Research Article

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Engineering of composite materials made of epoxy resins modified with recycled fine aggregate

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Abstract: The paper presents studies performed on polymer-cementitious composite made of epoxy resin coating modified with aggregate and cementitious substrate. Epoxy resin is a perfect material that can be used to protect cementitious materials. According to its manufacturer, it can be mixed with fine aggregate. Coarse aggregate made of building demolition wastes is mostly utilized in concrete mixtures or road structures. Fine aggregate is not widely used. Therefore, the novelty of this research was the utilization of recycled fine aggregate (RFA) in epoxy resin coatings. Natural fine aggregate (NFA) was also used as an extender in the coating. The natural aggregate in the coating was partially replaced with recycled aggregate in amounts of 0, 20, 40, 60, 80, and 100% of its weight. Sixteen specimens of polymer-cementitious composites were prepared for the flexural tensile strength test, and thirty-two specimens for the compressive strength test. The macroscale tests were performed after 35 days of curing (28 days – cementitious substrate, and 7 days – epoxy resin). The results show that the epoxy resin coating does not affect the flexural tensile and compressive strength of the analyzed composites. Moreover, the type of aggregate used in the coating does not have a significant impact on the measured properties of polymer-cementitious composites. Economic analysis was performed in order to estimate the cost of the natural and RFAs used in epoxy resin coatings. The

calculations show that a higher amount of RFA should be used to increase savings.

Keywords: epoxy resin coating, cementitious substrate, polymer-cementitious composite, durability, recycled fine aggregate, building demolition wastes, floor structure

1 Introduction

Concrete, stone, steel, wood, or ceramics are the main materials used in building construction [1–5]. Structures made of reinforced concrete are especially popular in the XXI century. However, cement-based structures are sometimes not properly designed. These types of cementitious constructions need strengthening, protection, or repair. The repair of cementitious constructions can be carried out using epoxy resin [6]. Reinforced concrete beams can be strengthened with Carbon Fiber Reinforced Polymer (CFRP) [7], or steel bars and rods [8]. Elements strengthened with CFRP are sensitive to high temperatures caused by fire [9]. Akhavan-Safar et al. [10] noticed that epoxy resin enhanced with microcork particles has a decreased lap shear strength in a temperature of 75°C. Much better results were obtained for specimens in –20°C. The mechanical properties of epoxy resin can decrease when above the glass transition temperature. The temperature during curing can even affect the mechanical properties of polymer [11]. Trapko [12] investigated the strengthening of concrete columns using the Fiber Reinforced Cementitious Matrix (FRCM). The results show that the specimens strengthened with FRCM does not lose their mechanical properties in high temperatures. On the other hand, cementitious materials do not have mechanical properties as good as polymers. Therefore, epoxy resin is commonly used as a protecting layer in horizontally formed cementitious floor constructions. A coating made of epoxy resin allows cementitious substrate to be protected in order to avoid mechanical failure. It also enables easy cleaning of the coating's surface.

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Moreover, epoxy resin has high chemical resistance and can therefore be used in chemical, pharmacy, or electronic industry buildings. Epoxy resin can be modified using powder or fine aggregate extender. Chowaniec and Ostrowski [13] modified an epoxy resin with glass powder. Their results show that the pull-off strength between the polymer coating and cementitious substrate can increase with the addition of glass powder. In this study, epoxy resin was modified with fine aggregate. The manufacturer of the epoxy resin allows it to be mixed with natural fine aggregate. However, due to a common problem concerning utilization, the authors decided to use wastes instead of natural aggregate in the epoxy resin coating. The construction industry is responsible for generating the highest amount of wastes in Europe – around 35% (Figure 1). The storing of wastes has become a real problem in fast developing countries. Cementitious and ceramic materials, or asphalt, are the most common wastes [14]. The coarse aggregate obtained from building demolition wastes is mostly used in the concrete matrix or in road structures [15–21]. However, aggregate with a grain size lower than 2 mm is not often utilized or reused. Therefore, the authors modified an epoxy resin coating with recycled fine aggregate sourced from building demolition wastes. The standard composition of the epoxy resin material was gradually changed with the use of recycled aggregate in order to obtain better parameters when compared to a homogeneous material [22], or a material that contains natural aggregate. A horizontally formed composite made of modified epoxy resin coating and cementitious substrate was analyzed in order to determine its mechanical properties and the influence of epoxy resin and the type of extender on the strength of the composite. Moreover, an economic assessment was performed in order to estimate the potential cost of using natural or recycled aggregate in epoxy resin coatings.

2 Materials and methods

2.1 Cementitious substrate

For two mechanical tests, one type of cementitious substrate sample was prepared. The specimens were prepared in steel forms with dimensions of $160 \times 40 \times 37$ (mm). To decrease the friction between the formwork and sample, the internal walls of the formwork were covered with special oil with antiadhesive properties intended for concrete formworks. The oil was applied using a brush. The cementitious substrate was prepared using a ready mix. This composition consists of limestone powder, Type I Portland cement, quartz aggregate with a grain size of 0–4 mm, and other additives. The water to ready-mix weight ratio was 0.1. The components were mixed together manually for 180 s using a trowel in order to obtain a uniform consistency. Compact samples were obtained after being manually vibrated for 30 s in three steps during the application of fresh concrete into the steel formworks. The specimens were cured for 28 days in controlled semi-dry conditions in a laboratory with an average temperature of $21 \pm 2^\circ\text{C}$.

2.2 Preparation of the cementitious substrate surface

One of the most important properties of floors is their pull-off strength. In order to obtain a pull-off strength of no lower than 1.5 MPa (normative minimal pull-off strength after 7 days of curing [24]), manufacturers of epoxy resins recommend treating cementitious substrate surfaces mechanically using grinding, followed by the

Figure 1: Waste generation by economic activities and households in Europe in 2018 [23].

application of a layer of bonding agent [25–27] that is often made of epoxy resin. However, after 28 days of curing, the cementitious substrate surface was only grinded, without applying a bonding agent. This is to avoid any influence of this layer on the results obtained during the studies. Krzywiński and Sadowski [28] proved that the pull-off strength of polymer-cement composite that is made without a bonding agent can be higher than 1.5 MPa. The specimens were grinded manually using a grinding stone with ceramic abrasive grain in order to avoid damage close to the edges of the samples (Figure 2a).

2.3 Epoxy resin coating

Epoxy resin made of three components was used to prepare the coating (StoPox BB OS, Sto Ltd., Wrocław, Poland). The first component (A) – an epoxy resin – is based on bisphenol. The second component (B) – a hardener – is based on aliphatic polyamines. The manufacturer allows the aggregate to be added to the mixture in order to fill the obtained coating, while at the same time reduce the use of epoxy resin. Therefore, the third component (C) is a fine aggregate with a grain size of up to 2 mm. The weight ratio of the three components A:B:C is 100:25:75. All the components were mixed together using a plastic spoon for 3 min with an average rotational speed of 180 rpm in order to obtain a uniform consistency. Then, the epoxy resin was applied on the cementitious substrate (Figure 2c). The polymer-cement composite was cured for 7 days in a controlled laboratory environment at

the temperature of $21 \pm 2^\circ\text{C}$ and with relative humidity of less than $60 \pm 5\%$.

2.4 Aggregate

In this study, recycled aggregate is used as an extender in the epoxy resin. A more compact epoxy resin (because of the extender) can be easily applied on large floor areas. Without the aggregate, a floor made of clean epoxy resin can be very expensive due to the high cost of materials. However, natural aggregate is extracted from natural sources. To decrease the extraction of natural aggregate and to obtain a low cost of epoxy resin coating, recycled aggregate was used as an extender. For each sample, the weight replacement of natural aggregate by recycled aggregate was different. Therefore, six weight ratio aggregates were prepared, which are illustrated in Figure 3.

Natural aggregate is one of the most popular building materials, and its extraction is still growing around the world. It is a commonly used material in the building industry, e.g., as a concrete component. In this study, natural aggregate (Zakład Przetwórstwa Kruszyw MARGO, Mietków, Poland) with a grain size lower than 2 mm was used as an extender in the epoxy resin. Figure 4d presents the aggregate sieve size distribution. The other properties of the natural aggregate, which were declared by the manufacturer, are presented in Table 1.

The recycled aggregate (Przedsiębiorstwo Rodzinne Merta & Merta Sp. z o.o., Wrocław, Poland) was prepared in the same way as the natural aggregate (Figure 4a–c). The

Figure 2: Preparation process of the samples: (a) cementitious substrate; (b) mixing of epoxy resin components; (c) samples after applying epoxy resin.

Figure 3: Scheme of the preparation process of the samples: (a) epoxy resin with different amounts of recycled and natural aggregate; (b) top view of the specimens after the application of epoxy resin on the concrete substrate – a darker color of the sample means a higher amount of recycled aggregate in the epoxy resin; (c) cross section of the prepared specimen.

same grain distribution in the case of both types of aggregates allows the obtained test results to be compared.

2.5 Macroscale laboratory tests

First, the flexural tensile strength of the specimens was measured. The test was performed on cuboid samples with dimensions of $160 \times 40 \times 40$ (mm) after 35 days of curing in a controlled laboratory environment at the temperature of $21 \pm 2^\circ\text{C}$ and with relative humidity less than $60 \pm 5\%$. The test was performed on samples with different ratios of the natural fine aggregate and recycled fine aggregate, and with epoxy resin located on top (as it is in the cross section of floors; Figure 5a), according to [29,30]. The height of the tested samples was 40 mm (37 mm of cementitious substrate and 3 mm of epoxy resin).

The compressive strength test was performed using a compression testing machine. The compressive strength tests were carried out on halved cuboidal specimens, which were obtained during the flexural tensile strength tests and had the epoxy resin applied on top of the specimen (as was the case during the flexural tensile strength tests). The performed compressive strength test and the failure model are presented in Figure 6.

3 Results and discussion

3.1 Macroscale analysis

In Figure 7a, it can be seen that there is a 0.30 MPa difference in the flexural tensile strength between the samples with 0 and 20% of recycled aggregate. The flexural tensile strength increases when the amount of recycled

Figure 4: The aggregate preparation process: (a) sieve process of the natural aggregate; (b) the recycled aggregate before the sieve process; (c) the view of the two types of aggregates; (d) the aggregate grain size distribution.

Table 1: The properties of the natural aggregate

Property	Description
SiO ₂ (%)	87.78
Loose bulk density of material (kg/m ³)	1,500
Aggregate bulk density (g/cm ³)	2.60

aggregate increases from 20 to 60%. When this amount is over 60%, the flexural tensile strength decreases. The flexural tensile strength of the specimens with 20, 80, and 100% of recycled aggregate is very similar. The highest result of flexural tensile strength was obtained by the sample with 60% of recycled aggregate – $f_t = 1.94$ MPa.

The compressive strength for the first three samples slightly increases from 9.96 to 10.78 MPa (Figure 7b). For the fourth sample with 60% of recycled aggregate, the compressive strength is $f_c = 16.98$ MPa. For sample No. 5, the value of f_c decreases to 7.16 MPa, and for sample No. 6, it slightly increases to $f_c = 8.35$ MPa.

It is visible from Figure 7 that the strength results are different for each weight ratio of aggregates. However, when we compare the results and put them together (Figure 8), a relationship can be seen. When analyzing compressive and flexural tensile strength together, the authors observed that these two curves are very similar to each other. The tendency can be noticed for each specimen. The compressive stress mostly causes failure of the sample in the cementitious substrate. During the

Figure 5: The flexural tensile strength test: (a) scheme of the test; (b) view of a specimen during the test with crack propagation highlighted with the red line; (c) destroyed specimens.

Figure 6: Compression strength test: (a) scheme of the test; (b) view of a specimen during the test with crack propagation highlighted with the red lines; (c) destroyed specimen.

Figure 7: Test results of: (a) flexural tensile strength; (b) compressive strength.

Figure 8: Comparison of the test results.

Table 2: The estimated unit cost of the fine aggregates used in the epoxy resin coating with RFA (\$/kg)

Raw materials	Unit cost [\$/kg]	
	Natural fine aggregate (NFA)	Recycled fine aggregate (RFA)
Without transportation	0.0009	0.0003
With transportation	0.0025	0.0012

flexural tensile strength test, the crack first occurs in the bottom area and then propagates to the top, in turn causing failure of the specimen. The epoxy resin coating was located in the top area of the samples, and therefore, could not have had a significant impact on the strength results. The strength properties of the cementitious substrate could have affected the results.

3.2 Economic performance of the recycled fine aggregate used in the epoxy resin coatings

The improvement of the mechanical properties of the epoxy resin coating is crucial; however, the reduction

Figure 9: Scheme of the distance between the location of use and the suppliers of the materials.

of the generated pollution is more important. Therefore, the extraction of river sand should be reduced and the recycling of demolition wastes that are stored near the construction site of use should be forced. Thus, the additional purpose of this study was to analyze the economic performance of the recycled fine aggregate used in epoxy resin coatings. The financial conditions summarized in Table 2 were used to calculate the costs for epoxy resin coatings. Most of the industrial halls near Wrocław are built in the area known as Wrocław Bielany (Figure 9), and therefore this location was chosen as the location for the assessment of distances between material suppliers and a new built hall. The EU transport costs in 2019 (5.18×10^{-5} \$/(km kg)) were estimated using the average transport costs offered by DELLATM Trucking INC. The considered distances are as follows:

- from the waste company (Przedsiębiorstwo Rodzinne Merta & Merta Sp. z o.o., Wrocław, Poland) to Wrocław Bielany – 17 km,
- from the mineral mine (Zakład Przetwórstwa Kruszyw MARGO, Mietków, Poland) to Wrocław Bielany – 31 km.

The preparation costs (3.4 \$/tons) of the recycled fine aggregate were estimated using the average production rate (250 tons per hour) of a 1412T Mobile Impact Crusher (TESAB Engineering Ltd). Table 3 presents the fine aggregate costs for each epoxy resin coating composition (in \$/m³).

Table 3: The estimated costs of each fine aggregate mix used in the epoxy resin coating with RFA (in \$/m³)

Series of composition	NFA portion (%)	RFA portion (%)	Natural fine aggregate	Recycled fine aggregate	Total cost without transportation	Total cost with transportation
1	100	0	2.29	0.00	2.29	6.47
2	80	20	1.83	0.17	2.00	5.80
3	60	40	1.38	0.34	1.72	5.14
4	40	60	0.92	0.51	1.43	4.47
5	20	80	0.46	0.68	1.14	3.81
6	0	100	0.00	0.85	0.85	3.14

Figure 10: Summary of the calculations and economic performance of the recycled fine aggregate used in the epoxy resin coatings. The scheme presents the type of aggregate that should be used in epoxy resin with regards to the distance from the aggregate source to the destination point.

The final costs of the RFA (including transportation) used in the epoxy resin coatings are 39% lower than the costs of the NFA. Due to the high price of the epoxy resin itself, additional cheap components can significantly reduce costs. Furthermore, it is important to use RFA to protect the environment. The costs of the recycled extender (without transportation) can be 63% lower than for NFA (100% substitution of NFA by RFA). Thus, demolition wastes should be used as an extender in epoxy resin coatings.

4 Conclusion

High strength, high abrasion resistance, and an easiness to clean are very desirable properties of floor constructions in industrial buildings intended for, e.g., pharmacy, and the production of food, electronics, or cars. The epoxy resin can ensure proper protection of cementitious constructions. In turn, the utilization of wastes can also be seen to be important. The performed studies show that recycled aggregate can be used as an extender in the epoxy resin coating of floor constructions. Thus, a coating

made of epoxy resin should be prepared with an extender in order to reduce costs. Moreover, based on the results of the performed analysis, the following conclusions can be drawn:

- the epoxy resin coating does not affect the compressive and flexural tensile strength of polymer-cementitious composite;
- the type of aggregate used in the epoxy resin coating does not have a significant impact on the strength of polymer-cementitious composite;
- the preparation process of the samples could have significantly affected the strength results. Each sample was prepared in steel forms and then manually vibrated. Therefore, the obtained strength results are different for each type of specimen. In future studies, the authors will only vibrate the specimens mechanically;
- the recycled fine aggregate that is used in the epoxy resin coatings, instead of NFA, decreases the total cost of a mix. Up to 63% of the fine aggregate costs can be saved using RFA, with an additional positive impact on the environment.

However, the performed calculations show that the application of recycled aggregate is only in some cases financially justified. Figure 10 shows that recycled aggregate should be used in epoxy resin coatings when the difference of distances between the construction site and wastes company or mineral mine Δx is lower than 10.7 km.

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References

- [1] Nawy EG, (editor). Concrete construction engineering handbook. New York: CRC press; 2008.
- [2] Smith MR, (editor). Stone: building stone, rock fill and armourstone in construction. London: Geological Society of London; 1999.
- [3] Burgan BA, Sansom MR. Sustainable steel construction. J Constr steel Res. 2006;62(11):1178–83.
- [4] Jasieńko J, Nowak T, Hamrol K. Selected methods of diagnosis of historic timber structures – principles and possibilities of assessment. Adv Mater Res. 2013;778:225–32 (Trans Tech Publications Ltd).

- [5] Goetzke-Pala A, Hoła J, Sadowski Ł. Non-destructive neural identification of the moisture content of saline ceramic bricks. *Constr Build Mater.* 2016;113:144–52.
- [6] Modesti LA, de Vargas AS, Schneider EL. Repairing concrete with epoxy adhesives. *Int J Adhes Adhesives.* 2020;101:102645.
- [7] Chastre C, Biscaia HC, Franco N, Monteiro A. Experimental analysis of reinforced concrete beams strengthened with innovative techniques. In 41st IAHS WORLD CONGRESS sustainability and innovation for the future. Albufeira, Algarve, Portugal; 2016 Sept. p. 1–10.
- [8] Franco N, Biscaia H, Chastre C. Experimental and numerical analyses of flexurally-strengthened concrete T-beams with stainless steel. *Eng Struct.* 2018;172:981–96.
- [9] Trapko T. Stress-strain model for FRCM confined concrete elements. *Compos Part B Eng.* 2013;45(1):1351–9.
- [10] Akhavan-Safar A, Barbosa AQ, Ayatollahi MR, da Silva LFM. Influence of microcork particles on the lap shear strength of an epoxy adhesive subjected to fatigue loading and different environmental conditions. *Proc Inst Mech Eng Part L J Mater Des Appl.* 2020;234(6):851–8.
- [11] Carbas RJC, Marques EAS, Da Silva LFM, Lopes AM. Effect of cure temperature on the glass transition temperature and mechanical properties of epoxy adhesives. *J Adhes.* 2014;90(1):104–19.
- [12] Trapko T. Fibre reinforced cementitious matrix confined concrete elements. *Mater Des.* 2013;44:382–91.
- [13] Chowaniec A, Ostrowski K. Epoxy resin coatings modified with waste glass powder for sustainable construction. *Tech Trans.* 2018;11(8):99–109.
- [14] Gálvez-Martos JL, Styles D, Schoenberger H, Zeschmar-Lahl B. Construction and demolition waste best management practice in Europe. *Resour Conserv Recycl.* 2018;136:166–78.
- [15] Debieb F, Kenai S. The use of coarse and fine crushed bricks as aggregate in concrete. *Constr Build Mater.* 2008;22(5):886–93.
- [16] Tam VW, Gao XF, Tam CM. Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach. *Cem Concr Res.* 2005;35(6):1195–203.
- [17] Lee GC, Choi HB. Study on interfacial transition zone properties of recycled aggregate by micro-hardness test. *Constr Build Mater.* 2013;40:455–60.
- [18] Zaharieva R, Buyle-Bodin F, Skoczylas F, Wirquin E. Assessment of the surface permeation properties of recycled aggregate concrete. *Cem Concr Compos.* 2003;25(2):223–32.
- [19] Katz A. Properties of concrete made with recycled aggregate from partially hydrated old concrete. *Cem Concr Res.* 2003;33(5):703–11.
- [20] Khatib JM. Properties of concrete incorporating fine recycled aggregate. *Cem Concr Res.* 2005;35(4):763–9.
- [21] Chen HJ, Yen T, Chen KH. Use of building rubbles as recycled aggregates. *Cem Concr Res.* 2003;33(1):125–32.
- [22] dos Reis MQ, Marques EAS, Carbas RJC, da Silva LFM. Functionally graded adherends in adhesive joints: an overview. *J Adv Join Process.* 2020;2:100033.
- [23] Eurostat statistics – waste generation [WWW Document]; Assessed Nov 2020. URL https://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics
- [24] EN 1542 Products and systems for the protection and repair of concrete structures—test methods—measurement of bond strength by Pull-Off. London, UK: British Standard Institution; 2006.
- [25] Frigione M, Aiello MA, Naddeo C. Water effects on the bond strength of concrete/concrete adhesive joints. *Constr Build Mater.* 2006;20(10):957–70.
- [26] Leone M, Matthys S, Aiello MA. Effect of elevated service temperature on bond between FRP EBR systems and concrete. *Compos Part B Eng.* 2009;40(1):85–93.
- [27] Al-Turaif HA. Effect of nano TiO₂ particle size on mechanical properties of cured epoxy resin. *Prog Org Coat.* 2010;69(3):241–6.
- [28] Krzywiński K, Sadowski Ł. The effect of texturing of the surface of concrete substrate on the pull-off strength of epoxy resin coating. *Coatings.* 2019;9(2):143.
- [29] ASTM Standard C293-293M. Standard test method for flexural strength of concrete (using simple beam with center-point loading). *ASTM Int.* 1971;31(1):1–4.
- [30] BS EN 12390-5. Testing hardened concrete – part 5: flexural strength of test specimens. London: British Standard; 2009 August. p. 1–22.