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Environmentally Friendly Concrete for Sustainable Overlays with Waste Mineral Powders: Problem Statement, Literature Survey, Economic Potential and Research Gaps

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Nowadays, the challenge for floor technology is to reduce the amount of cement necessary for the manufacturing of the overlays. It can be achieved thanks to waste mineral powders sourced from aggregate quarries. The chemical composition as well as particle size characteristics make this by-product of mining industry an attractive additive to be used in durable and sustainable cement-based matrices. Therefore, this article discusses the possibility to incorporate waste mineral powders as functional additives into sustainable and environmental-friendly overlays. For this purpose, short literature survey has been performed together with specified research gaps. The analysis presented in the article shows good perspectives and high economic potential of environmentally friendly concrete for the manufacturing of sustainable overlays with waste mineral powders.

1. Introduction

Civil engineering provides global foundation to the world's economy (Figure 1). Its major part is concrete and cement production, which according to (Benhelal et al., 2013) is responsible for around 5-7 % of CO_2 emission worldwide and according to (Naik, 2008) equals annually more than 0.4 m^3 of concrete production per person. Overlays are variable thick layers made of concrete or cement mortar placed on the existing concrete substrate (Sadowski, 2019). The challenge for floor technology is to reduce the amount of cement necessary in the manufacturing of the overlays. As discussed by (Czarnecki and Deja, 2021) it can be achieved rather thanks to the modification of the material (not the material substitution).

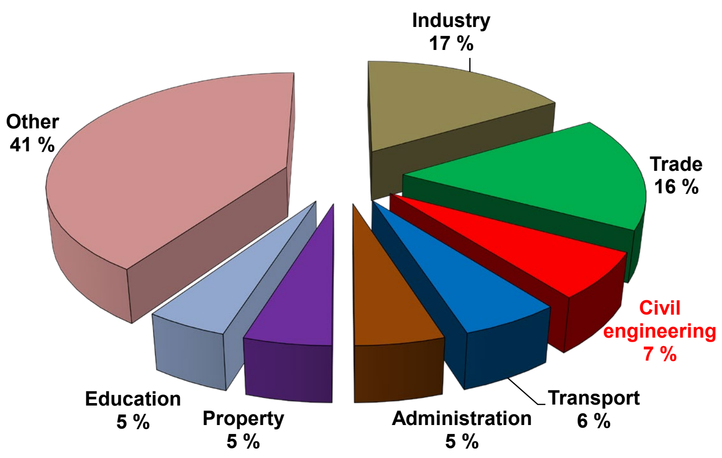

Figure 1: Share of the main sectors of the economy in gross domestic product (GDP) in Poland (STAT.GOV.PL, 2022)

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The most commonly used aggregate quarry waste materials are quartz, feldspar, marble, limestone, basalt, chalcedonite, magnetite and sepiolite and zeolite. Some of this waste (e. g. basalt for partial cement replacement (Li et al., 2021) or aggregates (Karasin et al., 2022); or granite powder, as presented in (Chajec, 2021), are usually "inert" materials that do not react with cement. However, the chemical composition as well as particle size characteristics make this by-product of mining industry an attractive additive to be used in durable and sustainable cement-based matrices. As pointed out by (Kajaste and Hurme, 2016) increasing the global replacement of clinker in cement composition with mineral components to a level of 34.2 % would save 312 Mt of CO_2 annually. Therefore, it is still a challenge for cement and floor industry to partially replace cement in overlay composition. Can it be achieved with mineral powders? Is it economically sensible? These are the questions that should be answered. Considering the above, the main novelty of this article is to state a problem of the possibility to incorporate waste mineral powders sourced from aggregate production as functional additives into sustainable and environmental-friendly concrete overlays. The goals of the article are to perform a short literature survey, define research gaps and present short analysis of the economic potential.

2. Problem statement

For most of the floor applications, the crucial parameters for overlays are:

- High abrasion resistance of the surface of the overlay (the most common requirement from the user operated on the surface),
- High tensile strength of the surface of the overlay (the most common requirement from the subcontractors in case laying the finishing layer),
- High adhesion to the existing concrete substrate.

To fully understand the overlay manufacturing the multi-disciplinary approach may be applied (Figure 2).

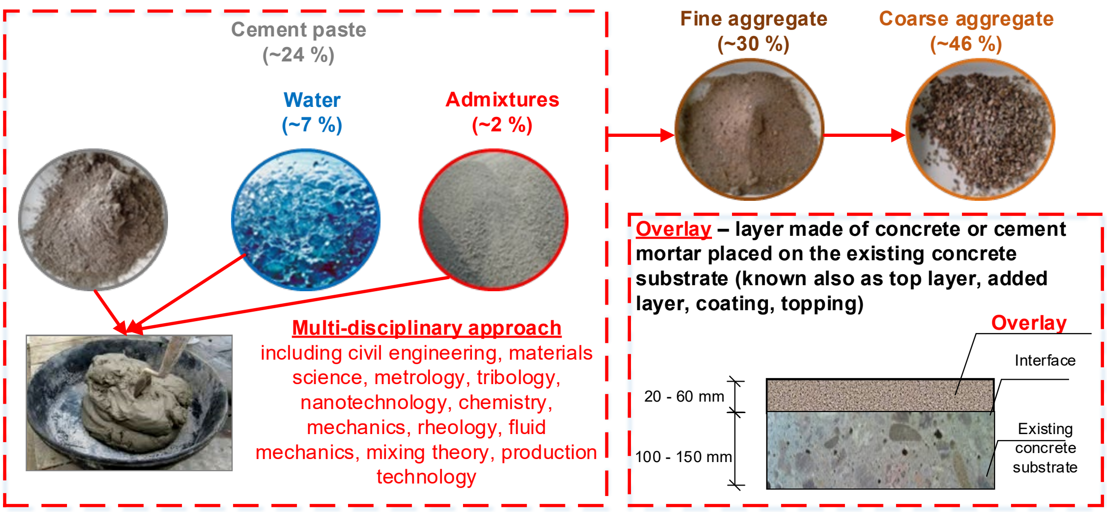

Figure 2: Multi-disciplinary approach of overlay manufacturing

Recently, more and more different types of actions are being undertaken in order to increase the performance of the overlays. As highlighted for example by (Szymanowski, 2019) these actions may include the:

- Strengthening of the surface of the overlay substrate using surface hardeners to improve the abrasion resistance of the surface of the overlay,
- Strengthening of the surface of the overlay substrate using impregnating agents to improve the tensile strength of the surface of the overlay,
- Applications of different bonding agents to increase the adhesion to the substrate,
- Appropriate treatment of the surface of the substrate to increase the adhesion to the existing concrete substrate.

These actions require substantial experience to find appropriate moment to apply surface hardener, find the way to impregnate the substrate, requires time to apply bonding agents or treat the substrate. These steps are expensive and extends the manufacturing process. Finally, they are error sensitive. Attempts to repair the fixed overlay are usually more costly than to remove the overlay and perform it again. Thus, the challenge is to find the way to significantly reduce the required number of actions and steps in the manufacturing process of the overlay *in-situ*. It can be possible by modification of the material composition of the overlay with carefully selected powders.

3. Short literature survey

As shown by (Tikkanen et al., 2011), attempts to modify concrete with mineral powders are effective, even though they generally result in a deterioration of their compressive strength (but increase of its freeze-thaw durability and abrasion resistance). Recent research showed that the addition of metakaolin (Moghtadaei et al., 2015), silica fume (Mohammadi et al., 2014) and fly ash (Li, 2013) are useful for the applications in overlays. That is why, such a modified concrete may be more sensible to be used in non-structural parts of the civil engineering structures, such as overlays. In the treatment of the mineral powders the tribology of mixed mineral powders are very important. Since the study performed by (Mathia and Louis, 1984) there are no studies related to the tribology of powders. This is facilitated by the growing interest in mineral powders in Google search, where since 2008 the word "powders" has gained popularity, even in relation to concrete (Figure 3).

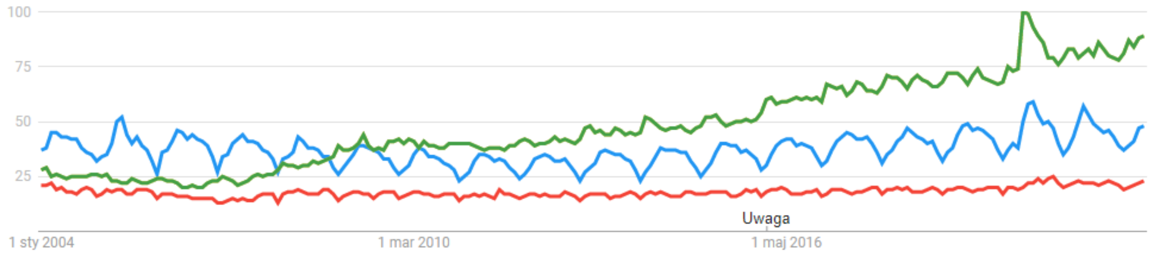

Figure 3: Activity of interests vs. time by keywords (concrete – cyclic evolution due to seasonal activity, mineral – stable, powder – increasing due to nanotechnology interest) – source (Google, date of search: 11.04.2022)

Mineral powders have been frequently used in concrete technology. As presented in Table 1, most of the available research results concern selected physical and mechanical properties of the hardened concrete with mineral powders. There are no studies in literature concerning the assessment of the effect of waste mineral powders modifying concrete overlays to its adhesion to concrete substrate.

Table 1: Existing research on concrete containing mineral powders („■” – studied property, „◆” – not studied property)

Studied property	Type of powder										
	MK	FA	SF	MP	SiO_2	Al_2O_3	CuO	TiO_2	ZnO	Fe_2O_3	Cr_2O_3
Workability	■	■	■	■	■	■	◆	◆	◆	◆	■
Porosity	■	■	■	■	◆	■	■	■	■	◆	◆
Absorptiveness	■	■	■	■	◆	◆	◆	◆	◆	■	■
Impermeability	■	■	■	■	◆	◆	◆	◆	◆	◆	◆
Freeze-thaw durability	■	■	■	■	◆	◆	◆	◆	◆	◆	◆
Compressive strength	■	■	■	■	■	■	■	■	◆	◆	◆
Tensile strength	■	■	■	■	■	◆	◆	◆	◆	■	■
Bending strength	■	■	■	■	■	■	◆	◆	■	■	■
Abrasion resistance	■	■	■	■	■	■	◆	◆	◆	◆	◆
Hardness	◆	■	■	◆	◆	◆	◆	◆	◆	◆	◆
Fracture mechanics parameters	■	■	■	◆	◆	◆	◆	◆	◆	◆	◆
Fracture initiating stress level	◆	■	◆	◆	◆	◆	◆	◆	◆	◆	◆
Critical stress level	◆	■	◆	◆	◆	◆	◆	◆	◆	◆	◆
Adhesion	■	■	■	◆	■	■	◆	◆	◆	◆	◆

Legend: MK – metakaolin, SF – silica fume, FA – fly ash, MP – mineral powder

It should be noted that (Pietrie, 2000) pointed out that the adhesion between concrete layers is a multi-scale issue. In recent years, the multi-scale approach has been successfully used by (Sadowski et al., 2021) in concrete surface morphology metrology. This demonstrates the need for research in this direction. The problem has yet to be described in literature. In literature there are no studies related to the effect of the modification of concrete overlays by waste mineral powders on their important physical and mechanical functional properties (tensile strength, freeze-thaw resistance, abrasion resistance, fracture energy or adhesion). In literature there are no studies on the effect of the modification of concrete overlays by waste mineral powders on the microstructure within the interface.

There is a documented attempt to use waste limestone (Chowaniec, 2021a) and granite (Chowaniec, 2021b) powders as a fillers in epoxy resin coating placed on concrete substrate. Considering the above, there is also no study in literature on the effect of the modification of concrete overlays by waste mineral powders on the mechanical parameters within the interface. Analysis presented in Table 2 shows also that there are no articles related to the adhesion between concrete overlays with waste mineral powders and concrete substrate. With this in mind, it seems reasonable to conduct research to examine this issue.

Table 2: Bibliographic analysis of the number of publications related to "concrete with mineral powders" searched in the abstracts, titles and keywords in the ScienceDirect database (date of search: 11.04.2022*)*

Keywords	*Number of articles*
1 keyword	
Concrete	76,205
Mineral	166,701
Powder	171,076
Overlay	13,541
2 keywords	
Concrete + Mineral	2,207
Concrete + Powder	1,823
Concrete + Overlay	339
3 keywords	
Concrete + Mineral + Powder	200
Concrete + Mineral + Overlay	2
Concrete + Powder + Overlay	3
4 keywords	
Concrete + Mineral + Powder + Overlay	0

From the analysis of existing knowledge, it is visible that there are no studies in literature that evaluate the properties of the overlays with mineral powders. To fill this knowledge a novel technique which combines nanoindentation and elemental mapping in scanning electron microscopy (SEM-EDX) should be useful. Based on the literature report the acoustic NDT methods of impulse response (IR), impact-echo (IE) and ultrasonic echo (UE) can be used in the evaluation of adhesion between concrete layers. This is very important phenomena for the overlays. (Silfwerbrand and Beushausen, 2005) studied this problem using the IE method. On the other side (Garbacz, 2007) found that, based on the analysis of the IE signal, it is possible to evaluate the quality of the interlayer bond between concrete layers. Recently (Sadowski and Hoła, 2022) stated that it is possible to evaluate the value of the pull-off adhesion between concrete layers in floors by using Artificial Neural Networks (ANN) based on parameters obtained by NDT methods. However, there is no study on the effect of the modification of overlays by waste mineral powders on the acoustic parameters determined by NDT methods.

4. Economic potential

Environmental-friendly overlays made of sustainable concrete are of great economic importance. Potential results can be used as basis to improve national and international standards as well as the exchange of data and experience. Results and findings can be used as basis to establish worldwide consensus and further coordinate development in this field. They will also be a good basis for education of young researchers and engineers and are therefore a good valuable investment in the future and the next generation. The target groups are research scientists, engineers, architects, industry, conservators and specialized advisors and contractors working in the field of construction and repair. Other target groups are cultural public and private organizations involved in the building sector and bearing a role in construction and choosing repair and conservation materials. Use the results of the research in this direction may have significant application in execution and production of environmental-friendly overlays. Figure 4 shows the percentage of the individual components C20 / 25 most often used for making the outer layers of the mass (Figure 4a), and the cost of (Figure 4b) 1 m^3 of concrete production most often used for making the concrete overlays. Average prices of concrete in 2021 in Poland (~71 EUR/m^3) were considered to transform Figure 4a,b. Figure 5 shows the predicted relationship between the cost of manufacturing of 1 m^3 of concrete and the percentage of waste mineral powder. Applications of waste mineral powders also lead to better economic outcomes. As an industrial by-product, they can be procured at a lower cost than cement (even taking into account the transport and treatment cost). For the analysis presented in Figure 5 the price of the raw material has been considered as zero and transport and treatment costs were considered to be similar to cement. The highest benefits will be when the distance between the aggregate quarry and concrete manufacturing company is small.

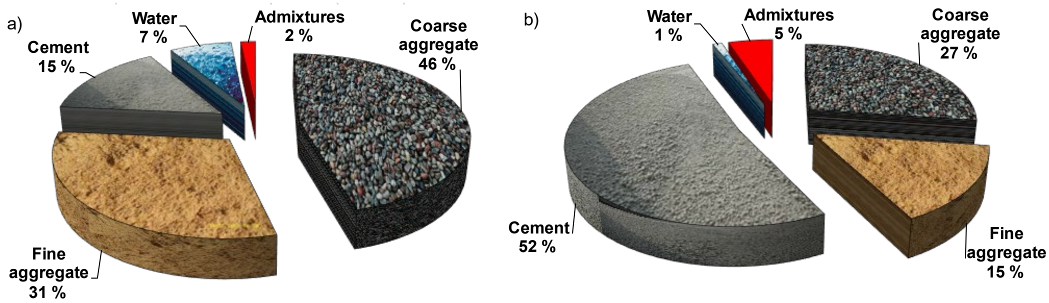

Figure 4: The usual percentage of the individual components C20/25 most often used for making the concrete overlays of the mass (a), and the cost to produce (b) 1 m^3 of concrete

Figure 5 shows that the potential savings resulting from the use of waste mineral powder (if the raw material is taken without any additional costs from the aggregate quarry) for the production of concrete may be above 20 %. Another positive aspect is the reduction of cement which not only makes business sense, but also lowers the environmental impact. It should be noted that the analysis presented in Figure 5 is just a rough calculation and each case should be calculated individually.

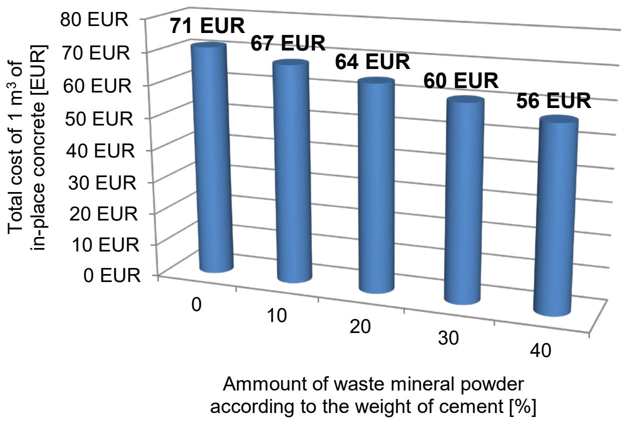

Figure 5: Average cost of 1 m^3 concrete production and the percentage of waste mineral powder used relative to the weight of cement

5. Conclusions and perspectives

This article discusses the possibility to incorporate waste mineral powders as functional additives into sustainable and environmental-friendly overlays. For this purpose, short literature survey has been performed together with specified research gaps. The analysis presented in the article shows good perspectives and high economic potential of environmentally friendly concrete for the manufacturing of sustainable overlays with waste mineral powders. The performance of functionalized concrete overlays should be perspectively analyzed following an original multi-disciplinary, multi-scale and multi-physics approach. Such an approach should be used to study the impact of waste mineral powder incorporation on the microstructure development as well as mechanical and physical properties of cement overlays and structural systems. This includes the following:

- Evaluation of physical and mechanical properties of modified concrete overlays,
- Characterization of acoustic parameters within the interface determined by novel non-destructive testing (NDT) methods,
- Assessment of the adhesion between modified concrete overlays and concrete substrate using pull-off method,
- Characterization of the material microstructure at the interface of concrete and modified overlay using micro-computed tomography (micro-CT),
- Evaluation of nano-mechanical interface properties using nanoindentation technique,
- Assessment of the chemical composition of the concrete within the interface between overlay and substrate using scanning electron microscopy (SEM).

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References

Benhelal E., Zahedi G., Shamsaei E., Bahadori A., 2013, Global strategies and potentials to curb CO_2 emissions in cement industry, Journal of Cleaner Production, 51, 142-161.

Chajec A., 2021, Granite powder vs. fly ash for the sustainable production of air-cured cementitious mortars, Materials, 14(5), 1208.

Chowaniec A., 2021, Using waste limestone powder as filler in a toxic epoxy resin coating and its influence on adhesive properties. Chemical Engineering Transactions, 88, 1063-1068.

Chowaniec A., 2021, The effect of the viscosity and the contact angle on the pull-off strength of epoxy resin modified with waste granite powders. 6th International Conference on Adhesive Bonding 2021, 83-102, Springer, Cham, Switzerland.

Czarnecki L., Deja, J., 2021, Sustainable building construction; in search of the Promethean transformation. Engineering and Construction, 77 (7), 300-308 (in Polish).

Czarnecki L. (Ed.), 2007, Adhesion in interfaces of building materials: a multi-scale approach. Aedificatio Publ. Freiburg, Germany.

Garbacz A., Non-destructive investigations of polymer-concrete composites with stress waves - repair efficiency evaluation, Scientific Works of the Warsaw University of Technology. Construction, (147), 3-208 (in Polish).

Kajaste R., Hurme M., 2016, Cement industry greenhouse gas emissions–management options and abatement cost. Journal of Cleaner Production, 112, 4041-4052.

Karasin A., Hadzima-Nyarko M., Işık E., Doğruyol M., Karasin I. B., Czarnecki S., 2022, The effect of basalt aggregates and mineral admixtures on the mechanical properties of concrete exposed to sulphate attacks. Materials, 15(4), 1581.

Li G., 2003, A new way to increase the long-term bond strength of new-to-old concrete by the use of fly ash. Cement and Concrete Research, 33(6), 799-806.

Li Y., Zeng X., Zhou J., Shi Y., Umar H. A., Long G., Xie Y., 2021, Development of an eco-friendly ultra-high performance concrete based on waste basalt powder for Sichuan-Tibet Railway. Journal of Cleaner Production, 312, 127775.

Mathia T., Louis F., 1984, Powder mechanics in tribology, Powder technology, 37(1), 155-167.

Mirmoghtadaei R., Mohammadi M., Samani N. A., Mousavi S., 2015, The impact of surface preparation on the bond strength of repaired concrete by metakaolin containing concrete, Construction and Building Materials, 80, 76-83.

Mohammadi M., Moghtadaei R. M., Samani N. A., 2014, Influence of silica fume and metakaolin with two different types of interfacial adhesives on the bond strength of repaired concrete, Construction and Building Materials, 51, 141-150.

Naik T. R., 2008, Sustainability of concrete construction, Practice Periodical on Structural Design and Construction, 13(2), 98-103.

Petrie E. M., 2007, Handbook of adhesives and sealants, McGraw-Hill Education. New York, United States.

Sadowski Ł., 2019, Adhesion in Layered Cement Composites, Springer, Cham, Switzerland.

Sadowski Ł., Hoła J., Czarnecki L., Mathia T. G., 2021, New paradigm in the metrology of concrete surface morphology: Methods, parameters and applications, Measurement, 169, 108497.

Silfwerbrand J., Beushausen H., 2005, Bonded concrete overlays: bond strength issues. International Conference on Concrete Repair, Rehabilitation and Retrofitting. Cape Town, South Africa, November 21-23, 19-21.

STAT.GOV.PL, 2022. Statistics Poland. Gross Domestic Product. <https://stat.gov.pl/en/metainformation/description-of-economic-indicators/description-of-economic-indicators-cso/gross-domestic-product-1629>, accessed 15/04.2022.

Szymanowski J., 2019, Evaluation of the adhesion between overlays and substrates in concrete floors: Literature survey, recent non-destructive and semi-destructive testing methods, and research gaps, Buildings, 9(9), 203.

Tikkanen J., Penttala V., Cwirzen A., 2011, Mineral powder concrete–effects of powder content on concrete properties, Magazine of Concrete Research, 63(12), 893-903.