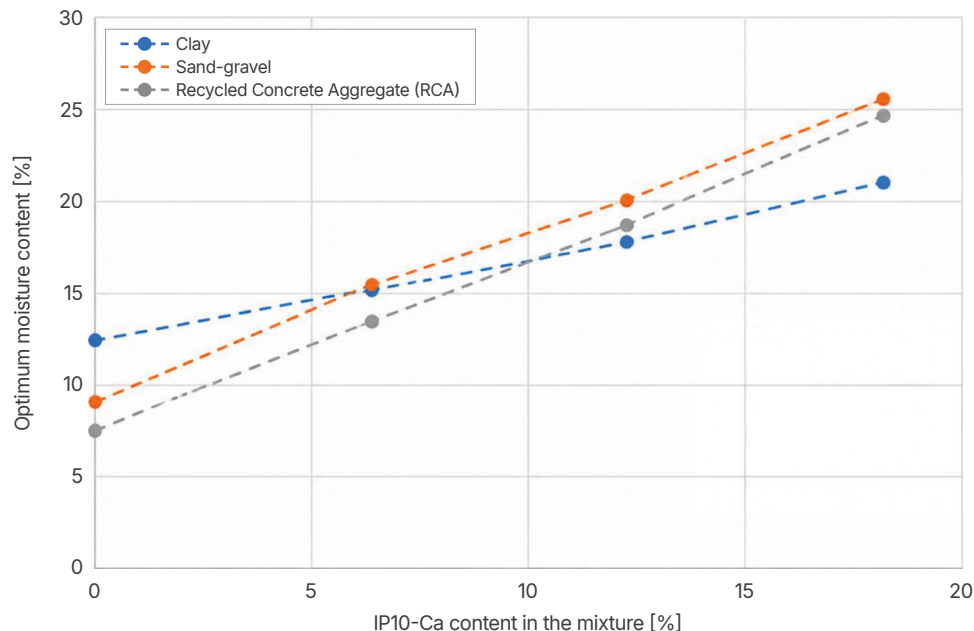


Fig. 5. Optimum moisture content versus shredded waste content

As expected, the maximum dry density of the mixtures decreased with increasing shredded waste content, whereas the optimum moisture content increased. At the highest IP10-Ca content (18%), the maximum dry density was approximately 1.40 g/cm^3 for clay, 1.30 g/cm^3 for recycled concrete aggregate and 1.25 g/cm^3 for sandy gravel. Within the investigated IP10-Ca range (6-18%), all lime-modified mixtures exhibited satisfactory compaction characteristics in the Proctor test. Accordingly, it is proposed that the minimum dry density requirement specified in PN-S-02205 should not be applied directly to this type of recycled material. It should also be noted that recycled materials with a maximum dry density below 1.6 g/cm^3 have already been reported in the recent literature, for example in [10].

The relationships between the maximum dry density and the shredded waste content are presented in Fig. 4, whereas the corresponding optimum moisture contents are shown in Fig. 5. Overall, the results confirm that increasing the proportion of IP10-Ca consistently reduces the maximum dry density and increases the optimum moisture content, irrespective of the type of soil or aggregate used.

The composition and basic properties of the unbound mixtures containing shredded waste are summarised in Table 3. Representative mixtures are shown in Fig. 6.

Table 3. Composition and properties of mixtures containing IP10-Ca

Unit	IP10-Ca – 6%	IP10-Ca – 12%	IP10-Ca – 18%
Clay			
Clay [%] dry mass	94.34	89.29	84.75
Lime [%] dry mass	0.52	0.98	1.39
191212 waste [%] dry mass	5.15	9.74	13.87
Maximum dry density [kg/m ³]	1703	1566	1403
Optimum moisture content [%]	15	18	21
Clay [kg/1 m ³]	1606.6	1398.3	1189
Lime [kg/1 m ³]	8.9	15.3	19.5
19 12 12 waste [kg/1 m ³]	87.7	152.5	194.6
Water [kg/1 m ³]	255.5	281.9	294.6
Sand-gravel			
Sand-gravel [%] dry mass	94.34	89.29	84.75
Lime [%] dry mass	0.52	0.98	1.39
19 12 12 waste [%] dry mass	5.15	9.74	13.87
Maximum dry density [kg/m ³]	1690	1497	1259
Optimum moisture content [%]	15.3	19.8	25.6
Sand-gravel mixture) [kg/1 m ³]	1594.3	1336.7	1067
Lime [kg/1 m ³]	8.8	14.7	17.5
19 12 12 waste [kg/1 m ³]	87	145.8	174.6
Water [kg/1 m ³]	258.6	296.4	322.3
Recycled Concrete Aggregate (RCA)			
Recycled Concrete Aggregate (RCA) [%] dry mass	94.34	89.29	84.75
Lime [%] dry mass	0.52	0.98	1.39
19 12 12 waste [%] dry mass	5.15	9.74	13.87
Maximum dry density [kg/m ³]	1824	1533	1317
Optimum moisture content [%]	13.5	19.0	24.9
Recycled Concrete Aggregate (RCA) [kg/1 m ³]	1720.8	1368.8	1116.2
Lime [kg/1 m ³]	9.5	15.0	18.3
19 12 12 waste [kg/1 m ³]	93.9	149.3	182.7
Water [kg/1 m ³]	246.2	291.3	327.9



Fig. 6. Representative mixtures containing the IP10-Ca additive

6. CALIFORNIA BEARING RATIO AND PERMEABILITY

California Bearing Ratio *CBR* and coefficient of permeability tests were performed for all types of unbound mixtures containing the IP10-Ca additive. The test results are summarised in Table 4 and illustrated in Figs. 7 and 8.

Table 4. Test Results for mixtures containing shredded waste IP10-Ca

Unit	IP10-Ca – 0%	IP10-Ca – 6%	IP10-Ca – 12%	IP10-Ca – 18%
Clay				
Optimum moisture content [%]	13	15	18	21
Maximum dry density $\rho_{d,max}$ [g/cm ³]	1.901	1.703	1.566	1.403
California Bearing Ratio <i>CBR</i> [%]	2.5	10.0	9.2	9.5
Coefficient of permeability k_{10} [m/day]	–	–	–	–
Sand-gravel				
Optimum moisture content [%]	9.0	15.3	19.8	25.6
Maximum dry density $\rho_{d,max}$ [g/cm ³]	1.846	1.690	1.497	1.259
California Bearing Ratio <i>CBR</i> [%]	14.7	10.5	3.6	1.9
Coefficient of permeability k_{10} [m/day]	0.49	0.65	1.05	2.38
Recycled Concrete Aggregate (RCA)				
Optimum moisture content [%]	7.5	13.5	19.0	24.9
Maximum dry density $\rho_{d,max}$ [g/cm ³]	2.215	1.824	1.533	1.317
California Bearing Ratio <i>CBR</i> [%]	108.8	23.9	6.9	5.1
Coefficient of permeability k_{10} [m/day]	0.02	0.06	0.15	0.41

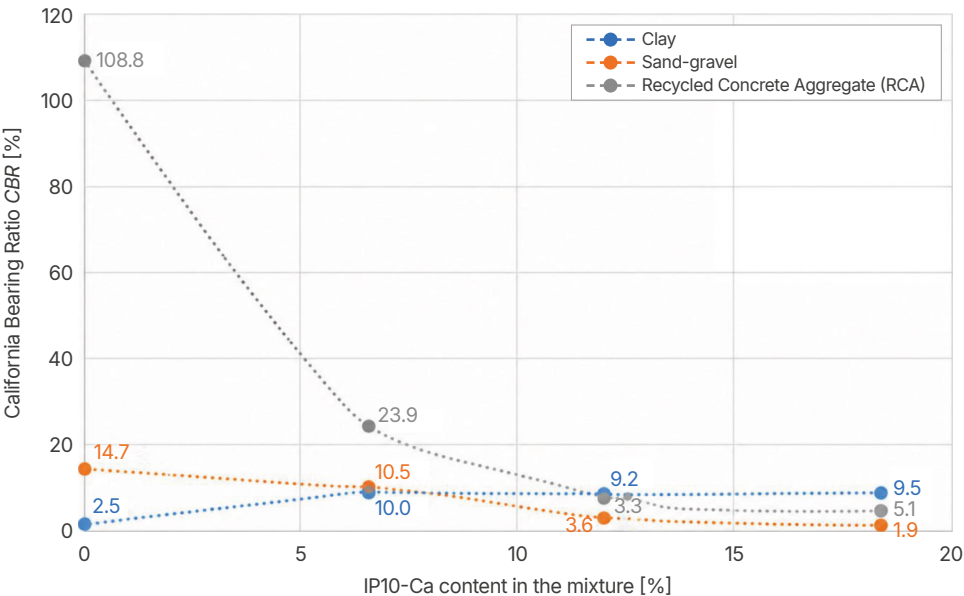


Fig. 7. California Bearing Ratio *CBR* as a function of shredded waste content in the investigated mixtures

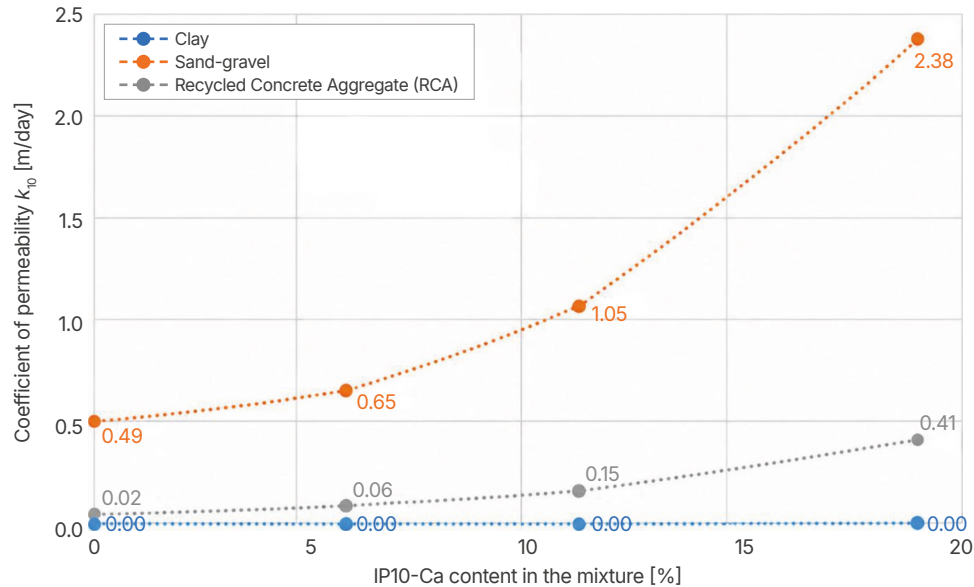


Fig. 8. Coefficient of permeability as a function of shredded waste content in the investigated mixtures

For recycled concrete aggregate (RCA), a pronounced decrease in bearing capacity was observed with increasing shredded waste content. The *CBR* value decreased from more than 100% for untreated RCA to approximately 5% for mixtures containing 18% IP10-Ca. A similar trend was observed for sandy gravel, where the *CBR* decreased from approximately 15% for the reference material to about 2% at an IP10-Ca content of 18%. Nevertheless, a *CBR* value of approximately 10%, corresponding to subgrade class G1, can still be achieved for both sandy gravel and RCA provided that the IP10-Ca content does not exceed 6%. In this case, the recycled concrete aggregate also satisfies the requirement for improved subgrade ($CBR > 20\%$) in the lower pavement layers according to the Polish Catalogues of Typical Pavement Structures [11-12]. Mixtures with higher IP10-Ca contents may still be used in the lower embankment layers in accordance with PN-S-02205. Similar potential use of waste-derived materials in road and earthwork applications has also been demonstrated in other studies. Recycled plastic granules combined with demolition wastes have been investigated as alternative road construction materials, with the obtained blends showing application potential depending on the type and proportion of the recycled component [13]. Similarly, geotechnical investigations of landfill-derived materials have included compaction, *CBR*, shear strength and hydraulic conductivity tests and have considered their potential use in embankment construction [14].

In contrast, clay mixtures exhibited a significant increase in bearing capacity following the addition of IP10-Ca. The *CBR* value increased from approximately 2.5% for untreated clay to approximately 10% for the modified mixtures. It should be noted that considerably lower *CBR* requirements (3-5%) for the lower embankment layers are reported in international practice [10], whereas PN-EN 16907 [7] and the current Polish Technical Specifications (WWiORB) [15-16] do not define minimum *CBR* values for such applications.

A distinct improvement in the coefficient of permeability was observed with increasing shredded waste content in both sandy gravel and recycled concrete aggregate mixtures. Sandy gravel containing 12-18% IP10-Ca satisfied the permeability requirement of $k_{10} > 1 \times 10^{-5}$ m/s specified in PN-S-02205 for embankment layers, with the exception of the upper 0.5 m layer, for which a higher value ($k_{10} > 6 \times 10^{-5}$ m/s) is required. The remaining materials, including clay mixtures containing IP10-Ca, may also be used in embankments in accordance with PN-S-02205 provided that a 4% transverse slope is applied. This finding is of practical importance because materials exhibiting adequate permeability are often difficult to obtain, particularly for drainage and separation layers. No improvement in the coefficient of permeability was observed for clay mixtures containing the IP10-Ca additive.

7. INTERNAL FRICTION ANGLE

The internal friction angle was determined using shredded waste from group 19 12 10. The suitability of the investigated materials for embankment slope construction was assessed by means of direct shear tests. The tests were carried out on cohesionless mixtures consisting of sandy gravel and recycled concrete aggregate modified with the IP10-Ca additive (shredded waste with lime).

Six mixtures with different shredded waste contents were investigated. Their composition and properties corresponded to those presented in Table 3. The shredded waste content in the unbound mixtures was increased by increasing the proportion of the IP10-Ca additive, following the procedure described in the previous section. Shear stresses were determined under normal stresses ranging from 100 to 300 kPa. The results obtained for sandy gravel mixtures are presented in Fig. 9, whereas those for recycled concrete aggregate are shown in Fig. 10.

The internal friction angles were determined from the failure envelopes constructed on the basis of the relationships shown in Figs. 9 and 10. The results are summarised in Fig. 11. The internal friction angle decreased markedly with increasing IP10-Ca content. However, mixtures containing recycled concrete aggregate exhibited higher internal friction angles (14.7°-39.6°) than sandy gravel mixtures (12.2°-31.4°).

Based on the results of the direct shear tests, it may be concluded that the incorporation of shredded waste into unbound mixtures reduces their shear strength parameters. Nevertheless, for IP10-Ca contents between 6% and 12%, the minimum internal friction angle remained approximately 19°, indicating that these mixtures may be used for embankment slopes with an inclination of 1:1.5 founded on competent subgrade. Comparable internal friction angles (15°-17°) have been reported for other unconventional materials, including cohesive soils improved with recycled concrete aggregate, for which embankment slopes up to 10 m high with a 1:1.5 inclination have been demonstrated [17]. These findings are also consistent with PN-S-02205 [6], which specifies a minimum internal friction angle of 20° for recycled ash-slag mixtures intended for embankment slope construction. Whenever unconventional materials are used in embankment slopes, a dedicated slope stability analysis should be carried out for the specific mixture composition, embankment height, loading conditions and foundation characteristics.

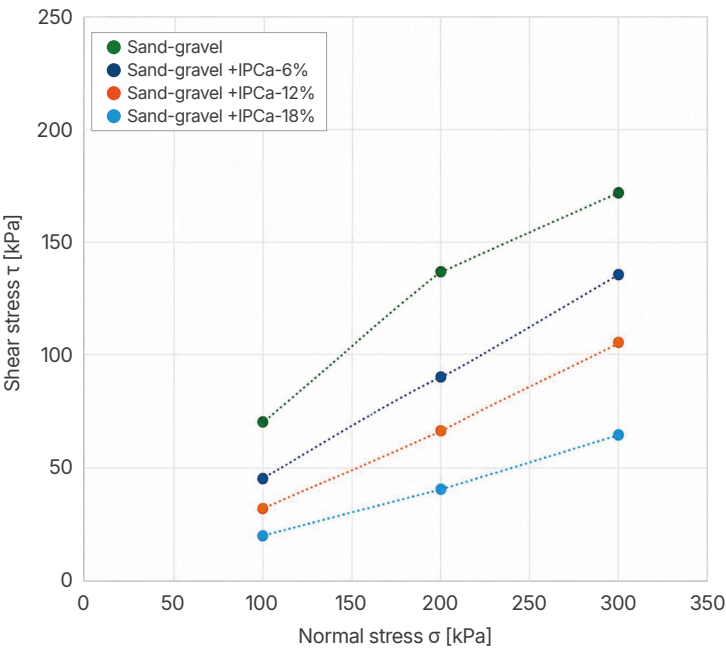


Fig. 9. Relationship between normal and shear stresses obtained from direct shear tests on sand gravel mixtures containing shredded waste from group 19 12 10 and lime

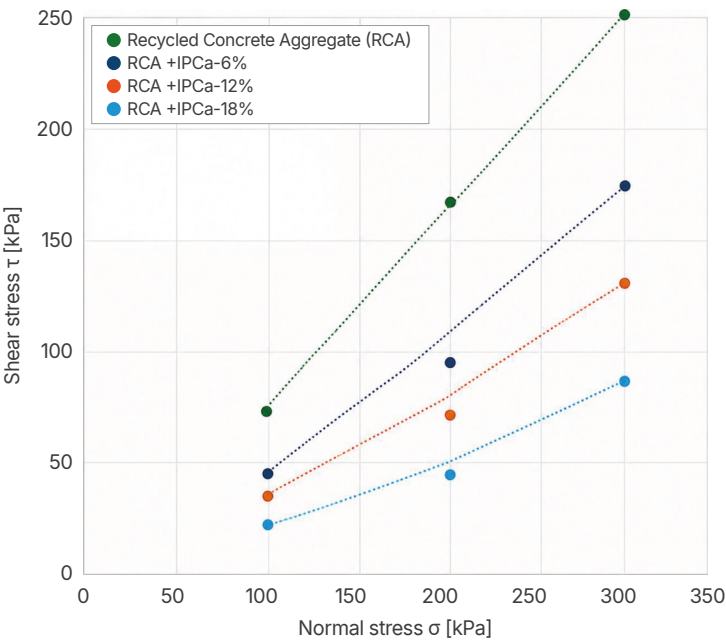


Fig. 10. Relationship between normal and shear stresses obtained from direct shear tests on recycled concrete aggregate mixtures containing shredded waste from group 19 12 10 and lime

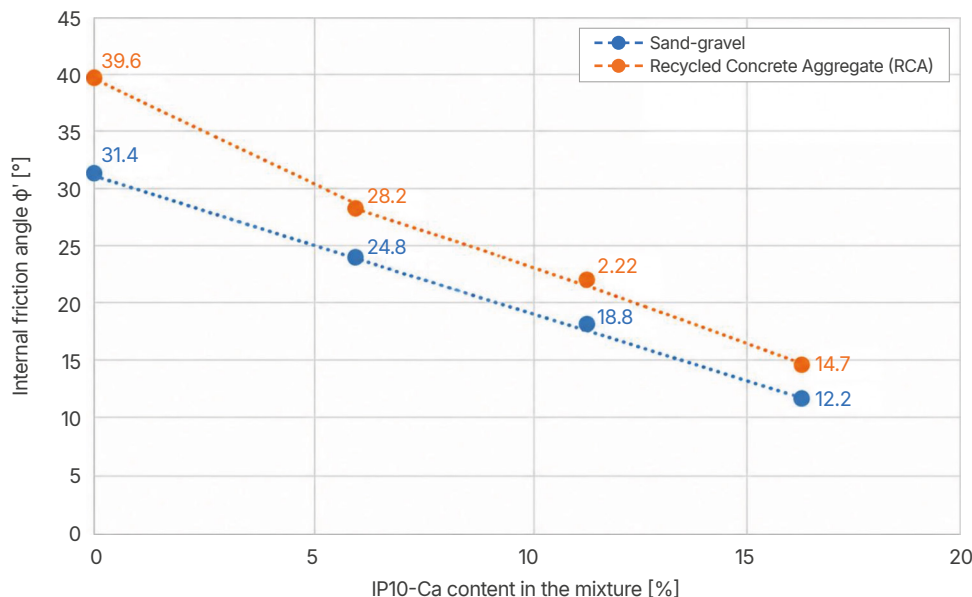


Fig. 11. Comparison of the internal friction angle of sand gravel and recycled concrete aggregate mixtures containing the IP10-Ca additive

8. CONCLUSIONS

The present study demonstrates the feasibility of using recycled materials obtained from the mechanical processing of waste streams (waste groups 19 12 10 and 19 12 12) in unbound mixtures for road embankment construction. In this way, the concept previously presented in [1-2] has been extended to address the current socio-economic and environmental challenge associated with the management of waste remaining after mechanical sorting. Based on the laboratory investigations and the obtained results, the following conclusions can be drawn:

1. The laboratory tests confirmed that unbound mixtures containing shredded waste and a small amount of lime can satisfy the requirements for selected unbound layers of road embankments, particularly in terms of compaction, permeability, *CBR* and shear strength.
2. The proposed solution offers environmental and economic benefits by reducing the consumption of natural aggregates, limiting transport demand due to the lower density of the mixtures, and enabling the beneficial use of waste streams that currently have limited recovery options. It provides an alternative route for the beneficial use of waste streams for which the current national waste management system is approaching its processing capacity. Approximately 7 million tonnes of waste classified as group 19 12 12 are generated annually in Poland, whereas only about 35% is currently recovered [18]. The use of such waste in road construction may therefore represent a viable contribution to solving an important socio-economic and environmental problem.
3. The engineering performance of the proposed mixtures depends strongly on the characteristics of the constituent materials, including the type of soil or aggregate, as well as the type,

density, particle size and impurity content of the shredded waste. Therefore, any modification of the mixture composition should be verified by laboratory testing before field application. The results presented in this study should be regarded as guidance for the development of innovative recycled materials rather than as universal design recommendations, since existing technical requirements were developed for conventional materials. Future research should focus on field investigations to evaluate the long-term mechanical behaviour and failure mechanisms of unbound mixtures containing shredded waste and lime, and to support the development of dedicated technical requirements for these innovative materials. The Authors recognise that long-term behaviour and the scale of laboratory testing are important limitations of the present study. Laboratory results alone cannot guarantee the performance of full-scale embankments. Differences in compaction equipment, layer thickness, scale, drainage conditions, loading and environmental exposure may affect field behaviour. Before implementation in full-scale infrastructure, the proposed materials should therefore undergo a staged validation procedure including in situ testing. Field performance should be assessed with respect to compaction, settlement, moisture conditions, permeability and mechanical properties, including potential degradation or decomposition of the waste material, over an extended period.

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Analiza możliwości wykorzystania rozdrobnionych odpadów z grupy 19 12 10/12 w mieszankach niezwiązanych do budowy nasypów

Streszczenie: Tematem artykułu są badania nad możliwością wykorzystania materiałów, pochodzących z segregacji i mechanicznej obróbki odpadów, w mieszankach niezwiązanych do budowy nasypów. Celem badań było określenie wpływu dodatku rozdrobnionych odpadów 19 12 10/12 na właściwości mechaniczne mieszanek niezwiązanych przeznaczonych do budowy nasypów drogowych oraz wyznaczenie dopuszczalnej zawartości odpadów, umożliwiającej spełnienie wymagań technicznych. Program badawczy obejmował przeprowadzenie badań laboratoryjnych zagęszczalności, wskaźnika nośności *CBR*, współczynnika filtracji i kąta tarcia wewnętrznego mieszanek niezwiązanych gruntów/kruszyw o różnej zawartości rozdrobnionych odpadów. Przeanalizowano możliwości i ograniczenia w stosowaniu tego typu materiałów. Wyniki badań odniesiono do obowiązujących wymagań technicznych oraz doświadczeń zagranicznych. Na podstawie otrzymanych wyników badań udowodniono możliwość wykorzystania rozdrobnionych odpadów z grup 19 12 12/10 w materiałach stosowanych do budowy nasypów. Wskazano przy tym istotne korzyści ekonomiczne, społeczne i środowiskowe.

Słowa kluczowe: mieszanki niezwiązane, nasyp drogowy, recykling, rozdrobnione odpady 19 12 10/12.