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Comparison of intergrinding and separate grinding for the production of natural pozzolan and GBFS-incorporated blended cements

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Abstract

A portland cement clinker, a natural pozzolan, and a granulated blast furnace slag (GBFS) were used to obtain blended cements that contain 25% mineral additives. The natural pozzolan, which was softer, was more grindable and granulated blast furnace slag, which was harder, was less grindable than the clinker. Two of the cements produced were obtained by intergrinding and the other two were obtained by separate grinding and then blending. All of the blended cements and the control cement without any additive had the same fineness as 3500 ± 100 cm^2/g Blaine fineness. During grinding, energy consumption of the mill was recorded and a sample corresponding to each energy level as taken from the mill at regular intervals and particle size distribution was determined. Cements produced were compared for change in particle size distribution during grinding and 1-, 2-, 7-, 28-, and 90-day compressive strengths points of view. Also, interactions between clinker and mineral additive portions of blended cements during intergrinding is highlighted.

Keywords: Grinding; Compressive strength; Mortar; Particle size distribution

In blended cement production, mineral additives can be introduced to the cement by separate grinding or intergrinding. These grinding methods provide different products from many aspects. For granulated blast furnace slag (GBFS)-incorporated cements, Blunk et al. have shown that separately ground and interground cements have appreciably different particle size distributions [1]. This phenomenon was explained by the fact that essentially harder granulated blast furnace slag particles abrade the clinker particles, providing an extra grinding effect in intergrinding [2]. The study of Tsivilis et al. has shown that intergrinding of raw materials is less energy-demanding than separate grinding, especially for the production of high-fineness products [3]. The study of Hosten and Avsar has shown that the grindability of the mixtures of trass and clinker (expressed as Bond work index) is not simply the weighted average of the grindabilities of clinker and trass [4]. In the light of this information, it is concluded that in blended cement production by intergrinding some interactions occur between the particles of different ingredients. As a result of these interactions, particle size distribution of interground blended cements is different than that of separately ground cements. The current study aims to show the effects of those interactions in intergrinding and to compare the grinding methods from particle size distribution and strength points of view.

1. Materials

A natural pozzolan and a blast furnace slag were used in the study. The clinker was an ordinary portland cement clinker. Properties of these materials are given in Table 1. The materials were crushed to 16-mm maximum size by a jaw crusher before feeding to the mill.

2. Methods

In the study, two types of blended cements with 25% mineral additive replacement by weight and 3500 ± 100 cm^2/g Blaine fineness were produced by both separate and intergrinding for each mineral additive used. Separately ground cements were produced by grinding mineral additive and clinker separately to 3500 ± 100 cm^2/g Blaine fineness and mixing them in ground form. Portland cement of the same fineness was also produced. Cements and their designations, grinding methods, fineness values, and required mill energies for the production are presented in Table 2. All the cements contain 4% gypsum by weight.

Grinding process was carried out in a two-compartment laboratory-type ball mill of 20-kg raw mix capacity. During

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Table 1
Chemical, mineralogical, and physical properties of the materials

	Clinker	N	S
MgO (%)	1.08	0.28	5.20
Al_2O_3 (%)	5.61	15.44	13.50
SiO_2 (%)	20.62	64.18	40.62
CaO (%)	63.61	4.16	34.48
Fe_2O_3 (%)	3.05	3.72	0.62
SO_3 (%)	2.75	0.35	0.34
K_2O (%)	0.86	2.98	1.27
Na_2O (%)	0.26	3.33	0.32
TiO_2 (%)	–	0.44	0.60
Mn_2O_3 (%)	–	–	1.63
Loss on ignition (%)	1.84	4.88	0.58
Density* (g/cm^3)	3.14	2.47	2.85
Minerals in the material	C_3S, C_2S, C_3A, C_4AF	Quartz, calcite, albite, sanidine, glassy phase	Glassy phase

* Density is given for the ground materials at 3500 cm^2/g Blaine fineness.

the process, energy consumption value of the mill was recorded at regular intervals and a sample corresponding to this level of energy consumption was taken from the mill. On these samples, particle size distribution was measured by laser diffraction. Blaine fineness values were determined according to ASTM C 204 [5]. 1-, 2-, 7-, 28-, and 90-day compressive strengths of the cements were determined according to ENV 196-1 [6].

3. Results and discussions

Particle size distributions of the cements corresponding to different energy levels are presented in Table 3. In this table, the values for the interground cements were directly found by using the samples taken from the mill at each energy-consumption level. On the other hand, the values for the separately ground cements were calculated by weighted mean of the values of each ingredient at the same energy level. For example, at 52 kWh/ton energy consumption level, portland cement and natural pozzolan have 35.9% and 20.5% material coarser than 30 μm. Thus the amount of material coarser than 30 μm in portland (P) + natural pozzolan (N) (separately ground) cement for 52 kWh/ton energy consumption is $0.75 \times 35.9 + 0.25 \times 20.5 = 32.0\%$, where 0.75 and 0.25 represent the amounts of clinker and natural pozzolan in the blended cement, respectively.

The particle size distribution of separately ground blended cements is given as a percentage of the values of interground cements in Table 3. For instance, for P + N at 52 kWh/ton energy level, the amount of material above 30-μm size was calculated as 32.0%. This value is presented as percentage of the amount of material above 30-μm size for PN (interground) at the same energy level (28.8%). Thus, for separate grinding (P + N), material coarser than 30 μm was presented as $(32.0/28.8) \times 100 = 111\%$.

A study of Table 3 leads to the following discussions.

1. For both of the separately ground cements [P + N and P + blast furnace slag (S)], with increasing energy level, amount of material above a specific size increases when it is expressed as percentage of the values of interground cements. To illustrate, at 22 kWh/ton energy level, PN cement has 21.4% material above 90 μm. Whereas, considering material above 90 μm P + N cement has 124% of this value (26.5%). When higher energy levels such as 45 kWh/ton are considered, above the same size (90 μm) interground PN has 2.4% material and separately ground P + N has 149% of this value (~3.6%). This means that grinding to higher energy levels makes separately ground cements relatively coarser when compared with interground cements. In other words, at higher energy consumption levels, intergrinding provides finer cements and increasing energy level widens the gap between the particle size distributions of the products of intergrinding and separate grinding.
2. For separately ground cements, at a specified energy level, the amount of material above different sizes tends to decrease with decreasing size. In other words, for separately ground cements, the values tend to decrease from left to right on the same row. This is true at each energy level for P + N and at energy levels higher than 37 kWh/ton for P + S. For instance, at 52 kWh/ton energy level, material above 90 μm for P + S cement is 130% of the value of PS cement (at 52 kWh/ton PS has 4.3% material above 90 μm). At the same energy level, 130% decreases to 103, 101, and 100% for 45-, 30-, and 15-μm sizes, respectively. This means that particle size distribution difference between the products of intergrinding and separate grinding decreases when the size considered gets smaller. This is attributed to fewer interactions between the ingredients for interground cements at small

Table 2
Cements produced and their energy consumption

Cement type code	Grinding method	Blaine fineness (cm^2/g)	Energy consumption (kWh/ton)
P	–	3460	52
PN	Intergrinding	3490	39
P + N	Separate grinding	3460 + 3530	45*
PS	Intergrinding	3430	65
P + S	Separate grinding	3460 + 3520	59*

* The consumed energies of separately ground cements were calculated by weighted mean of consumed energies of the ingredients to reach 3500 cm^2/g.

Table 3
Particle size distributions of the cements corresponding to different mill energy-consumption levels

	Cements with 25% natural pozzolan							
	Interground (PN)				Separately ground (P + N)			
Energy (kWh/ton)	>90 μm (%)	45 μm (%)	>30 μm (%)	>15 μm (%)	>90 μm (%)	>45 μm (%)	>30 μm (%)	>15 μm (%)
12	51.1	66.9	74.6	84.7	101	100	100	100
15	45.3	62.1	70.4	81.7	103	101	101	101
22	21.4	44.4	56.0	71.9	124	109	106	103
37	4.2	23.7	38.5	59.3	156	113	106	102
45	2.4	18.1	32.3	54.1	149	117	110	104
52	0.8	14.6	28.8	51.0	291	124	111	104
	Cements with 25% blast furnace slag							
	Interground (PS)				Separately ground (P + S)			
Energy (kWh/ton)	>90 μm (%)	45 μm (%)	>30 μm (%)	>15 μm (%)	>90 μm (%)	>45 μm (%)	>30 μm (%)	>15 μm (%)
12	68.0	79.4	84.5	90.9	96	98	99	99
15	60.2	74.1	80.4	88.4	101	100	100	100
22	40.3	61.6	70.6	81.8	98	98	98	99
37	13.1	38.8	52.6	69.8	103	94	95	97
45	7.4	29.8	44.3	63.8	112	100	100	100
52	4.3	25.1	40.2	60.6	130	103	101	100

particle sizes. Thus, it can be stated that the interactions between the ingredients of interground blended cements mostly occur between larger particle sizes.

3. For separately ground P + N cement all the values presented in Table 3 are higher than 100%. This means that when the natural pozzolan and a clinker are ground to the same energy level and then mixed, the blended cement obtained has a coarser particle size than interground blended cement of the same composition and of the same energy consumption. This seems to be valid for the cases in which clinker and softer mineral additives are interground. However, in order to provide generalizations, more tests on soft additives should be carried out. On the other hand, for separately ground P + S cement, while the values belonging to low-energy levels are lower than or equal to 100, the rest are higher than 100. This means that at the preliminary stages of grinding (mainly in the first compartment of the mill where larger steel ball size is used for coarse grinding) product of separate grinding is finer than the product of intergrinding, whereas in the second compartment of the mill (where smaller size steel balls are used as the grinding media), separate grinding is disadvantageous for slag cements. Particle size distributions of the cements produced to the same Blaine fineness (3500 ± 100 cm^2/g) are given in Table 4 and 1-, 2-, 7-, 28-, and 90-day compressive strengths determined according to ENV 196-1 are presented in Table 5. Simultaneous interpretation of Tables 2, 4, and 5 leads to the discussion given below.
4. For cements containing natural pozzolan, intergrinding consumes less energy than separately grinding to reach 3500 cm^2/g Blaine fineness and the strength values of interground cements are higher at all the ages.
5. For cements containing blast furnace slag, unlike the natural pozzolan-incorporated cements, intergrinding consumes more energy than separate grinding to reach 3500 cm^2/g Blaine fineness. However, the lower energy-consuming separately ground P + S cement still shows lower strength values than higher energy-consuming interground PS cement.
6. The lower strength of both of the separately ground cements at all the tested ages can be explained by the particle size distribution of these cements when compared to interground cements of the same composition (Table 4). Also, as it is known, intergrinding provides more homogeneous products, which may be the second reason for higher strengths of interground cements.
7. The difference between the compressive strengths of the separately ground and interground cements of the same composition and the same fineness decreases with age (Table 5).

Table 4
Particle size distribution of the cements with 3500 cm^2/g Blaine fineness

	>90 μm (%)	>60 μm (%)	>45 μm (%)	>30 μm (%)	>15 μm (%)	>10 μm (%)
P	2.9	11.6	21.1	35.9	56.6	66.4
PN	4.2	13.1	22.5	37.0	58.1	68.0
P + N	4.6	13.8	23.2	37.7	58.3	68.0
PS	2.0	9.6	18.4	33.2	55.0	65.2
P + S	3.2	11.4	20.5	35.3	56.4	66.5

Table 5
Compressive strengths of the cements*

	Consumed energy (kWh/ton)	1 day	2 days	7 days	28 days	90 days
P (MPa)	52	13.1	22.5	40.2	53.6	59.6
PN (MPa)	39	8.4	14.7	27.8	41.4	49.2
P + N (%)	45	93	94	95	98	98
PS (MPa)	65	8.7	15.6	30.5	49.1	59.2
P + S (%)	59	92	96	96	98	102

* All these cements have the same Blaine fineness (3500 ± 100 cm^2/g). Strengths of separately ground cements were given as percentage of the strengths of interground cement of the same composition at the same age.

4. Conclusions

The following conclusions were drawn through the interpretation of the data obtained:

1. Products of intergrinding and separately grinding do not have the same particle size distributions at the same energy levels. This means that during intergrinding, different ingredients do not show the same behavior as in the case of separate grinding. Therefore, it was concluded that during intergrinding some interactions occur between the particles of different ingredients of blended cements.
2. Interactions between the ingredients in intergrinding is much more pronounced for higher particle size ranges since the difference between the particle size distributions of the products of different grinding methods is higher at these ranges. The interactions during intergrinding are not significant for small particle sizes.
3. Interground cements become relatively finer than the separately ground cements with increasing grinding energy consumption. This result is independent of whether the mineral additive is harder or softer than clinker.
4. For the cements produced by intergrinding and separate grinding and having the same Blaine fineness and composition, the difference between the compressive strengths decreases with age.

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