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The Impact of Cement Aggregates on the Fire Resistance Properties of Concrete and its Ecological Footprint

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The strength properties of concrete are significantly influenced by the type of binder used. In the case of cement, the use of cement-containing admixtures (CEM II) is becoming increasingly popular from a durability and environmental point of view. The first question was how cements containing different admixtures behave and how their compressive strength changes under high temperatures (fire). First, the experiments were carried out with the cement tests, and then the concrete specimens were checked for the extent to which the addition of admixtures modifies the favourable effect measured for cement. Under thermal loading, the value of the residual compressive strength of the cement paste increased with the addition of the admixture content. The results of the compressive strength test and the developed crack patterns were consistent with each other. The most severe cracking was observed in the Portland cement specimens, and the decrease in strength was also the most significant. Based on the results of the cement tests, several types of cement were used for the concrete tests. The second research question was: Which concrete recipe has the lowest specific ecological footprint? Therefore, for each formulation, the specific ecological footprint is crucially influenced by the type and amount of substitute used, as their specific CO_2 emissions are typically lower than those of Portland cement. Based on our previous studies, a reduction in the specific ecological footprint of up to 10 % can be achieved by using substitutes. The novelty of our research lies in the combined use of fire resistance and ecological aspects, which helps to select a formulation with better technical properties and, at the same time, more sustainable.

1. Introduction

In Hungary, the practical application of ecological footprint calculations in industrial projects is still in its early stages, but it has great potential (Harangozó et al., 2015). In everyday practice, the focus in concrete design is on the verification of one or more technical and durability parameters (e.g. water resistance, fire resistance, wear resistance, chemical resistance, etc.). Concrete is often produced by repeating well-established formulations. Usually, major industrial and scientific research provides the opportunity for a wider range of tests on mixed formulations. Coupled with these research results, there is an opportunity to look at concrete mix designs not only from a technical point of view but also from an ecological economics point of view. In our article, Éva Lublóy's doctoral research (Lublóy, 2008) analysed the formulations used in the testing of concrete recipes optimised for fire resistance from the point of view of their ecological footprint. In the paper, in addition to performing this analysis, a general procedure for practical work is recommended, which allows the designer to perform an ecological-economic analysis at the same time as the technical optimisation and to minimise the ecological footprint of the designed concrete. As a first step in a general concrete recipe is shown, why can it be said that the ecological footprint of concrete is primarily influenced by the quantity and quality of cement and that by choosing these factors in a conscious way, the ecological footprint can be reduced substantially and the technical parameter under consideration, in this case, fire resistance, can be improved. The methodology follows the traditional way of thinking, whereby the first step in the technical analysis is to find the technical optimum. The results of the technical analysis are fed back as primary input to the ecological economic analysis, where the reference output can be compared with the optimal or near-optimal output.

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This approach is considered advantageous because the results of research on the search for the technical optimum are abundantly available, and the Authors can supplement these with their own ecological footprint calculations, which will give us a more accurate picture of the environmental impact of our built environment. With this method, the Authors can easily link to ongoing research on the technical issues of high-slump self-compacting concretes (Kanagaraj et al., 2023), heavyweight concretes (Ali et al., 2023), and geopolymer concretes (Balamurali et al., 2023).

2. Relevance of the problem under consideration

Population growth and improvements in human lifestyles today have led to a rapid increase in the demand for buildings (Farooq et al., 2021), which contributes to the growing economic importance of the construction industry. The economic importance of the construction industry is well illustrated by the fact that it provides more than 100 million jobs worldwide (Saáry et al., 2021), 6 % of global GDP and a significant weight in supply chains (Pató et al., 2022). The value added to the construction industry is about 5 % of GDP in developed countries and 8 % of GDP in developing economies. The demand for infrastructure is expected to remain high over the next two decades (Varga et al. 2021), with global infrastructure investment estimated at 3.7×10^{12} USD/y by 2040 (MP, 2023). The problem is that the production of cement – one of the most important raw materials for construction, has a negative impact on the environment, as it emits large amounts of carbon dioxide into the atmosphere (Akhtar et al., 2022). The cement manufacturing industry is one of the major emitters of CO_2 worldwide and contributes to 8 % of global carbon dioxide emissions (Farooq et al., 2021). Annual greenhouse gas emissions from Portland cement production are estimated at about 1.5 Gt, which is 6 % of total emissions (Amran et al. Therefore, exploring a low-carbon transition (LCT) pathway for the construction industry is of great importance for the sustainable development of the construction industry and the achievement of the international carbon neutrality target (Yao et al., 2023). Making the use of concrete more environmentally friendly is an important research issue today. Environmentally friendly reinforcement methods are also becoming more and more common (Aminova et al., 2022). The consideration of the ecological footprint over the whole lifetime of a structure is also called for by several authors, as the structure may undergo several renovations during its lifetime, and therefore, in addition to the ecological footprint of the construction, the maintenance can be a major burden (Eisinger et al., 2022) In addition to these aspects, the issue of circular gas management is increasingly being addressed (Tóth et al., 2022).

3. General studies

In this study, the concrete formulation was examined, shown in Table 1, as a reference formulation in terms of CO_2 emissions using a product-level, bottom-up methodology (Csutora-Harangozó, 2017). Since the ecological footprint calculation is based on kg CO_2, in the first step of the study, the specific emissions based on the ICE v1.6a version were considered. Since the Authors could not find any data for the liquefier in this version, they took it from ICE v3.0 as an approximation for the safety benefit in kg CO_{2e} dimension,

Table 1: The investigated concrete mix-1.

Component	Volume	Specific CO_2 emission (kg CO_2 /kg)	Total CO_2 emission (kg CO_2)	CO_2 content (%)
cement type and volume(kg/m^3)	350 (CEM I 42.5 R)	0.9300	325.500	96.500
water (kg/m^3)	151.0	0.0010	0.151	0.045
aggregate 0-4 mm (kg/m^3)	912.0	0.0048	4.378	1.298
aggregate 4-8 mm (kg/m^3)	485.0	0.0048	2.328	0.690
aggregate 8-16 mm (kg/m^3)	544.0	0.0048	2.611	0.774
super plasticiser (kg/m^3)	1.4	1.6700	2.338	0.693
Σ	-	-	**337.306**	**100.000**

The calculation shows that for concrete with pure quartz aggregate, 96.5 % of the CO_2 emissions from concrete are due to the cement in the concrete. The analysis of the mixing water can be disregarded because of its minor impact. The emissions of quartz aggregate are 2.762 %, while those of the superplasticiser are 0.693%. It can be seen that a significant reduction can be achieved by a deliberate change in the content and type of cement. It is important to note that, overall, aggregate is not a decisive factor in terms of ecological footprint but plays an important role in economic terms. As mentioned earlier, it is not always possible to find specific emission values for all substances in a single data set. Often, as illustrated in the previous example, there is a difference in the dimensions (kgCO_2 or kgCO_{2e}). For the vast majority of substances, there is no significant difference between the two values, but in special cases, glaring differences can be found in our work. In order to assess whether the kg CO_{2e} value is an approximate proxy for the ecological footprint, a comparison was made using the values in Table 2 from ICE v1.6a and v3.0 (Hammond et al., 2008). As can be seen in Table 2, there is no significant difference between the two values reported in ICE v1.6a, the difference for cement being only 2.15 %. Since it has been shown that this is practically insignificant within concrete, the determination of the percentage difference has been omitted in the other cases. If we look at the evolution of the values reported in ICE v1.6a and ICE v3.0, we see that the specific emission values decrease slightly as a result of more environmentally friendly industrial production. In the case of cement, this is 4.4 %. Based on the analyses, the negligible difference between kg CO_2 and kg CO_{2e} when considering the ecological footprint of pure silica fume concrete is concluded. Thus, although methodologically incorrect, the use of either of the available quantities is permissible for the concretes tested. In order to monitor the timeliness, it is always advisable to use the most recent data available.

Table 2: Comparative study

Material	kg CO_2 (ICE v1.6a)	kg CO_{2e} (ICE v1.6a)	kg CO_{2e} (ICE v3.0)
CEM I 42.5 R	0.9300	0.9500	0.910000
aggregate	0.0048	0.0052	0.004930
water	0.0010	-	0.000344
admixture	-	-	1.670000

4. Fire resistance test

The laboratory experiments were carried out in three stages. In the first stage, the residual compressive strength after thermal loading of hardened cement paste specimens made of different cement types was investigated. The types of cement tested were as follows: Portland cement, coal slag Portland cement, blast furnace slag cement, and composite cement. The aim of the tests is to clarify the sensitivity of types of cement to thermal stress and the choice of cement for the concrete tests planned in the second phase. The types of cement included in the study were CEM I 42.5 R, CEM II/A-V 42.5 R, and CEM II/A-P 42.5 N. In the choice of cement, care was taken to ensure that the cement was made from the same clinker and with the same grinding fineness. In the concrete experiments, the effect of the amount of trash and fly ash added to the cement was investigated. As the behaviour of cement is fundamentally influenced by its oxide composition, these are summarised in Table 3 for each type of cement tested. Based on the preliminary experiments with cement, 3 types of cement were selected and used for the concrete experiments.

Table 3: Oxide composition of cement types (%) based on data provided by Holcim Hungária Zrt.

	CEM I 42.5 R	CEM II /A-V 42.5 R	CEM II /A-P 42.5 N
$Si0_2$	19.71	23.750	28.23
$Al_2\,0_3$	4.46	6.680	6.10
$Fe_2\,0_3$	2.97	4.730	3.42
Ca0	64.59	55.310	54.54
Mg0	1.00	2.660	1.00
$K\,0_2$	0.69	0.850	1.15
$Na\,0_2$	0.31	0.470	0.67
SO_3	2.63	2.790	2.84
Cl	0.02	0.027	0.01
relative cost of cements	2,800/25 kg	2,400/25 kg	2,250/25 kg

The concrete design was carried out using the Palotás-Bolomey method. The composition calculated in the concrete design is given in Tables 1 and 4. The type of cement in the concrete mix varies accordingly, but the composition by weight is the same in all three cases. During the preparation of the concrete, the consistency was adjusted with a superplasticiser so that the area was between 410 and 450 mm. The water-cement ratio and the type of cement were varied in the design of the concretes with silica fume aggregate.

The test specimens were stored in water for 7 days and then in laboratory air for 21 days. After 28 days of age, the cubes were heated in an oven to the given temperature and then kept at the given temperature (50 °C, 150 °C, 300 °C, 500 °C, 800 °C) for 2 h. In the experiments, a heating curve close to the standard one, i.e. the one applicable to high-rise structures and halls, was used. After the mix preparation, hardening and curing, the

residual compressive strength, the residual flexural-tensile strength and the residual modulus of elasticity of the concrete after thermal loading were investigated. The variable parameters of the experiment were the different cement types. The aim of the tests was to determine to what extent and how the cement type influences the mechanical, physical and chemical properties of concrete after thermal loading.
The heated and cooled specimens were visually inspected, and the size and number of cracks were observed before the compressive strength test, and then the laboratory measurements were taken. Based on the measurements, it has been experimentally verified that the number and size of cracks observed on the surface decrease with increasing cement admixture content at high temperatures, and the relative reduction in compressive strength is smaller for both hardened cement paste and concrete with quartz aggregate (Figure 1).

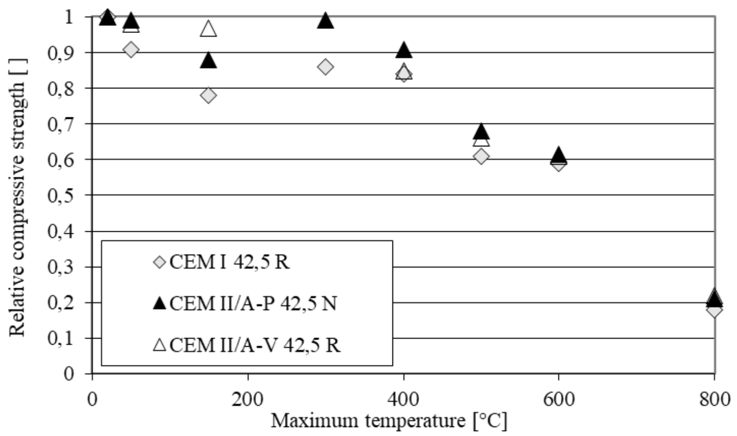

Figure 1: Relative residual compressive strength of concrete in related to the cement type and the maximum temperature of thermal load (specimens at the age of 28 days, average of 3 measurements)

The importance of this study is that it has demonstrated that the much more expensive CEM I can be effectively replaced by CEM II types of cement from a fire resistance point of view. This statement is not only decisive from the point of view of technical performance and price but also from the point of view of sustainability, as the use of additives as secondary raw material can be considered to be in the interest of the national economy. Following the thermomechanical tests carried out, an ecological-economic study of the concretes cured with Portland cement, and the supplementary tank-mix types of cement were also carried out.

5. Ecological economic studies

During the calculations, the condition is that there is no difference in the transport distance of each material. Therefore, the environmental impact of the transport of each material is not considered. Based on this assumption, the environmental burden determined for the three formulations depends only on the quantity of the materials incorporated and their specific emissions. As the available data are scarce, the values for CEM II cements are used as typical values for CEM II/A-V.
For the practical calculation, the average of the two values, i.e. 0.815 kg CO_2/kg, was taken. To determine the reduction from the results summarised in Table 1. CEM I, a repeat study was performed, which is CEM II, the results of which are summarised in Table 4.

Table 4: The investigated concrete mixture

Component	Volume	Specific CO_2 emission (kg CO_2 /kg)	Total CO_2 emission (kg CO_2)	CO_2 content (%)
cement type and volume(kg/m^3)	350 (CEM II/A-V 42.5 R)	0.8150	285.250	96.026
water (kg/m^3)	151.0	0.0010	0.151	0.051
aggregate 0-4 mm (kg/m^3)	912.0	0.0048	4.378	1.474
aggregate 4-8 mm (kg/m^3)	485.0	0.0048	2.328	0.784
aggregate 8-16 mm (kg/m^3)	544.0	0.0048	2.611	0.879
super plasticizer (kg/m^3)	1.4	1.6700	2.338	0.787
Σ	-	-	**297.056**	**100.000**

The calculation shows that for pure quartz aggregate concretes, 96.026 % of the CO_2 emissions of the concrete are due to the cement in the concrete. The analysis of the mixing water can be disregarded because of its minor impact. The emissions of the quartz aggregate are 3.137 %, while those of the superplasticiser are 0.787 %.
Based on the analysis, it can be found that the specific CO_2 emissions per 1 m^3 of concrete paved with CEM I cement are 337.306 kg, while the specific CO_2 emissions per 1m of concrete paved with CEM II cement are 297.056 kg. The difference in emissions between concrete mixed with the two formulations is 40.250 kg. This value represents an emission saving of 11.9 % for the concrete mix mixed with CEM I cement.
The calculation of the ecological footprint is based on $kgCO_2$ per 1 m^3 of concrete. Using the calculated results, a value for the ecological footprint can also be given. For this, the emission calculated in tons has to be multiplied by 0.338 gha/t (Lin et al., 2018), giving a value of 0.114 gha/m^3 for concrete mixed with CEM T cement and 0.100 gha/m^3 for concrete mixed with CEM II cement. This value implies that for concrete mixed with CEM I cement, 1,140 gm^2 of hypothetical land area is needed to produce one m^3 of concrete, and for the CEM II cement mix, 1,000 gm^2 of hypothetical land area is needed. The gha or gm^2 is expressed in terms of the world's average productive land area (Lin et al., 2018). The difference between the two values is 140 gm^2 /m^3.

6. Conclusions

Due to the numerous fires that have occurred in recent decades, there is a worldwide effort to impose the strictest possible fire safety regulations. As temperatures rise, concrete strength deteriorates, its strength decreases, its ductility increases, its structure undergoes irreversible processes, internal micro-cracks develop, and explosive spalling of the concrete surface can occur. Concrete does not regain its original properties during cooling, and in many cases, further delamination of the concrete surface can occur during cooling. In this study, it was shown, from a fire resistance point of view, that concretes made with CEM II cement containing the admixture are much better than those made with CEM I Portland cement. As a result, they show a lower loss of strength under thermal stress, a lower rate of deterioration and narrower, more distributed cracks. From an ecological point of view, our analysis has shown that switching to CEM II cement for concrete mixes with CEM I cement results in a saving of 11.9 % in CO_2 emissions. Converting the emissions obtained, it can be found that 1,140 gm^2 of hypothetical land area is needed to produce one m^3 of concrete for a formulation of concrete mixed with CEM I cement type 1,140 gm^2, and 1,000 gm^2 for a formulation mixed with CEM II cement type. The gha or gm^2 is the world's average productive land area (Lin et al., 2018). The difference between the two values is 140 gm /m^3.
As a generalization of the analysis, the following conclusions can be made:

- Compared to pure Portland cement (CEM I), supplementary cementitious materials (CEM II) have better fire resistance and ecological and economic properties. They also have a lower price so that concrete made from them can be produced at a lower cost.
- The use of additional materials as secondary raw materials is of non-economic interest, reduces the need for primary raw materials and reduces the amount of material landfilled as waste, thus creating space for landfill reclamation.
- Even though the specific CO_2 emissions of the various additives (plasticisers, curing accelerators, air-entraining agents, etc.) are very high, they have little detectable effect on concrete-specific emissions, as they are used in small quantities as secondary additives. If they can be used to reduce the quantity of cement, their use may be justified from an ecological economics point of view, but it will have the effect of increasing the price of concrete.

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