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Preliminary report

Influence of cement replacement with limestone filler on the properties of concrete*

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ABSTRACT

This paper presents an experimental research of one type of green concrete in which Portland cement was replaced with two types of limestone filler of the same origin and mineralogical composition, but with a different fineness of particles. Ten concrete mixtures were designed in which 0%, 15%, 30% and 45% (by mass) of cement were replaced with filler. The water to cement ratio for each mixture was constant (w/c=0.54), and the water to powder ratio was decreasing with increasing cement replacement. Particle size distribution was selected using Funk and Dinger, as well as using Fuller's model. The results showed that it is possible to increase the compressive strength of concrete by reducing 45% of cement, but further research should be focused on improving the workability.

1 Introduction

Concrete is the most widely used building material in the construction industry, with its use increasing steadily over the last 50 years due to its relative ease of production and relatively low price. The production of cement, one of the constituents of concrete, releases a large amount of carbon dioxide (CO_2), one of the gasses most responsible for the negative effects of the greenhouse effect. It is estimated that about 7% of the total carbon dioxide emissions into the atmosphere come from cement production [1]. Reducing its amount in concrete production has a positive impact on the environment. This fact leads to an increased interest in the development of strategies dealing with the partial replacement of cement. Cement can be replaced with by-products of other industries, such as fly ash and slag [2], or by natural raw materials, such as various types of fillers [3]. Fillers are small inert particles where the inert property prevents the binder component of the concrete from being easily replaced by a filler. Therefore, in concretes where the cement has been replaced by a filler, it is necessary to obtain satisfactory physical and mechanical properties by choosing the right amount of material and the type of mix design. In case of these concretes, it is possible to increase the packing density of the solid particles (aggregate, cement and filler) by adding fillers, which reduces the voids between them and thus reduces the water required to fill the remaining voids [4,5]. Since the water to cement ratio is an indicator of the quality of the concrete, it is possible to keep the water to cement ratio constant in the manner previously described, thus ensuring the desired quality of the concrete.

This paper presents experimental studies of concrete in which cement is replaced by limestone filler (by weight) at 0%, 15%, 30% and 45%. In addition, the influence of aggregate particle size distribution on the properties of concrete was considered using different methods. In all mixtures, the water to cement ratio was constant and the water to powder ratio decreased with increasing percentage of cement replacement.

2 Particle size distribution of aggregate

The choice of aggregate particle size distribution is one of the most important tasks in concrete technology. It has been shown that satisfactory properties of fresh and hardened concrete can be obtained if the aggregate particle size composition is selected according to certain optimization curves [6]. They are mainly represented as continuous curves, and one of the most common is the Fuller curve, given by the function:

$$Y(d) = \left(\frac{d}{d_{max}}\right)^{0.5} \tag{1}$$

where:

Y (d) - percentage of passage through the sieve of diameter d,
d - the diameter of the sieve,
d_{max} - the diameter of the nominally largest particle of the aggregate.

The optimization curve of Funk and Dinger is represented by a modified Fuller curve. The modification refers to the

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introduction of the influence of the nominally smallest particle on the particle size distribution. The distribution function is:

$$Y(d) = \frac{d^q - {d_{min}}^q}{{d_{max}}^q - {d_{min}}^q} \qquad (2)$$

where:

d_{min} - the diameter of the nominally smallest particle in the mixture,

q - distribution coefficient.

The value of the distribution coefficient q depends on the desired performance of the concrete mixture; a value of 0.23 is recommended for concretes with a more fluid consistency (self-compacting concretes) and a value of 0.32 is recommended for roller-compacted concretes [7]. The exponent q = 0.37 ÷ 0.4 is the recommended value for mixtures leading to the optimum value of the packing density [8,9], where the packing density is the volume of solid particles per unit volume. The Funk and Dinger curve using the distribution coefficient q gives the possibility to introduce small particles (cement and filler) in the process of particle packing optimization.

3 Green concrete with low cement content and addition of fillers

Considering the mixture of solid particles (aggregate, cement and filler) and water, Figure 1, it can be concluded that in the mixture all voids between the particles must first be filled (void water) and then "additional" water (excess water) must be added. "Additional" water coats the particles with a layer of water and thus ensures workability [5].

As mentioned earlier, fillers have no binding properties, so replacing cement with a filler would result in a proportional decrease in compressive strength. One way to compensate for this decrease is to increase the packing density by adding a filler that is finer than the cement particles while reducing the water content. When the packing density is increased, the content of voids between the solid particles is lower, so less water is needed to fill the voids between the particles. With a reduced amount of cement and a reduced amount of water, it is possible to keep the water to cement ratio constant. However, in these concretes, the presence of very fine particles, the fillers, increases the total specific surface area of solid particles. In this case, more "additional" water is needed to ensure the workability of the mixture [4]. Therefore, instead of increasing the amount of water to ensure the desired workability, superplasticizers are added, chemical additives that lubricate the particles by coating them with a thin layer [6].

4 Experimental program

Concrete mixtures were prepared to study the influence of cement replacement with limestone filler on concrete properties, as well as the influence of curve selection in the choice of particle size distribution of aggregate. The study was carried out on fresh and hardened concrete.

4.1 Materials

Ordinary Portland Cement CEM I 42.5 R and two types of limestone fillers were used, differing in the fineness of the particles, the larger being referred to as KF1 and the smaller as KF2. The particle size distribution is shown in Figure 2. The cement was larger than the filler particles; the average particle size of the cement was d_{50} = 12.35 μm, the limestone filler KF1 had d_{50} = 4.66μm while the limestone filler KF2 had d_{50} = 2.89μm.

In addition, natural river aggregate distributed in three fractions, (0/4 mm), (4/8 mm) and (8/16 mm), superplasticizer - latest generation hyperplasticizer based on polycarboxylate (SP), and water were used.

4.2 Mixture design

Experimental tests were carried out with a total of ten mixtures which are shown in Table 1. The mixtures were divided into two parts. The first part refers to the optimization of the particle size distribution of cement and aggregate of the reference mixture according to the Funk and Dinger curve, and the second part refers to the optimization of the particle size distribution of aggregate according to the Fuller curve. These two parts were introduced to observe the influence of aggregate optimization by different models. The percentages of the different fractions of aggregate are given in Table 2. In order to consider the influence of the distribution coefficient q of the Funk and Dinger curve, the test of the bulk density of the aggregate in compacted state was carried out for several mixtures. The mixtures had different proportions of aggregate fractions, with each mixture corresponding to one distribution coefficient. The results are shown in Figure 3.

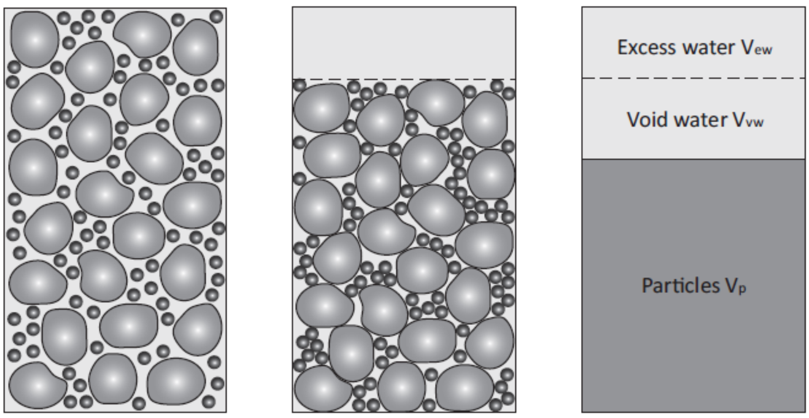


Figure 1. Mixture with its constituents [4]

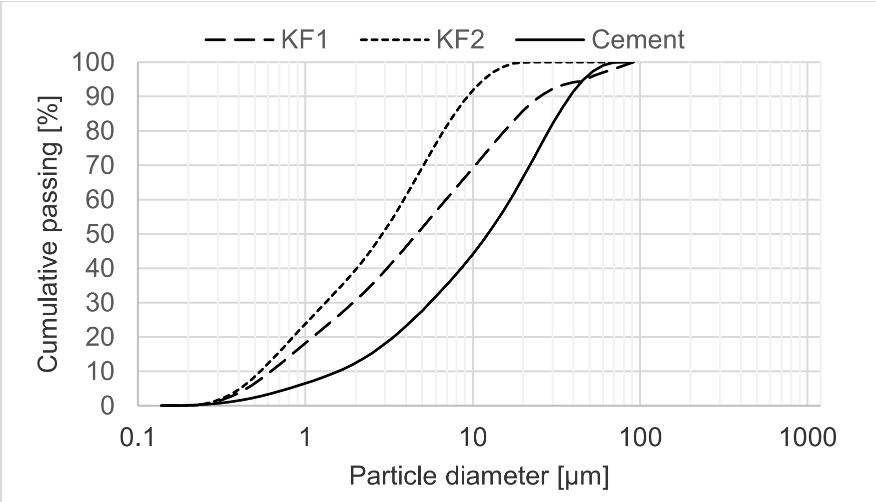


Figure 2. Particle size distribution of cement and limestone fillers

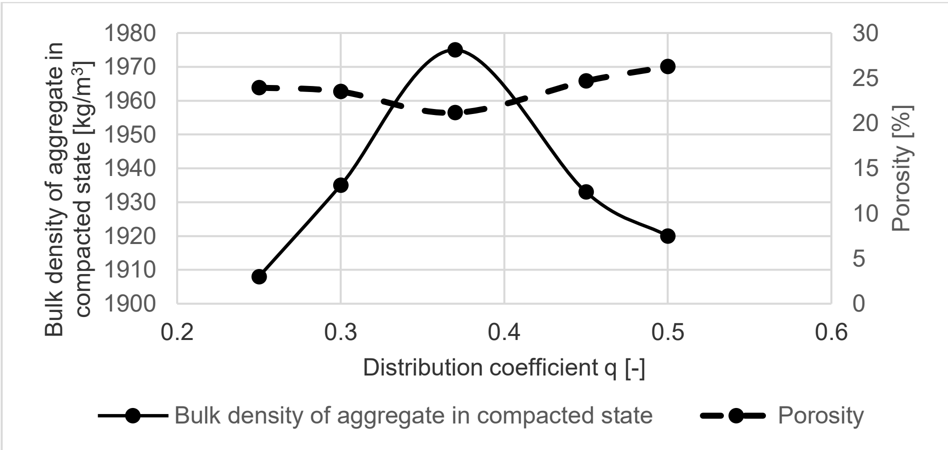


Figure 3. Bulk density of aggregate in the compacted state and porosity for different distribution coefficients of the Funk and Dinger curve

Table 1. Mixture design.

		CEM I 42.5 [kg/m^3]	**KF1** [kg/m^3]	**KF2** [kg/m^3]	**(0/4)** [kg/m^3]	**(4/8)** [kg/m^3]	**(8/16)** [kg/m^3]	**Water** [kg/m^3]	**w/p** [-]	**SP** [kg/m^3]
Funk and Dinger	B-REF	330	-	-	963	387	500	178	0.54	1.16
	BK-15-1	280	50	-	963	387	500	151	0.46	1.32
	BK-15-2	280	-	50	963	387	500	151	0.46	1.32
	BK-30-1	230	100	-	963	387	500	124	0.38	6.6
	BK-30-2	230	-	100	963	387	500	124	0.38	6.93
	BK-45-1	180	150	-	963	387	500	97	0.29	10.73
	BK-45-2	180	-	150	963	387	500	97	0.29	11.55
Fuller	B-REF-F	330	-	-	738	646	461	178	0.54	1.16
	BK-15-1-F	280	50	-	738	646	461	151	0.46	1.32
	BK-30-1-F	230	100	-	738	646	461	124	0.38	6.6

Table 2. The percentages of the different fractions of aggregate used in concrete mixtures.

	Aggregate fraction [%]	
	Funk and Dinger	Fuller
(0/4)	52	40
(4/8)	21	35
(8/16)	27	25

The greatest bulk density of the aggregate in compacted state corresponded to the value of the coefficient q = 0.37, indicating the optimal "packing" of the mixture. Therefore, this coefficient value was used in the optimization of the particle size distribution using the Funk and Dinger curve.

Then, in the first part, the cement was replaced with limestone filler at 15%, 30% and 45%. For each replacement, a larger and then a smaller limestone filler was used. In the second part, the cement was replaced with a larger filler at 15% and 30%. As the amount of cement decreased, the amount of water also decreased, so that the water to cement factor (w/c) had a constant value of 0.54. With the increase of cement replacement, the water to powder factor (w / p) decreased, where the powder referred to the cement and filler content. The amount of superplasticizer in the mixture was determined so that the mixture obtained sufficient workability.

4.3 Methods

After the concrete mixtures were prepared, the workability of the concrete was tested using the slump method according to the standard [10]. Then, 10 cm cubes of concrete were made, which were demoulded after one day. They were then stored in water at a temperature of 20 ± 3 °C until the concrete was tested for its compressive strength. This property of the concrete was tested at the age of the specimens of 7 and 28 days according to the standard [11].

5 Results

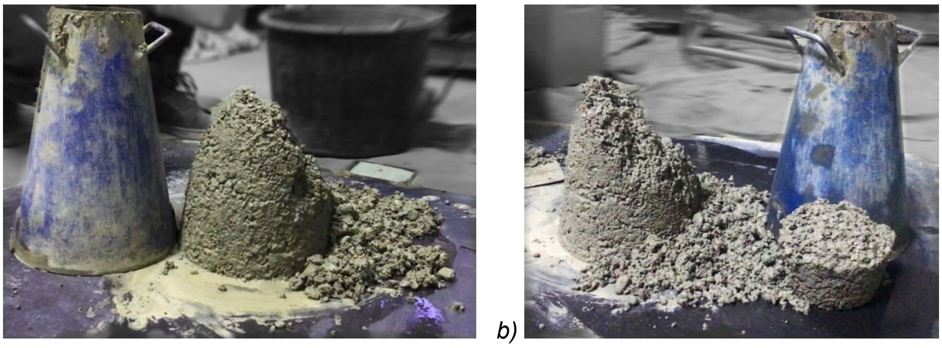
5.1 Workability

The results of workability test of concrete are presented in Table 3. It was observed that the workability of the mixtures decreases as the cement replacement ratio increases. This phenomenon is expected since the water to powder factor (which can be considered as an indicator of workability) decreases with increasing cement replacement ratio. Even if the mass amount of the powder component of each mixture is constant, the specific surface area of the powder component increases with increasing cement replacement. In this case, the amount of water required to coat all the particles and ensure the "flow" of the mixture increases, further affecting workability.

Table 3. Workability test results.

		Slump Δh [mm]
Funk and Dinger	B-REF	60
	BK-15-1	25
	BK-15-2	25
	BK-30-1	-
	BK-30-2	-
	BK-45-1	0
	BK-45-2	-
Fuller	B-REF-F	80
	BK-15-1-F	40
	BK-30-1-F	-

However, at higher cement replacements (30% and 45%), probably due to the lack of cement paste, an irregular form of slump occurred in the workability test, which is described by the standard as an unacceptable and unmeasurable form of slump. The cause of this phenomenon is most likely the absence of a binder component that provides cohesion and plasticity of the fresh concrete mass. An example of such slump is shown in Figure 4.



a) *b)*

Figure 4. Workability test according to slump method a) BK-30-1 i b) BK-45-2

Considering the results obtained with mixtures where the choice of particle size distribution was made according to two different curves, it is noticed that the mixtures where the Fuller model was applied had better workability. Considering the proportions of the different aggregate fractions given in Table 2, it is concluded that due to the higher proportion of the first fraction in the Funk and Dinger model, a larger amount of water is required to achieve the desired workability, since the specific surface area is larger. This fact is held responsible for the improved workability in mixtures having Fuller optimization curve for the selection of the particle size distribution.

5.2 Compressive strength

The results of compressive strength testing of concrete on 10 cm cube specimens at the age of 7 and 28 days with optimization using the Funk and Dinger curve are shown in Figure 5.

Although all the mixtures had the same water to cement factor, it was observed that the strengths reached higher values for the concrete that had a limestone filler in its composition. The highest strength increase was recorded for the highest percentage of cement replacement (45%) with a smaller filler, and this increase was 22.5% at the age of 7 days and 9.4% at the age of 28 days. All the mixtures showed higher strengths than concrete mixtures without fillers. Considering the compressive strength of concrete as a basic indicator of concrete quality, cement was successfully replaced with limestone filler. A comparative plot of the compressive strength of concrete at the age of 7 and 28 days in mixtures in which the particle size distribution was carried out with two different models is shown in Figure 6. The choice of particle size distribution has an influence on the concrete compressive strength; better packing in mixtures in which the optimization of the solid fractions was carried out according to the Funk and Dinger model contributed to the increase in concrete strength. The largest increase was observed in the reference mixtures and is 3.9%. However, the tests carried out showed that this increase is not significant and, in some cases, it was even non-existent. This leads to the conclusion that the introduction of fine particles (cement and filler) in optimization curves (Funk and Dinger model) make a more complex particle size distribution process and do little to improve the compressive strength compared to the Fuller curve.

6 Conclusions

The main objective of this experimental research was to investigate the possibility of replacing cement with fine powder material, filler, while maintaining the basic properties of concrete that allow it to compete with traditional concrete, thus offering the possibility of using this type of concrete in reinforced concrete structures. This would lead to an effective reduction in the amount of cement compared to traditional concrete and thus its harmful effects on the environment.

From this study, it was concluded that it is possible to replace up to 45% of the cement with a high fineness limestone filler while maintaining and even increasing the compressive strength. However, the concept of concrete where cement has been replaced with filler requires some reduction in the amount of water, with the reduced amount of cement affecting the workability and cohesion of the mixtures. It was also found that in these concretes, superplasticizer helps to improve these properties, but not enough for such concretes to be competitive with traditional concretes. The impaired workability can be partially compensated by a better choice of aggregate particle size distribution. It is concluded that the value exponent q = 0.37 of the distribution of the Funk and Dinger curves leads to an optimal packing and that this contributes to increasing the compressive strength of the concrete, but not significant compared to the more easily applicable Fuller curve. Since

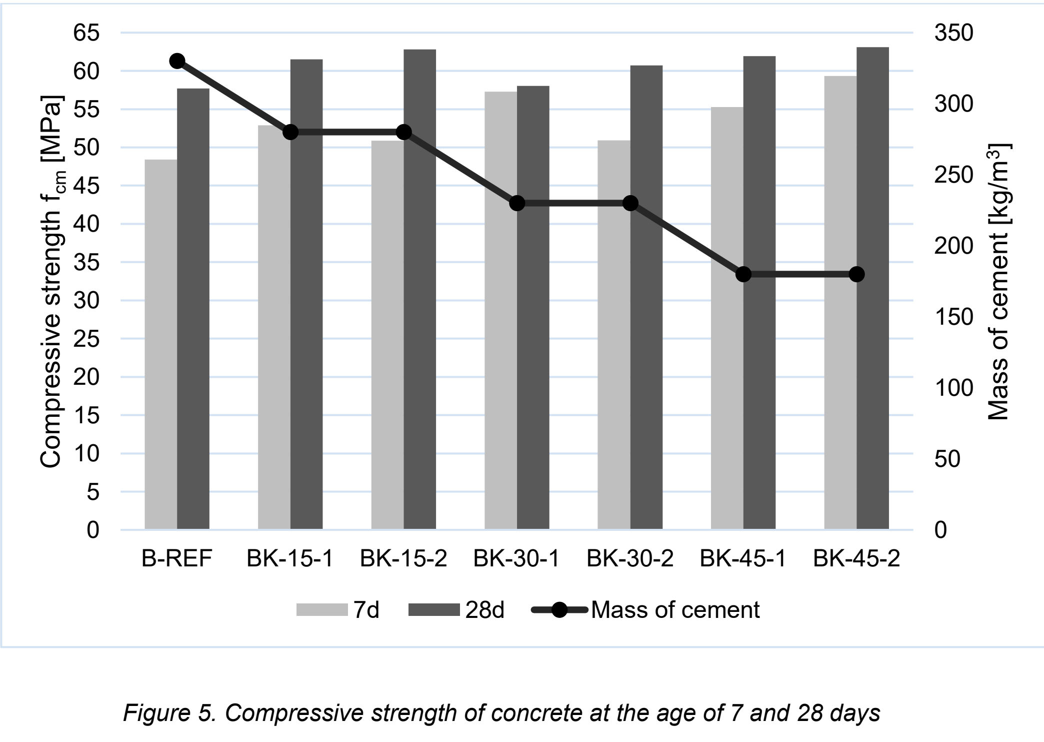


Figure 5. Compressive strength of concrete at the age of 7 and 28 days

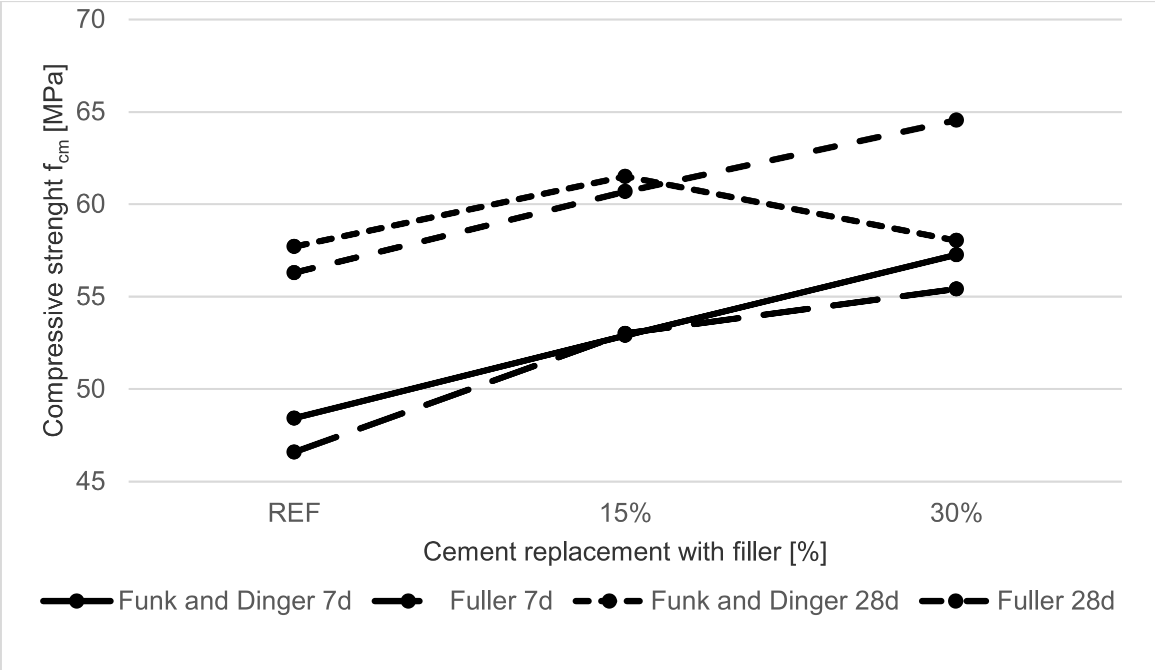


Figure 6. Comparison of the compressive strength of concrete at the age of 7 and 28 days in mixtures where the particle size distribution is selected according to two different optimization curves.

the choice of Fuller curve leads to better workability of concrete mixture with lower percentages of cement replacement, it is recommended to use this, widely used method for the selection of aggregate particle size distribution.

Further research must focus on improving the technological properties of these concretes so that this type of concrete can compete with traditional concrete.

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