Possibilities of filling polymeric anchors with secondary raw materials with effect on price and final parameters

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Abstract

Within this work different types and amounts of the suitable secondary raw materials as filler to polymer anchor were tested as possible substitution of currently used primary fillers. Physical and mechanical properties of the fast curing anchoring material based on epoxy resin were determined. The aim of this research was to achieve the anchor containing high amount of the secondary raw materials with the same or better final properties than reference anchors. As the suitable secondary raw materials, waste transparent packaging glass (TPG), high temperature filter fly ash (HTF) and circulating fluidized bed combustion filter fly ash (FCA) contaminated by the selective non-catalytic reduction (SNCR) denitrification technology were chosen. To use as much as possible suitable secondary raw materials to limit its landfilling and save the price for the expensive epoxy resin was verified. It was found out that the developed polymer anchors containing up to 45% contaminated filter fly ash shows better physical and mechanical properties than the reference anchors utilizing only primary materials. This ascertainment should make the production of polymer anchor both environmentally and financially less demanding. Furthermore, the microstructure of the developed anchors was investigated by the CT tomography, and it was found out that even after the pull-out force of 120 kN there was no deterioration of the polymer anchor, and a filler in the form of fly ash (HTF, FCA) and waste packaging glass (TPG) was evenly distributed in the polymer mass (EPB1).

Keywords: Polymer anchor, secondary raw material, filler, strength, economical aspect, green material.

Introduction

Within this research the suitability of using secondary raw materials as a filler in polymeric anchoring materials based on epoxy resin was examined. Epoxy resin was selected as a binder because, after curing, it has excellent physical and mechanical properties and also very good chemical resistance [**1**]. The secondary raw materials selected were transparent waste glass and high-temperature and fluid filter power plant ash contaminated by ammonium ions due to the denitrification of flue gas. The goal was to use the highest amount of these raw materials as possible in order to reduce the resulting product price and to use as many secondary raw materials as possible. This would also reduce the landfill of these raw materials, which would be beneficial to the environment. One of our four monitored fillers was transparent waste glass, which is particularly suitable because of the high content of SiO_2 with good physical and mechanical properties (hardness, strength) and very good chemical resistance. Prior to the use of the waste glass, the unwanted substances, components and foils had to be removed and the glass dried (if necessary) and then adjusted to the required granulometry. The use of waste glass in polymeric materials was discussed by Saribivik *et al.* [**2**] in their research, which focused on the use of waste glass in polymer concrete.

In addition, this research deals with the use of power plant filter ash contaminated by the denitrification of flue gases. Specifically, this was a high-temperature fly ash from a thermal power plant in the Slovak Republic (HTF) and a circulating fluidized bed combustion ash (FCA) from a power plant in the Czech Republic, both burning brown powdered coal. The production of these fly ashes is several thousand tons per year. When mixing these ashes with water or in an alkaline environment, a massive amount of ammonia (NH_3) is released and therefore it can no longer be used as an active ingredient in cement concrete. It is also problematic to deposit such fly ashes, because if the ashes are deposited in the outdoor environment, moisture and rain may cause soil and water contamination. Therefore, the utilization of fly ashes is researched in order to minimize the landfill of this secondary raw material. These fly ashes seem suitable filler in polymeric materials because no ammonia is released when mixing contaminated ashes with polymeric materials. The possibility of using these contaminated ashes as a filler in epoxy repair mortar has already been solved by Hodul *et al.* [**3**] in their experiment, where they found that these fly ashes were a suitable filler in polymeric materials and at the same time achieved up to 70% filling of bisphenol, an epoxy resin using the polyamines, with the help of the tested fly ash. During this filling, they have achieved very high compressive strengths of about 100 MPa and high bending strengths of about 35 MPa. Atzeni *et al.* [**4**] also researched the use of fly ash in the epoxy matrix and reached the conclusion that the epoxy mortar with fly ash has the same quality, or even better, properties as the reference silica sand mortar. Lokuge *et al.* [**5**] investigated the resulting properties of polymer concrete made from polyester, vinyl ester and epoxy resin with different percentages of fly ash filling. Dorsilit quartz sand with high purity was used as the reference filler. The use of chemical anchors and their testing in natural stone was the focus of Contrafatto *et al.* [**6**] in their experiment, and Barnat *et al.* [**7**] observed the interfaces of glued anchors.

Experimental

Identification of the materials

Transparent packaging glass (TPG)

This is a waste glass made of glass bottles and glasses, which must first be cleaned of undesirable substances and impurities and then crushed and milled to the desired fraction. The experimentally determined density of this glass is 2530 kg/m^3. The chemical composition is shown in **Table 1**, where it is seen that the glass used contains up to 72% of SiO_2, which mainly guarantees the hardness and chemical resistance of the glass.

Quartz sand – Reference filler (REF)

This sand is made from dried Dorsilit quartz sands in graded fractions. It is perfectly clean and has an ideal grain shape that guarantees the creation of a perfectly dense structure in the polymer mass. Normally, this sand is used as filler in mortars, backfilling, polymeric materials and polymer concrete. It is very clean and contains 99.5% SiO_2 with a density of 2640 kg/m^3. Two fractions of this sand were used, 0–0.063 mm and 0–0.63 mm. The smaller fraction was chosen to compare formulations containing fly ash. The specific surface area of the sand with the 0–0.063 mm fraction was 29 m^2/kg. The chemical composition is shown in **Table 1**.

Circulating fluidized bed combustion ash (FCA)

This is a denitrified filter fluidized fly ash (FCA) from a thermal plant with fluidized bed combustion. The specific gravity of this fly ash was 2872 kg/m^3, determined experimentally by the gas pycnometer AccuPyc II 1340. The specific surface of the fly ash was 627 m^2/kg. The chemical composition is shown in **Table 1**. The ammonium ion concentration was 30.11 ppm.

High-temperature fly ash (HTF)

This is a denitrified filter high-temperature fly ash obtained also from separators with a density of 2114 kg/m^3 and a specific surface area of 440 m^2/kg. The chemical composition is shown in **Table 1**. The ammonium ion concentration in this ash is slightly lower than that of the FCA fly ash, namely 20.05 ppm.

Table 1. Chemical composition of the fillers tested to the polymer anchor.

Fly ash	HTF	FCA
SiO_2	50.1	35.2
Al_2O_3	18.6	19.8
Fe_2O_3	9.77	5.8
CaO	4.79	18.5
MgO	1.95	1.05
K_2O	1.72	0.63
Na_2O	0.68	0.02
TiO_2	0.57	0.01
Sírany	0.69	5.88
MnO	0.15	0.01
P_2O_5	0.18	0.10

	TPG	REF
SiO_2	72.0	99.5
Al_2O_3	2.52	0.61
Fe_2O_3	0.04	0.03
CaO	7.32	0.04
MgO	2.04	0.01
K_2O	0.30	0.22
Na_2O	14.42	0.03
TiO_2	0.01	0.03
Li_2O	0.00	0.00
BaO	0.00	0.01
ZrO_2	0.00	0.01

Bonding component – polymeric materials based on epoxy resin

EPB1 – This is a low-viscosity, two-component, solvent-free, epoxy-based compound. Component A (epoxy resin) contains epoxy resin (alkoxymethyl), oxirane (alkyl C12-C14) and solvent naphtha (petroleum) light aromatic. Component B (curing component) contains benzyl alcohol, benzeneamine polymer, hydrogenated formaldehyde, 2,4,6-tris (dimethylaminomethyl) phenol, 4,4-methylenebis (cyklohexamine) and N,N-dimethylpropane-1,3-diamine.

EPB2 – This is a high-viscosity, two-component, solvent-free, epoxy-based compound. Component A (epoxy resin) contains the epoxy resin (alkoxymethyl), oxirane (alkyl C12-C14) and solvent naphtha (petroleum). Component B (curing component) contains 2, 4, 6-tris (dimethylaminomethyl) phenol. For both types, polyamine-based hardeners were used.

Description of the tests being carried out

Determination of compressive strength and flexural strength

These tests were carried out on anchors with the EPB 1 matrix binder according to European harmonized standard EN 13892-2 (Methods of test for screed materials – Part 2: Determination of flexural and compressive strength). Flexural strength determination was performed on test scantlings measuring 20 × 20 × 100 mm and compressive strength was determined on fractions of these beams.

Pull-out method

This test was carried out in accordance with the procedure laid down by European harmonized standard EN 1881 (Products and systems for the protection and repair of concrete structures – Test methods – Testing of anchoring products by the pull-out method). First, test blocks from C 40/50 concrete were developed. After 28 days, openings with a diameter of 20 mm were drilled into the concrete to a depth of 150 mm. For the anchoring, steel threaded rods 16 mm in diameter, marked 8.8 and 10.9, were fastened to the cleaned holes. The pull-out test was performed 7 days after the elements were anchored. During the pull-out test, the anchor was subjected to such tensile force that the steel thread rod of the 8.8 grade steel could not handle it and broke. Therefore, a high-strength steel bar was used in further testing. The testing of embedded anchors in high-strength concrete was also carried out by Barnat *et al.* [**8**].

Microstructure monitoring using CT tomography

A Phoenix v|tome|x m 300 tomograph was used to determine the anchor details of the steel threaded rod with a polymer anchor in concrete. It is a multi-purpose tomograph for analysis and 3D imaging of a large spectrum of material that works with voltage up to 300 kV/500W. CT scanning was performed on core concrete boreholes with an anchored steel element. The bore length of 75 mm diameter was approximately 30 cm and the steel rod was anchored along the entire length of the bore. Boreholes were drilled only after the tensile test to see if there was any disruption of the anchor joint with the steel element and the concrete. Scanning was done horizontally across the bore.

Results and discussion

Fig. 1 graphically assesses the flexural strength of the anchoring materials with different amounts of very fine filler fraction <0.063 mm. **Fig. 2** shows the flexural strength of the anchoring materials with a different amount of coarse filler fraction 0–0.63 mm. As can be seen from the graphs, using coarser filler (fraction 0–0.63 mm) allowed the choice of a higher filling percentage (up to 80%) than can be chosen for the anchoring materials with fine ash, where the maximum percentage of filling was 65%. The finer filler increases the viscosity of the fresh mixture more significantly with lower filling as it has a higher specific surface area, and a larger amount of resin is required to coat the individual grains. From the resulting flexural strengths, it can be seen that anchor materials with coarser filling (packaging glass) exhibit significantly lower flexural strength than materials with fine fly ash. This is probably because the coarser and harder filling causes a more pronounced inhomogeneity of the mass and a larger area of the binder/filler contact zone, where the damage most often occurs with mechanical loading. For masses with a larger amount of coarse filler there is an apparent increasing tendency of flexural strength with the increasing percentage of filling. This fact is mainly due to a better distribution of the filler in the mass and to the elimination of its sedimentation. However, this fact would also need to be verified by studying the microstructure of the matter. In the case of anchor matter with fly ash, however, this tendency decreases as inhomogeneity increases and the particles are insufficiently coated with resins. The resulting flexural strength values for coarse filler materials ranged from 17 MPa to 30 MPa and the anchor matter with finer filler exhibited flexural tensile strengths ranging from 20 MPa to 54 MPa. This shows that for better flexural strength, finer filler such as fly ash is more suitable than coarser filler such as waste glass.

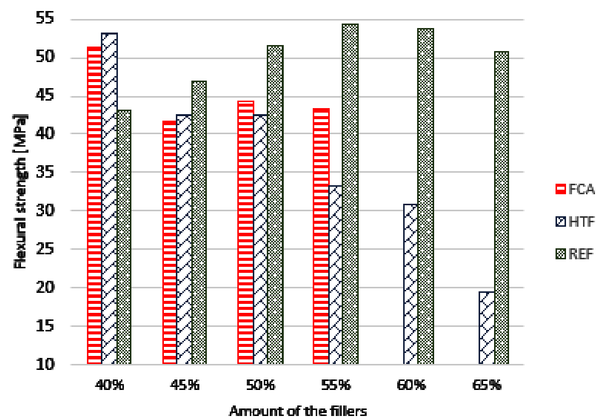

Fig. 1. Dependence of flexural strength on the percentage filling of polymer anchor containing finer fillers (<0.063 mm).

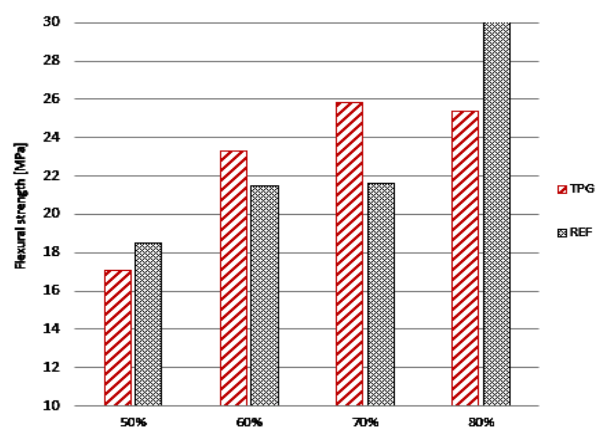

Fig. 2. Dependence of flexural strength on the percentage filling of polymer anchor containing coarser fillers (0–0.63 mm).

The resulting values of compressive strengths are graphically demonstrated in **Figs. 3** and **4**. It can be seen that the strength values are very high, reaching almost 130 MPa. The results also show that the largest compressive strength had an anchor mass with the reference filler, fine silica sand with a particle size of 0–0.063 mm, whereupon 130 MPa was reached and the increasing filling rate had almost no effect on the resulting strength – all values were over 120 MPa and did not differ significantly. **Figs. 3** and **4** also show that the compressive strength of the masses with fly ash and fine sand are greater than the compressive strengths of the samples with the coarser filler (waste glass and reference sand of the 0–0.63 mm fraction). For these samples with a coarse filler fraction of 0–0.63 mm, the compressive strength values ranged from 62 MPa to 85 MPa and the differences between the strengths of the mass with the glass and the reference sand were negligible. The compressive strength of the anchoring materials with fly ash was in the range of 80 MPa to 115 MPa, while the anchoring compound with FCA fly ash had a greater compressive strength. This is because the ash from fluidized bed combustion is finer and has a larger specific surface area, which means that, just like at the flexural test, there is a smaller contact zone where the sample breaks, the homogeneity increases, and the content of air pores is reduced.

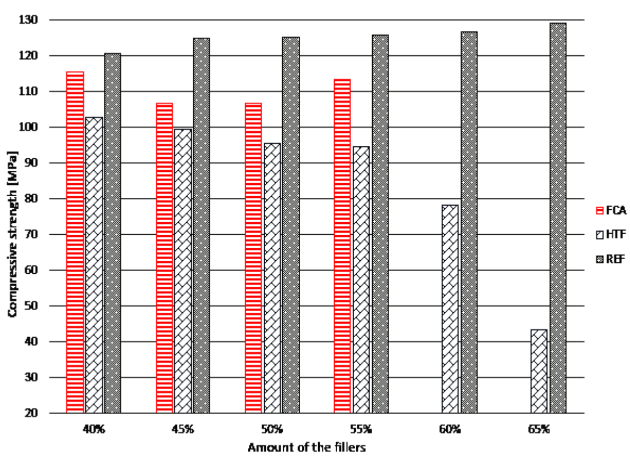

Fig. 3. Dependence of compressive strength on the percentage filling of polymer anchor containing finer fillers (<0.063 mm).

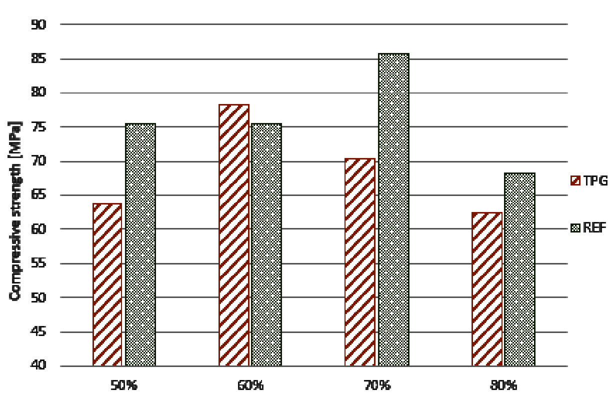

Fig. 4. Dependence of compressive strength on the percentage filling of polymer anchor containing coarser fillers (0–0.63 mm).

Pull-out method

Only some materials were selected for the pull-out test – ones that were easy to process and exhibited high compressive and flexural strengths. **Table 2** shows the resulting values of the anchoring force and the displacement from the course of the pull-out test. A total of 6 anchoring materials were subjected to the test, the effect on quantity, kind and size of filler being observed on the course of the anchoring force, depending on the displacement of the anchored steel rod.

Table 2. Resulting values of anchoring forces and displacements.

Type of polymer anchor	Maximum achieved force [kN]	Shift at maximum force [mm]	Shift at force 75 kN [mm]
EPB1 REF <0.063	112.27	0.927	0.563
EPB1 45% HTF	111.73	1.144	0.522
EPB1 45% FCA	122.76	0.839	0.511
EPB1 50% HTF	100.86	0.815	0.534
EPB1 70% TPG	81.32	0.763	0.572
EPB2 40% TPG	48.69	0.943	-

In order for the anchoring material to comply with the EN 1881 European standard requirement, it was necessary to achieve a maximum displacement value of 0.6 mm at a pull-out force of 75 kN. As shown in the table, almost all anchoring materials fulfilled these requirements, which means that the used power plant ashes as well as the waste glass with larger granulometry are suitable fillers for anchoring materials on epoxy resin bases. Furthermore, it can be seen that the anchor materials with fly ash and fine silica sand exhibit a higher anchoring force than the anchoring material with coarse waste glass. This is because an 8.8 grade standard steel threaded rod was anchored by the anchoring material with the waste glass, which did not allow for further increase in the pull-out force, because with a further increase in the pull-out force the steel threaded rod broke. The anchoring materials with ashes showed an even greater anchoring force, up to 120 kN, because they were used to anchor threaded rods of high-strength steel grade 10.9. Despite this high pull-out force, the anchored steel element did not emerge. The only anchoring material that failed to meet this requirement was the EPB2. In this material, complications arose mainly due to the very fast tightening of the mass, which caused insufficient leaking of the fresh material into the concrete pores – weak physical anchoring and low cohesion between the concrete and the anchoring material. During the rest, the anchor mass, along with the anchored rod, was pulled completely out of the hole, which showed the problem of insufficient anchoring of the mass. This violation was monitored by CT tomography for further clarification.

Microstructure monitoring using CT tomography

To determine the detail of the anchoring of the steel threaded rod in concrete loaded with anchoring force **(see Table 2),** two boreholes were drilled, which were further examined by CT tomography. **Figs. 5** and **6** illustrate parts of the cross-section of the bore holes in the horizontal direction. **Fig. 5** is a steel threaded rod anchored by the EPB1 material with 70% of 0–0.63 mm fraction waste glass (TPG). **Fig. 6** is a steel threaded rod anchored by the EPB2 material with 40% of 0–0.63 mm fraction waste glass (TPG). The higher the density of the material, the brighter the images from the CT scanner. In the middle of both shapes it can be seen a perfectly anchored steel threaded rod. The slightly visible shadow of the threaded rod (CT device noise) is caused only by the high contrast between the steel and the epoxy resin due to a considerable difference in material density. It is evident from **Fig. 5** that, even after the pull-out test, there are no cracks in the polymer anchoring mass and the contact areas between the threaded rod and the anchoring mass, and the anchoring mass and the concrete, remain intact. It is shown in **Fig. 6** that during the pull-out test the anchor was subjected to a more pronounced displacement of the whole matter with the anchored threaded steel rod. It is therefore possible to state that the material was very fast curing, which caused an incomplete connection of the anchoring material with the concrete, and during the pull-out test the entire anchoring mass was displaced. It is also possible to observe the optimal distribution of the filler in the polymer mass throughout the anchor height. The research also demonstrated that CT tomography can detect hidden defects in anchored elements that have been damaged. This method can also serve as evidence during expert-opinion solutions in the field of anchoring to concrete structures, in conjunction with determining the main cause of the failure of the anchored element in the structure.

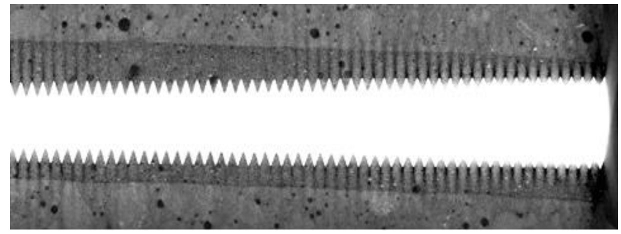

Fig. 5. Steel threaded rod anchored by the polymer anchor EPB1 with 70% TPG filler firmly anchored in concrete even after the anchoring force load of 81 kN.

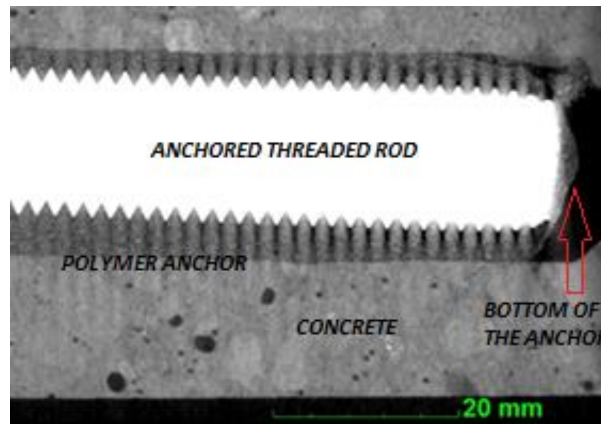

Fig. 6. Threaded rod anchored by the polymer anchor EPB2 containing 40% TPG filler – visible displacement of the whole anchor mass from the concrete in the bottom.

Economic evaluation

From an economical point of view, the developed polymeric anchoring material appears to be very advantageous because a large number of secondary raw materials have been used to replace a substantial portion of the epoxy-resin-based binder component, which is the most expensive item of the whole mass. The denitrified power plant fly ash appears to be the best filler, because this secondary raw material is being purchased just for transport costs due to its contamination with NH_3 ions, and does not need to be further modified. It can be used immediately for the preparation of anchor materials. On the other hand, when using waste glass, it is necessary to first remove unwanted components from the glass (not in case of TPG), then crush it, grind it and separate it according to the fraction size and only after these technological operations is it possible to use the prepared filler for the production of anchoring materials. The use of the treated waste glass in a low viscosity epoxy resin makes it possible to incorporate a larger quantity of this filler (up to 70%) than fly ash (up to 50%); but, because the preparation of the filler from the glass is considerably more expensive, the contaminated ash is the most suitable filler from an economical point of view. The price of commercially available epoxy resin anchor in the market ranges from 30 to 58EUR per package, which is usually 200 ml. The production price of the developed anchoring material is currently approximately 9EUR per 1 kg. The fly ash material is a little cheaper (8 EUR/kg), because the cost of pre-treatment of the filler is eliminated. These results show that the production of this polymer anchor material is very economical.

Conclusion

This research, which dealt with the possibility of using secondary raw materials as filler in anchoring materials, revealed that a very suitable secondary raw material is denitrified power plant filter fly ash. The compressive strengths of the developed anchor materials were around 110 MPa, flexural strength was about 50 MPa, and an anchoring force of up to 122 kN was achieved during the pull-out test. Compared to the reference mass, these values are approximately 10% lower, which is essentially negligible in relation to economic and environmental benefits. Up to 50% of the fly ash filler was used for anchors, allowing for the incorporation of a relatively large amount of this secondary raw material, thereby reducing the final product price. For this reason, this anchoring material is environmentally acceptable and economically advantageous. In addition, microstructure monitoring was carried out using CT tomography when it was found that the tested substance EPB1 with the appropriate content of secondary raw materials showed no violation even after the anchoring force load test. By examining images from CT tomography, it has also been found that the developed anchors exhibit excellent adhesion to the anchored steel rod and also confirm the ideal viscosity of the fresh mass. Overall, we can say that the new technology for detecting internal defects of anchored steel elements by means of chemical anchors was for the first time successfully tested. At the same time, progressive anchoring materials have been developed to reduce the ecological footprint, the production costs of which are negligible compared to commercial materials.

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Author's contributions

Conceived the plan: Rostislav Drochytka, Jakub Hodul, Tomáš Žlebek; Performed the expeirments: Tomáš Žlebek, Jakub Hodul; Data analysis: Tomáš Žlebek, Jakub Hodul; Wrote the paper: Jakub Hodul, Tomáš Žlebek, Rostislav Drochytka. Authors have no competing financial interests.

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