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Modelling of Mechanical Properties of Eco-Friendly Cementitious Composites Used in Floors: State of the Art and Research Gaps

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The reason, why the most expensive and advanced structural elements of spacious buildings are floors, is the fact that the materials and process of erecting them are very specialized. Floors are usually made of two layers: a substrate and an overlay made of cementitious composites. The properties of cementitious composites: compressive strength, near-surface tensile strength, abrasive wear, creep strain and shrinkage are affected by numerous aspects and are important for the proper performance of the floors. Recently, to meet the expectations of sustainable development, more attention has been paid to increasing the usage of eco-friendly admixtures on floors. These admixtures are often obtained during industrial processes (milling, cutting, burning, etc). Previously the following by-products were used: fly ash as the most popular, ground granulated blast furnace slag was less popular, and granite powder was not used on floors previously. Unfortunately, novel models have to be designed to describe the mechanical properties of cementitious composites with eco-friendly admixtures, before such a solution will be widely applied. The increasing number of studies that consider the topic of prediction using various machine learning algorithms of mechanical properties of eco-friendly cementitious composites proved that this topic became interesting for scientists and will be even more interesting in the future. In this review, the author would like to present a state of the art, the main research gaps and the perspectives for further research. Thanks to this review, the alternative approach to modelling the mechanical properties of eco-friendly cementitious composites will be emphasized.

1. Introduction

Taking into account that concrete is one of the most consumed material in the world, it can be stated that the consumption of cement is also significant (Gagg, 2014). Cement, although it is a very important ingredient in concrete mixture, has recently been replaced by supplementary cementitious materials (SCM). The main reasons for this behaviour are the aim of decreasing the price of concrete, designing structures according to sustainable development and circular economy.
The most commonly used supplementary cementitious materials is fly ash due to their pozzolanic activity and potential improvement in the resistance to sulphate and chloride and alkali silica reaction due to pore refinement (Lemougna et al., 2018). Recently, the material commonly used as a substitute for cement is ground granulated blast furnace slag. It is mainly due to the possibility of manipulating the setting time and workability (Nedunuri and Muhammad, 2021). In addition, to the supplementary cementitious materials mentioned above, also mineral powders have recently been used as cement substitutes. One of a kind is granite, which in the form of powder is treated as a filler or substitute in cementitious composite mixtures (Chajec, 2021).
This approach of decreasing the amount of cement in mortar or concrete, visualised in Figure 1, is also a great opportunity to protect the natural environment from being flooded by these wastes. Recently, more researchers are starting to use different possibilities to utilize these wastes by incorporating them into concrete mixtures. However, it is worth highlighting that, in addition to cleaner production by decreasing the amount of cement and the carbon footprint, as well as the price of the final product, it also has a disadvantage, which is greater uncertainty of the properties of such hardened cementitious composite.

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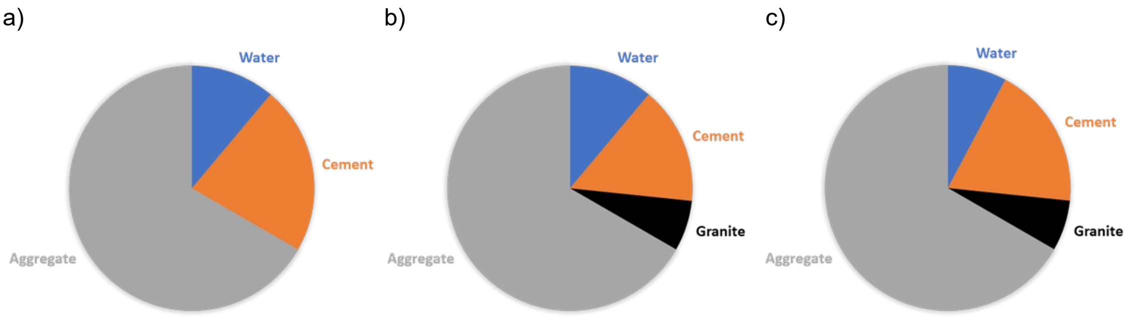

Figure 1: Cementitious composites mixture with: a) ordinary Portland Cement, b) granite powder as a cement substitute, c) granite powder as a cement paste substitute

Analysing the literature survey on the design of cementitious composites mixtures, it is difficult to evaluate the properties of hardened concrete that can be achieved by modifying them with SCMs (Rudnicki, 2021).
The problem becomes more serious while the element for which this cementitious composite is used is the floor. The floors are widely used in the construction of different types of buildings. In case of industrial buildings such floor is exposed to adverse influences, e.g., chemical aggressive environment, abrasion, and heavy load (Sadowski et al., 2020). To meet the strict requirements of these elements, floors must be properly designed with high precision. There is a need to implement the novel method of designing cementitious composites mixtures with the possibility of accurately predicting the properties of hardened concrete or mortar. For this purpose, recent attention has been paid to machine learning techniques as a solution of this problem (Naser et al., 2020). The most commonly used algorithms are neural networks (NN), support vector machines (SVM) and different decision trees (DT) based algorithms. Their popularity is schematically presented in Figure 2, as the number of articles published in scientific journals in the ScienceDirect database, using as keywords the name of the technique in addition to the phrase 'concrete mixture design'.
According to this figure, it can be seen that recently this topic has become more popular, which is presented by the significant increase in number of publications. Especially it is visible while taking neural networks as an example which number of publications increase almost twice when comparing years 2021 and 2020. Also, it should be noted that in addition to the fact that neural networks are very often the most popular for these purposes, which was also denoted in (Nunez et al., 2021), SVM and DT based algorithms are also commonly used for the design of concrete mixtures.

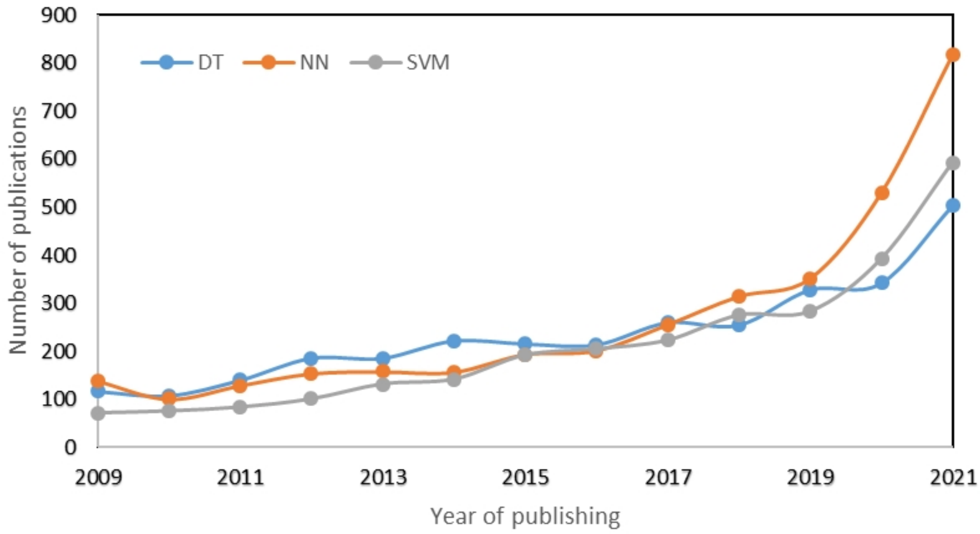

Figure 2: Comparison of the publications number with respect to the year of publication and the machine learning algorithm used

However, in analysing the literature, the design of cementitious composites is the most commonly based on compressive strength, which in some cases, e.g. industrial floors, is not always the most important property. For this purpose, in this article, the author has analysed the literature in order to present the trends in modelling the mechanical properties of eco-friendly cementitious composites dedicated to floors. It should also be highlighted that, in addition to compressive and tensile strength, the author introduces the problem of the lack of research presenting models for predicting properties such as creep strain and shrinkage and abrasive wear of cementitious composites containing SCMs, which should not be neglected in terms of cleaner floor production. The novelty of this research is emphasizing the problem of lack of complex research describing, using machine learning algorithms, the unpopular properties of cementitious composites containing SCMs that are important in the case of floors. For this purpose, the author compared the models, in terms of number and accuracy, prepared for predicting compressive strength and tensile strength with those prepared for evaluating creep strain, shrinkage, and abrasive wear. In the conclusion section, a summary of recent knowledge is provided with potential future perspectives to fill research gaps.

2. Investigated properties

As it was mentioned in the introduction in case of floors, besides the compressive strength there are other properties worth modelling in order to meet the requirements. In this section, the short description of them and recently developed models are presented also for: near-surface tensile strength, abrasive wear, creep strain, and shrinkage.

2.1 Compressive strength

Analyzing the properties of the cementitious composites with the addition of SCMs, it is usually obligatory to describe its compressive strength because, very often, this property can be correlated with others such as flexural strength, tensile strength, or durability.
Machine learning algorithms were recently used to model various cementitious composites containing SCMs compressive strength. The previous works proved that it is possible to successfully predict this mechanical property based on numerical analyses performed using machine learning algorithms. In Figure 3 the frequency of published articles with respect to the year of publication and the SCM used in the cementitious composite mixture has been presented.

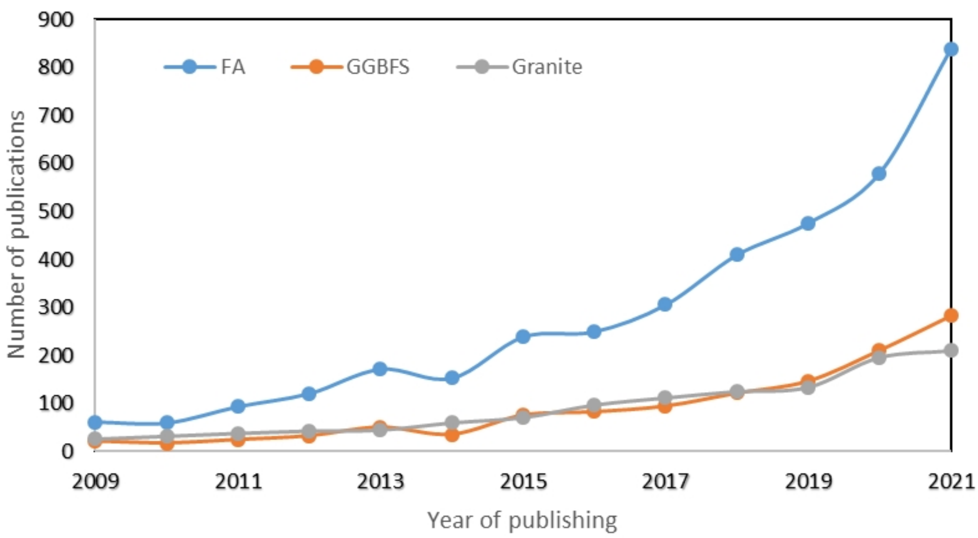

Figure 3: Comparison of the number of publications on the year of publication and the type of SCM used in the prediction of compressive strength of cementitious composites

It can be seen that fly ash (FA) is the most popular and is twice as often used in prediction models as ground granulated blast furnace slag (GGBFS) and combined granite. It is also expected that the models used to predict the compressive strength of such composites are the most accurate, which is presented by very good model performance parameters that usually are: coefficient of determination, mean average error, root mean squared error, and mean average percentage error (Kovacevic et al., 2021). It has been proven by (Asteris et al., 2021) obtaining very good correlation between the values obtained experimentally and evaluated by machine learning algorithms using only cementitious composites mixtures as input parameters.

However, in some cases, as it was shown in (Czarnecki et al., 2021) using non-destructive tests can improve the quality of the model allowing to obtain more accurate results for concrete containing GGBFS. While preparing the model, it is important to properly design the mixes based on which later the machine learning algorithms will learn on. It has been proven in (Karimipour et al., 2021) that even for concretes containing many different SCMs, including granite, limestone, mud, and marble slurry, there is a possibility to very accurately represent the experimental value of self-consolidating concrete compressive strength.

2.2 Tensile strength

As presented in Figure 4 usually while preparing the model for compressive strength, scientists also prepare the model for tensile strength. It can be seen that in more than half of the publications where the compressive strength was predicted, the researchers also used machine learning algorithms to predict the tensile strength. Comparing the model accuracy parameters obtained in work (Ting et al., 2021) it can be seen that also in case of tensile strength it is possible to obtain very accurate models of such prediction. The reason for this can be a correlation between compressive strength and tensile strength in cementitious composites, and it is not strongly affected by the incorporation of SCMs into the mixtures.

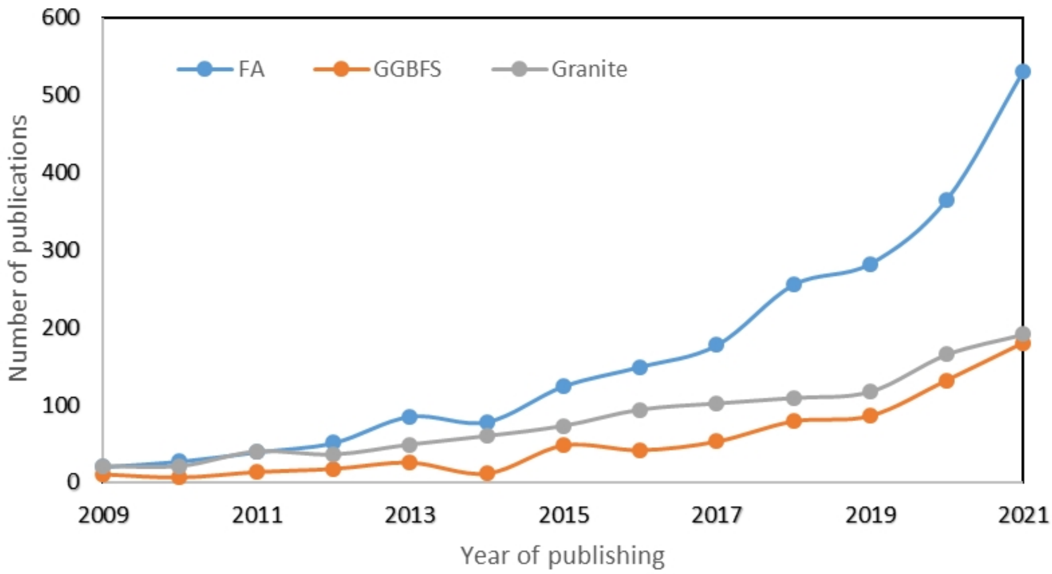

Figure 4: Comparison of the number of publications with respect to the year of publication and the type of SCM used in the prediction of tensile strength of cementitious composites

2.3 Abrasive wear

As was mentioned in the Introduction, floors operate under various environmental conditions and heavy load is one of them (Sadowski et al., 2020). This kind of load is very often caused by static load, however, in the case of industrial buildings it is also caused by the dynamic influence of moving vehicles or people. For such a reason, complex phenomenon, not only compressive and tensile strengths are important, but also abrasive wear, in order to maintain the durability of the elements.

Unlike compressive strength and tensile strength, there are just a few publications covering the topic of predicting the wear of material due to abrasion. In contrast, a smaller number of publications does not mean that the results are not successful. In the study (Malazdrewicz and Sadowski, 2021) it has been proved by experimental research that obtaining a very accurate model of prediction is possible. It has to be noted that similarly to work (Karimipour et al., 2021), Malazdrewicz and Sadowski used an extensive data set. However, still there is a possibility to fill research gaps in this field while, as concluded in (Gencel et al., 2011) the researchers investigating abrasive wear usually used different methods than machine learning algorithms. Taking into account that very often these methods required obtaining samples, there cannot be used everywhere, which makes the computational modelling techniques more attractive and competitive to the previous one.

2.4 Creep strain and shrinkage

Designing cementitious composite mixtures for floors is also a very difficult task from a rheological point of view. Floors are spacious areal elements that are very prone to excessive drying which causes shrinkage. Autogenous shrinkage is an important property in terms of aesthetics, cracking and in time durability of concrete. On the contrary, creep strain can affect the long-term durability of the floor. Similarly to compressive strength and tensile strength, creep strain and shrinkage are modeled together by the researchers (Faridmehr et al., 2022). However, in comparison to works presented for the prediction of compressive and tensile strength, as well as for abrasive wear, the algorithms used to evaluate these rheological properties are more advanced. Faridhmehr et al. (2022) used the Whale Optimization Algorithm while Sadowski et al., 2019 used the firefly algorithm to predict the creep deformation of concrete containing GGBFS. Nevertheless, the results obtained by the prepared models present very high accuracy. These results might be compared in the future by other researchers.

3. Analysis and discussion

Analysing recent models used for predicting the properties of cementitious composites containing SCMs, it can be divided into two parts: the frequency of publications covering the particular topic and the performance of mathematical model. These analyses are schematically presented in Table 1.

Table 1: The knowledge of the problem

Modelled property	FA	GGBFS	Granite
Compressive strength	Numerous papers presenting accurate models	Numerous papers presenting accurate models	Numerous papers presenting accurate models
Tensile strength	Numerous papers presenting accurate models	Numerous papers presenting accurate models	Numerous papers presenting accurate models
Abrasive wear	A few papers but presenting very high accuracy of models	A few papers but presenting very high accuracy of models	Lack of papers presenting accurate predictive models
Shrinkage and Creep Strain	A few papers but presenting very high accuracy of models	A few papers but presenting very high accuracy of models	Lack of papers presenting accurate predictive models

As can be seen in Table 1 there are various levels of modelling of the properties of cementitious composites with regard to the supplementary cementitious materials used in the mixtures as well as the modelled property of hardened composite. The main reason is the fact that in the case of compressive and tensile strength, these properties are important not only for floors but also for regular design of concrete structures. In contrast, abrasive wear, which is a very specific property of concrete, is not that commonly evaluated. There is a lack of complex research to understand and model this phenomenon by means of machine learning algorithms. It is slightly better in terms of modelling the shrinkage and creep strain, while they are not only important in floors but also in some structures itself.

4. Conclusions

Concluding the aforementioned statements it can be seen that even though machine learning algorithms are widely used in order to model the properties of hardened cementitious composites containing supplementary cementitious materials, there is still a lot of work to be done in terms of prediction of properties other than compressive and tensile strength, as well as the approaches taken in order to evaluate these properties. For this purpose, more models can be presented in terms of abrasive wear, shrinkage, and creep strain and also with more advanced algorithms in order to obtain more accurate results.

Taking into account that fly ash is more often used as SCM in comparison to ground granulated blast furnace slag and granite, there are many more models of different properties evaluated of cementitious composites containing this material. However, due to some similarities in modelling between fly ash and blast furnace slag, it can be seen that the models prepared for cementitious composites containing GGBFS are on a similar level in terms of accuracy. In case of granite as SCM it can be seen that for some properties, especially abrasive wear, shrinkage and creep strain, there are possibilities to build and improve the models of prediction.

Comparing the models in terms of algorithms, it is hard to judge which algorithm is the most efficient while even the algorithms based on decision trees can be the most effective in terms of modelling accuracy. However, as it was presented, there might be a necessity of using more advanced algorithms in order to model some properties or while using different approach than for example just mixture content.

The future in terms of modelling the properties of eco-friendly cementitious composites will provide numerous studies, while it is recently an interesting topic for researchers. Further attempts will be made in terms of predicting the compressive and tensile strengths while in terms of cleaner production novel waste materials will be incorporated into the cementitious composites. However, there is a possibility that other properties of eco-friendly cementitious composites will be modelled such as creep strain, shrinkage and abrasive wear. Therefore, the design of floors will become more commonly aided by machine learning algorithms.

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