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A study on the applicability of the efficiency factor of supplementary cementitious materials to durability properties

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HIGHLIGHTS

- Efficiency factor *k* is often used as a practical approach for determination of the role of SCMs on concrete strength.
- The applicability of *k*-values to durability-related properties is questionable.
- Strength-derived *k*-values showed to be appropriate as a proxy-criterion only for carbonation resistance.
- Specific *k*-values are needed for chloride-resistance performance.
- These *k*-values were around 1.5 for fly ash and slag and lower than 1 for ground limestone and pozzolan.

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ABSTRACT

Supplementary cementitious materials (SCMs), such as fly ash, pozzolan or blastfurnace slag, are widely used to produce blended portland cements, since they lead to a significant reduction in CO_2 emission in the production phase compared to portland cement. A practical and generally accepted approach to evaluate the contribution of SCMs to the strength of the hardened concrete is through the concept of the SCMs efficiency factor (i.e. *k*-value concept), which expresses the fraction of portland cement that can be replaced by a SCM at unchanged strength. In the literature some studies have also been focused on the use of the *k*-value approach also for the resistance against carbonation and chloride penetration of blended portland systems. However, limitations of applicability of SCMs efficiency factor to durability properties are not clear. In this paper the *k*-value of different SCMs, such as ground limestone, fly ash, natural pozzolan and ground granulated blastfurnace slag, was investigated to detect firstly if it can be applied to carbonation- and chloride-related properties and, secondly, if strength can be considered as a proxy-criterion for durability properties. Results showed *k*-values lower than 1 for all the SCMs with respect to compressive strength and that these values were valid also for resistance to penetration of carbonation. As far as the resistance to chloride penetration is concerned, *k*-values derived from strength tests were not applicable and specific *k*-values should be evaluated; values higher than 1 were calculated for fly ash and ground granulated blastfurnace slag, whilst values lower than 1 were obtained for ground limestone and natural pozzolan.

1. Introduction

A remarkable contribution towards a sustainable development of the cement and concrete industries can be achieved by the utilization of cementitious and pozzolanic by-products, such as fly ash (FA) and ground granulated blastfurnace slag (GGBS), produced by thermal power plants and metallurgical industries, or natural pozzolanic additions (PZ) as well as limestone [1,2]. The use of such supplementary cementitious materials (SCMs) leads to a significant reduction in CO_2 emissions per mass of concrete and, for some additions, it also allows to utilize by-products of industrial manufacturing processes.

Considering the percentages of replacement for the ordinary portland cement (OPC) indicated in the European Standard EN 197-1 (Cement – Part 1: Composition, specifications and conformity criteria for common cements – 2011), a practical and generally accepted approach to evaluate the contribution of SCMs to a specific property is the concept of the efficiency factor, i.e. *k*-value concept, firstly proposed by I.A. Smith [3]. The efficiency factor is defined as the fraction of SCM in a concrete, which can be

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considered equivalent to portland cement, without changing the property being studied ($k = 1$ for portland cement). The SCM efficiency has been traditionally determined with regard to the compressive strength of concrete; however the *k*-value concept has been also extended to other properties, e.g. the durability properties. For instance, the last version of the European Standard EN 206 (Concrete – Specification, performance, production and conformity – 2013) clearly indicates that this concept can also be applied to durability properties of concrete. However, as suggested by several Authors, it is not possible to determine a unique and universal *k*-value for any addition or property considered [4–8]. Indeed, EN 206 Standard implicitly recognizes this by stating that the *k*-value concept resulting from strength properties cannot be considered as a proxy-criterion for durability properties unless otherwise demonstrated. Therefore, there is a need for more investigations in this field.

It should be observed that, in general, the *k*-value approach is based on the assumption of the existence of a relationship between the tested property and a compositional parameter. The evaluation of the *k*-value, with regard to the compressive strength, is usually made from the relationship between strength and the water/cement ratio, i.e. the Abram's law, for the reference portland-cement concrete, however also other approaches have been applied, e.g. the comparison of the strength of two mixes having the same workability [9]. In other cases, correlations between the *k*-value and the pozzolanic activity as well as the active silica content have been proposed [10].

The European Standard EN 206 broadly permits the *k*-value approach, without referring to a specific percentage of mineral admixture, curing time or *w/b* ratio and without clearly specifying the property to which it is referred. Nevertheless, it indicates a specific value of 0.4 for fly ash, whilst for ground granulated blast-furnace slag an "open value", which should be set in the national regulations, is indicated, however suggesting the value of 0.6 as a starting point.

As far as the *k*-value proposed in the literature is concerned, Table 1 reports a summary of the *k*-values evaluated by several Authors, considering different SCMs and different percentages of replacement, usually in the ranges indicated, for each material, in the European Standard EN 197-1 [4,7,10–15]. Most Authors agree that the SCMs efficiency factor depends on the type of addition, curing time and also the strength class of portland cement.

As far as GGBS is concerned with regard to 28-day compressive strength, for low percentage of replacement (i.e. lower than 15%), a *k*-value around 1.28 was found [7,11], whilst it decreased to 0.6 when the percentage of replacement was about 80%. The *k*-value of fly ash, evaluated after 28 days of curing, was about 1 for low percentage of replacement and it dropped to values around 0.35

Table 1
Reported values of *k*-values for different properties, curing times and types of addition.

Property	Curing (days)	Addition Type	*w/b*	Percentage	*k*-Value	RefS.
Strength	28	Fly ash	N.A. [a]	10–75	1.25–0.35[b]	[4]
	28	GGBS	0.25–0.75	10–80	1.29–0.7[b]	[11]
	28	Low-Ca fly ash	0.38–0.71	5–15[c]	0.5	[12]
		High-Ca fly ash	0.38–0.71	5–15[c]	1	
	91	Low-Ca fly ash	0.38–0.71	5–15[c]	0.7	
		High-Ca fly ash	0.38–0.71	5–15[c]	1	
	2	Low-Ca fly ash	0.42–0.5	10–20[c]	0.8	[10,13]
		High-Ca fly ash	0.42–0.5	10–20[c]	0.8	
		Natural pozzolan (vulcanic tuff)	0.42–0.5	10–20[c]	0.4	
		Natural pozzolan (diatomaceous earth)	0.42–0.5	10–20[c]	0.2	
	7	Low-Ca fly ash	0.42–0.5	10–20[c]	1.0	
		High-Ca fly ash	0.42–0.5	10–20[c]	0.9	
		Natural pozzolan (vulcanic tuff)	0.42–0.5	10–20[c]	0.3	
		Natural pozzolan (diatomaceous earth)	0.42–0.5	10–20[c]	0.2	
	28	Low-Ca fly ash	0.42–0.5	10–20[c]	1.1	
		High-Ca fly ash	0.42–0.5	10–20[c]	0.9	
		Natural pozzolan (vulcanic tuff)	0.42–0.5	10–20[c]	0.3	
		Natural pozzolan (diatomaceous earth)	0.42–0.5	10–20[c]	0.2	
	90	Low-Ca fly ash	0.42–0.5	10–20[c]	1.2	
		High-Ca fly ash	0.42–0.5	10–20[c]	0.9	
		Natural pozzolan (vulcanic tuff)	0.42–0.5	10–20[c]	0.3	
		Natural pozzolan (diatomaceous earth)	0.42–0.5	10–20[c]	0.2	
	28	Fly ash	0.5–0.93	15–58	1.25–0.4	[14]
	180	Fly ash	0.5–0.93	15–58	1.3–0.3	
	1	GGBS	0.4–0.7	15–85	0.5–0.7	[7]
	4	GGBS	0.4–0.7	15–85	0.8–0.5	
	7	GGBS	0.4–0.7	15–85	0.9–0.6	
	28	GGBS	0.4–0.7	15–85	1.28–0.6	
	91	GGBS	0.4–0.7	15–85	1.58–0.65	
	182	GGBS	0.4–0.7	15–85	1.62–0.62	
	266	GGBS	0.4–0.7	15–85	1.39–0.58	
Carbonation Resistance	365	Low-Ca fly ash	0.38–0.71	5–15[b]	0.5	[12]
		High-Ca fly ash	0.38–0.71	5–15[b]	0.7	
Chloride Resistance	365	Low-Ca fly ash	0.38–0.71	5–15[b]	3	
		High-Ca fly ash	0.38–0.71	5–15[b]	2	
	90	Low-Ca fly ash	0.42–0.5	10–20[b]	2.5	[13]
		High-Ca fly ash	0.42–0.5	10–20[b]	2	
		Natural pozzolan (vulcanic tuff)	0.42–0.5	10–20[b]	1	
		Natural pozzolan (diatomaceous earth)	0.42–0.5	10–20[b]	1	
	28	GGBS	0.5	50–85	1.3–1.9	[8]
	28	FA	0.45 and 0.6	25–43	0.2–1.8	[15]
	90	FA	0.45 and 0.6	25–43	0.5–2	

[a] N.A. = not available.
[b] Value of the overall efficiency factor, which is a combination of the two factors "general efficiency factor" and "percentage efficiency factor".
[c] The SCM was both replaced to the cement and aggregates.