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EFFECT OF GRINDING METHOD ON ENERGY CONSUMPTION AND PARTICLE SIZE DISTRIBUTION OF BLENDED CEMENTS*

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Abstract– The benefits of using mineral admixtures as a partial replacement of portland cement (PC) are well established in the literature. Economic and environmental advantages by reducing CO_2 emissions are well known. This paper examines the influence of intergrinding and separate grinding on the amount of energy consumption, Blaine fineness and particle size distribution (PSD) of blended cements, namely portland pozzolana cement (PPC), portland limestone cement (PLC), and portland composite cement (PCC). In this study, 18 types of cements including two types of portland cement (PC), four types of portland -limestone cement (PLC), four types of portland -pozzolan cement (PPC), and eight types of portland -composite cement (PCC) were used. The results show that particle size distribution (PSD) of blended cements varies for each method. In intergrinding method, interactions between cements components can affect final product properties positively or negatively. In other words, proper use of these interactions not only promotes process of grinding in multi components cements, but also improves particle size distribution of these cements.

Keywords– Intergrinding, separate grinding, blended cements, energy consumption, particle size distribution

1. INTRODUCTION

The majority of the cementitious binder used in concrete is portland cement clinker, the manufacture of which is an energy-intensive process. Approximately 2% of world energy is spent in this process [1]. Considering the annual production of 1.6 billion tonnes of portland cement, the cement industry itself is responsible for 7% of the total CO_2 emissions. On the other hand, the concrete industry is one of the major consumers of natural resources. In order to reduce energy consumption, CO_2 emissions, and to increase their production, cement plants produce blended cements comprised of supplementary cementations materials (SCM) such as slag, natural pozzolans, fly ash, and limestone [2-5].

For example, during the last decades, production of portland limestone cement (PLC) has rapidly increased in the cement industry in order to achieve the above mentioned goals. According to CEN, the use of CEM II limestone cements increased from 15% in 1999 to 31.4% in 2004 and has become the single largest type of cement produced [6].

In the conventional process of cement production, 30–80 kWh/t specific energy is consumed in cement grinding which equals 30% of the total energy consumption. Furthermore, approximately 60–70% of the total electrical energy used in a cement plant is utilized for the grinding of raw materials, coal, and clinker. As a result, a small gain in grinding efficiency can have a large impact on the operating cost of a plant [7-8].

Blended cements can be produced by two different methods, either by intergrinding of portland cement clinker, SCM and gypsum, or by blending the separate grinding of portland cement (clinker + gypsum) and SCM [4, 9-12].

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A good understanding of the grinding technology is an essential step in the development of a multi-component cement. Whether separate grinding or intergrinding is preferred depends on the type of SCM used, economical considerations (energy consumption), their replacement levels, the necessary fineness, and on the required strength and durability properties of the blended cement.

The main difference between intergrinding and separate grinding of a multi-component cement is that during intergrinding, the different components interact with one another. The interactions among the constituents are mostly due to the relative difference in grindability. This interaction can help or hinder the grinding, and influence the relative content of each component in different size fractions and the particle size distribution of the ground products.

As a result of these interactions, particle size distribution (PSD) of interground blended cements is different than that of separately ground cements. PSD is vital for the rheology and the early-age hydration process which determines the early properties of cement, such as water demand, heat release, strength development and early-age volume change [13]. It has been shown that intergrinding requires less energy than separate grinding, especially for the production of high-fineness products [14].

The main objective of this study was to understand the real influence of method of grinding on the amount of energy consumption, Blaine fineness, and particle size distribution (PSD) of blended cements, namely portland limestone cement (PLC), portland pozzolana cement (PPC) and portland composite cement (PCC). Limestone and Trass pozzolan were used as SCM in this research.

2. MATERIALS AND METHODS

a) Materials

The clinker used was an ordinary portland cement clinker (equivalent to ASTM Type II). A natural pozzolan (Trass) and a limestone were used in the study. Chemical and physical characteristics of the clinker, gypsum, Trass, and limestone are shown in Table 1. These materials were in accordance with EN 197-1 specifications. For example, the standard specifies that the limestone should meet three requirements:

Table 1. Chemical and physical characteristics

	Clinker (Type II)	Gypsum	Trass	Limestone
Calcium oxide (CaO) (%)	64.2	39.53	2.99	51.01
Silicon dioxide (SiO_2) (%)	22.35	-	69.38	2.48
Magnesium oxide (MgO) (%)	2.05	0.64	1.61	2.46
Aluminium oxide (Al_2O_3) (%)	4.71	0.7	12.66	1.55
Ferric oxide (Fe_2O_3) (%)	2.95	0.42	2.16	0.45
Sulphate oxide (SO_3) (%)	0.75	28.1	-	0.03
Potassium oxide (K_2O) (%)	0.584	-	1.905	0.151
Sodium oxide (Na_2O) (%)	0.185	-	1.513	0.196
Titanium oxide (TiO_2) (%)	0.15	-	-	-
Phosphorus oxide (P_2O_5) (%)	0.05	-	-	-
LOI (%)	1.41	7.4	7.43	41.68
Free water (%)	-	0.18	-	-
Combined water (%)	-	7.13	-	-
SiO_2 + Insoluble water (%)	-	6.6	-	-
$CaCo_3$ (%)	-	-	-	91.1
TOC (%)	-	-	-	0.09
MBA (gr/100 gr)	-	-	-	0.14
Moisture Content (%)	-	-	-	0.37
Specific Gravity (gr/cm^3)	3.15	2.31	2.32	2.68

(a) The $CaCO_3$ content should be greater than 75%; (b) The clay content, determined with Methylene blue test (MBA), should be less than 1.20 g/100 g; and (c) the total organic carbon (TOC) content shall conform to one of the following criteria:

- LL: shall not exceed 0.20% by mass.
- L: shall not exceed 0.50% by mass [15].

The used limestone satisfied all these requirements.

b) Methods

In the study, 10 types of cements including two types of portland cement (PC), two types of portland limestone cement (PLC), two types of portland pozzolana cement (PPC), and four types of portland composite cement (PCC) were used. The blended cements were prepared using clinker, gypsum (4% by weight of clinker), Trass, and limestone.

Portland cements were produced by intergrinding 96% clinker and 4% gypsum, with 3200 ± 100 cm^2/g and 4000 ± 100 cm^2/g Blaine finenesses. In both finenesses, the percentage of 45-µm residue was determined by Alpine sieving apparatus, and this value was considered as a criterion in categorizing types of blended cements. The percentage of 45-µm residue for PC with 3200 ± 100 cm^2/g and 4000 ± 100 cm^2/g Blaine finenesses were obtained 7% and 2.8% respectively. Eight types of blended cements were also produced by two methods of intergrinding and separate grinding.

In the separate grinding method, blended cements were produced by grinding PC and SCM separately, then blending them uniformly; however, in the intergrinding method, they were produced by intergrinding clinker, gypsum (4% by weight of clinker), and SCM. In both methods, the process of grinding was continued until the content of 45-µm residue reached 7% and 2.8% respectively.

The materials were crushed to 2-mm maximum size by a jaw crusher before feeding to the mill. The grinding process was carried out in a one-compartment laboratory-type ball mill of 20-kg raw mix capacity. The grinding time value was recorded for each mixture, which is directly related to energy consumption. On these mixtures, particle size distribution was measured by laser diffraction. Blaine fineness values of cements and compressive strength of cement mortars were determined according to ASTM C 204 and EN196-1-2005, respectively [16-17]. Cements and their designations, grinding methods, fineness values, and grinding times are presented in Table 2. Also, the particle size distributions of cements are presented in Table 3.

Table 2. Cements produced and their properties

Cement type	*designation*	*Components*	*Grinding method*	*45-µm residue (%) (By Alpine apparatus)*	*Blaine fineness (cm^2/g)*	*x' (µm)*	*d_{50} (µm)*	*Specific Gravity (gr/cm^3)*	*Time of grinding (min)*
Limestone	L (C)	-	-	7	7844	22.05	11.07	2.68	70
	L (F)			2.8	9419	18.05	9.36		163
Trass	T (C)	-	-	7	6539	11.74	7.75	2.32	37
	T (F)			2.8	9503	8.94	6.23		75
Portland Cement (PC)	PC (CI)	%96C+%4G	intergrinding	7	3176	24.4	17.3	3.12	50
	PC (FI)		intergrinding	2.8	3995	20.22	14.25		85
Portland Limestone Cement (PLC)	PLC10 (CI)	%90PC+%10L	intergrinding	7	3719	22.77	15.27	3.07	48.5
	PLC10 (FI)			2.8	5981	21.08	14.36		144
	PLC10 (CS)		Separate grinding	7	3643*	23.65	15.57		52*
	PLC10 (FS)			2.8	4537*	19.29	14.18		92.8*
Portland Pozzolana Cement (PPC)	PPC25 (CI)	%75PC+%25T	intergrinding	7	4721	20.57	13.43	2.88	42
	PPC25 (FI)			2.8	5880	15.44	10.41		64
	PPC25 (CS)		Separate grinding	7	4017*	20.87	13.58		47*
	PPC25 (FS)			2.8	5322*	16.08	10.6		83*
Portland Composite Cement (PCC)	PCC25 (CI)	%75PC+%15T+%10T	intergrinding	7	4395	18.86	12.75	2.93	45
	PCC25 (FI)			2.8	5642	16.74	11.05		65
	PCC25 (CS)		Separate grinding	7	4147*	22.11	14.33		50*
	PCC25 (FS)			2.8	5364*	17.73	11.72		91*
	PCC35 (CI)	%65PC+%25T+%10T	intergrinding	7	5003	18.51	12.5	2.85	42
	PCC35 (FI)			2.8	6432	14.8	9.82		65
	PCC35 (CS)		Separate grinding	7	4484*	21.29	13.75		49*
	PCC35 (FS)			2.8	5914*	16.1	10.73		90*

* : The Blaine fineness and Time of grinding related to separately ground cements were calculated by weighted mean of the ingredients to reach the content of 45-µm residue to %7 and %2.8.

C : Coarse , F : Fine, I : Intergrinding, S : Separate grinding

Table 3. Particle size distributions of the cements

Cement type		Intergrinding (%)					Separate grinding (%)				
		<90 (μm)	<45 (μm)	<30 (μm)	<15 (μm)	<5 (μm)	<90 (μm)	<45 (μm)	<30 (μm)	<15 (μm)	<5 (μm)
Portland Cement	PC (C)	99.6	88.9	72.3	46	19.2	-	-	-	-	-
	PC (F)	99.4	94.5	80.4	53	23.6	-	-	-	-	-
Portland Limestone Cement	PLC10 (C)	99.7	88.8	73.8	50.3	23	99.5	88.9	73.1	48.1	21.1
	PLC10 (F)	99.5	90.8	76.6	53	24.9	99.5	93	80.5	55	25.3
Portland Pozzolana Cement	PPC25 (C)	99.7	89.6	76.2	54.3	25.6	99.5	89.5	76.1	53.5	24.8
	PPC25 (F)	99.5	94.3	84.5	63.3	30.9	99.8	94.9	84.5	62.1	30.6
Portland Composite Cement	PCC25 (C)	99.7	91.1	78.9	57	27.5	98.7	87.8	74	51.9	24.4
	PCC25 (F)	100	94.2	83.1	60.8	29.9	99	92.6	81.1	59	28.8
	PCC35 (C)	99.4	90.5	78.3	57.9	28.2	99	87.5	74	53.8	25.9
	PCC35 (F)	99.7	94.7	84.9	64.7	32.8	100	93.5	82.7	62.1	31.3

3. RESULTS AND DISCUSSIONS

a) Time of grinding (energy consumption)

In order to evaluate the amount of energy consumption in grinding process, changes of the 45-µm sieve residue were determined at different grinding times. In Fig. 1ac, the relationship between time of grinding and R(t)/R(0) are shown on semi-logarithm scale. In this Figure, R(0) and R(t) are the percentage of 45-µm residue at the beginning and at the time of (t), respectively. PC was produced by intergrinding and Trass and limestone were produced by separate grinding.

In Fig. 1a, variation of relative sieve residue with grinding time, for PC (96% clinker +4% gypsum), Trass and limestone is shown.

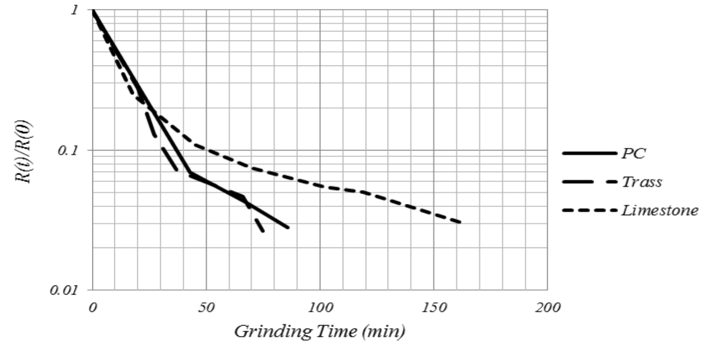
It shows that in the initial stages of grinding (<10 min), all three components are comminuted, similarly; between 10 and 25 minutes, limestone is comminuted better than PC and Trass; however, this is not the case at later stages of grinding (>25 min).

In other words, by increasing time, achieving the same percentage of 45-µm residue for limestone needs more time or consumes more energy compared to PC and Trass for grinding. This is similar to the findings of Lu Difen et al. [11]. This behavior is due to large brittleness region of limestone which is reduced as grinding time increases, so the velocity of breakage decreases.

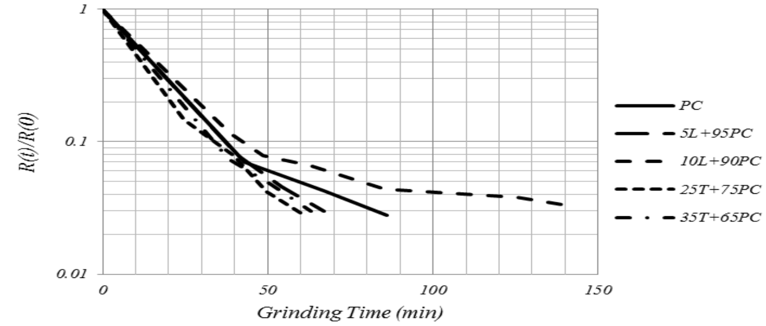
Figure 1b shows variation of relative sieve residue with grinding time for PC, PLC, and PPC produced by intergrinding. According to the results, the process of grinding PLC containing 5% limestone and PPC containing 25% and 35% Trass consumes an approximately equal amount of energy and less than that of PC; however, PLC containing 10% limestone consumes more energy. Therefore, more energy is required for achieving the same percentage of 45-µm residue (2.8%) for PLC containing more than 5% limestone.

Sprung et al. [18] pointed out that in portland limestone cements (containing 30% limestone), the saving of fuel energy that comes about by substituting limestone for some of the clinker is partially offset by the additional electrical energy required for the finer grinding to produce cement with the same strength.

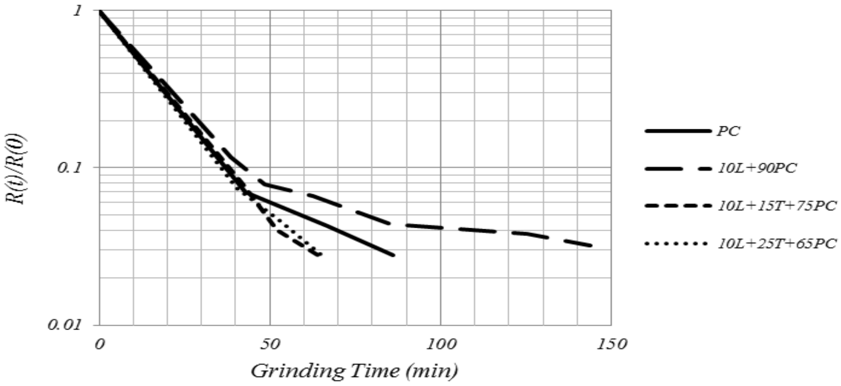
Figure 1c shows variation of relative sieve residue with grinding time for PCC and PLC produced by intergrinding. In the grinding process, PCC containing 25% SCM (15% Trass + 10% limestone) and 35% SCM (25% Trass + 10% limestone) consume approximately equal energy, yet less than that for PLC containing 10% limestone. These results explain that the negative effect of limestone on energy consumption is eliminated by incorporation of Trass in the mix.



(a)



(b)



(C)

Fig. 1. Variation of relative sieve residue with grinding time

Overall, based on the results shown in Fig. 1, achieving the same percentage of 45-µm residue (2.8%), intergrinding materials is less energy-demanding than separate grinding. Tsivilis et al. also found similar results [15].

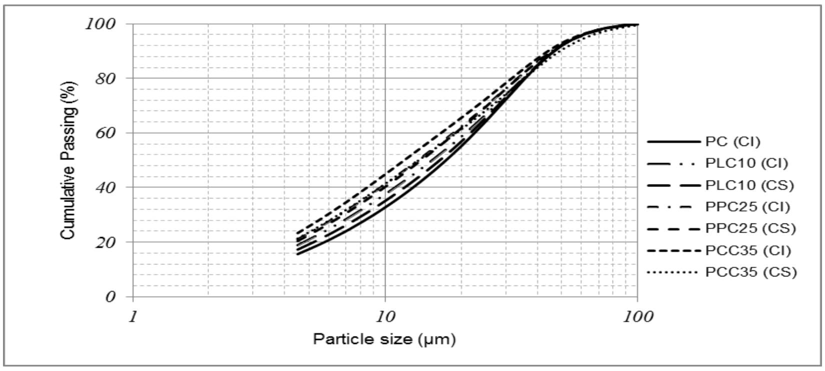
b) Fineness

It is an undeniable fact that the fineness of type of cements has increased during the past 50 years and is continuing to increase. One of the main reasons for moving towards finer cements is the ever increasing emphasis on high early-age strengths and fast-track construction by much of the industry. Finer cements, with their higher surface area, are more reactive at early ages, producing the desired higher early-age strengths [19].

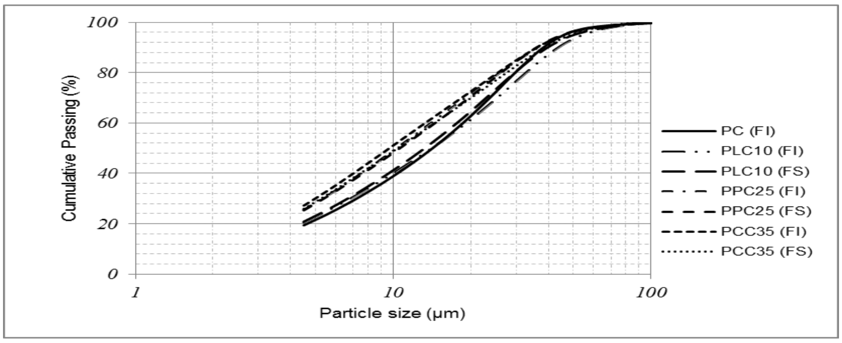
Fineness of cements or supplementary cementitious materials (SCM) are evaluated by several methods such as determining their Blaine surface area, finding out the amount retained on 45µm sieve, or assessing the particle size distribution using laser diffraction [20]. All these methods have some advantages and disadvantages in showing the fineness of the materials. It is claimed that Blaine air-permeability method may give misleading results, especially for porous materials [21]. On the other hand, the method for determination of the amount retained on 45µm sieve may be insufficient in showing the fineness of the material since it provides only a single value and supplies no information on the size of grains smaller than 45µm [22]. It is stated that using laser diffraction method is a more informative method since it shows the particle size distribution of the materials [23]. However, this technique is based on volumetric measurements and it is difficult to compare the data obtained from this method with the results of conventional sieve analysis [24].

In this investigation, the above three methods have been used to determine the fineness of blended cements.

1. Particle size distribution: Particle size distributions of the cements are presented in Table 3 and Fig. 2. The values for all cements (interground and separately ground cements) were directly found by laser diffraction. Also, the position parameter (x') for all of the cements is expressed in Table 2. The position parameter is defined as the equivalent spherical diameter by which 38.6% mass of the material is coarser than that. A study of Table 2 and 3 leads to the following conclusions:



(a) Coarser cements (containing 7% residue on 45µm sieve)



(b) Finer cements (containing 2.8% residue on 45µm sieve)

Fig. 2. Particle size distribution curves for PC, PLC, PPC, and PCC

a) PC with 4000 cm^2/g Blaine fineness had a significantly finer PSD than PC with 3200 cm^2/g Blaine fineness. As shown in Table 2, x' in PC (C) was less than PC (F). In other words, with increasing PC fineness, x' reduced from 24.4 to 20.22.

b) Generally all blended cements had finer PSD compared to the PC, and in these cements, existence of SCM led to reduction in the characteristic diameter and widening of the particle size distribution. Several researchers [9, 25-27] have reported that the presence of limestone filler or Trass extends the width of the PSD where clinker particles are in the larger sizes and limestone or Trass in the smaller ones.

c) In all blended cements, the effect of interactions between components with different grindability is quite clear.

d) In PLC containing 10% limestone:

- In order to manufacture cement with coarser PSD, intergrinding resulted in a slightly finer PSD curve compared to separate grinding. This is obvious in grains smaller than 15 µm, particularly. In addition, x' in separate grinding was approximately 6% greater than intergrinding.
- Nevertheless, in order to manufacture cement with finer (widest) PSD, separate grinding resulted in a finer PSD curve compared to intergrinding. For example, x' in separate grinding was approximately 9.3% smaller than intergrinding. This could be due to limestone particles agglomeration that reduces the efficiency of the mill. The negative effect of agglomeration phenomenon on the grinding process is more apparent when cement is finer and particularly when the method of grinding is intergrinding. Research has shown that the extent of agglomeration depends on the specific characteristics of the materials to be ground, the fineness of the cement particles, etc [28].
- According to the National Standard (ISIRI 4220-2005) and the European Standard (EN 197-1-2000), up to 20% and 35% limestone for PLC is allowable respectively [15, 28]. As shown earlier, with increasing limestone and in order to produce PLC with the widest PSD, separate grinding produces a finer PSD curve compared to intergrinding, and also increases energy consumption in both grinding method. Therefore, in order to produce high quality PLC, use of grinding aids is vital, especially for the intergrinding method.

Although the prime use of grinding aids is to reduce agglomeration of cement particles, their use will also assist in:

- the total or partial elimination of the ‘‘coating” effect on the media,
- an improvement in the separator efficiency due to increased fluidity of fine particles,
- a decrease in pack-set problems in storage silos and bulk delivery trucks,
- an increased bulk and bag cement quality,
- improved grinding production capacity [7].

e) In PPC containing 25% Trass:

- In both grinding methods, for manufacturing cement with coarser PSD, cement was produced with relatively uniform PSD, but for cement with finer PSD, intergrinding resulted in a slightly finer PSD curve compared to separate grinding. For instance, as shown in Table 2, the position parameter (x') of PPC (CI) was 1.5% lower than PPC (CS), and for PPC (FI), it was 4% lower than PPC (FS).
- In PPC containing Trass, pozzolan acts as a grinding aid and in these cements, application of grinding aids is not necessary.

f) In PCC containing Trass and limestone:

- Increasing the SCM content from 25% (15% Trass + 10% limestone) to 35% (25% Trass + 10% limestone), led to reduction in the characteristic diameter and widening of the particle size distribution.
- Intergrinding method provided a finer PSD in all cases. As shown in Table 3, suitability of this method is more obvious in coarser cements. This is because the negative effect of limestone particles agglomeration on the grinding process is less apparent when cement is coarser.

g) The best PSD for coarser cements (those with 45-µm residue content of 7% as determined by Alpine sieving apparatus) was for PCC containing 35% SCM (PCC35 (CI)) produced by intergrinding method.

h) The best PSD for finer cements (those with 45-µm residue of 2.8% as determined by Alpine sieving apparatus) was for PCC containing 35% SCM (PCC35 (CI)) that is produced by intergrinding method, also.

i) Overall, it can be expressed that in order to produce coarser cement, because of interactions between the constituents in all blended cements (PLC, PPC, PCC), intergrinding method is the best method of production to improve the PSD. But for producing finer cement, this method is only suitable for PPC and

PCC. In other words, it is concluded that in coarser cements, adding both limestone and Trass help with grinding and the grindability of multi-component mixture is better than that of PC, but in finer cements, only adding Trass helps with grinding.

2. Blaine: In the cement industry, the specific surface area of cement is most often determined with the Blaine air permeability apparatus. In this method, the time necessary to get a fixed amount of air through a bed of cement under defined conditions is measured and the specific surface is calculated from the air permeability of the bed of cement, its porosity, its density, and the viscosity of the air.

Blaine finenesses of the cements are presented in Table 2. Blaine fineness of separate grinding cements was calculated by weighted mean of the ingredients to reach the content of 45-µm residue of 7% and 2.8%.

A study of Table 2 leads to the following conclusions.

a) It is evident that for a similar residue on the 45µm sieve, all blended cements showed an obvious higher Blaine fineness than PC due to difference in morphology. The study of Turanli et al. [29] has shown that higher Blaine fineness of the blended cements may be caused by the higher carbon content of SCM, which is indicated by the high loss on ignition value.

b) In all blended cements, interground cements had a higher Blaine fineness value compared to separate grinding cements. This is due to the interactions between the constituents.

c) As the results obtained for the PSD show, in both production methods, the highest Blaine fineness required for a similar residue on the 45µm sieve was for PCC containing 35% SCM.

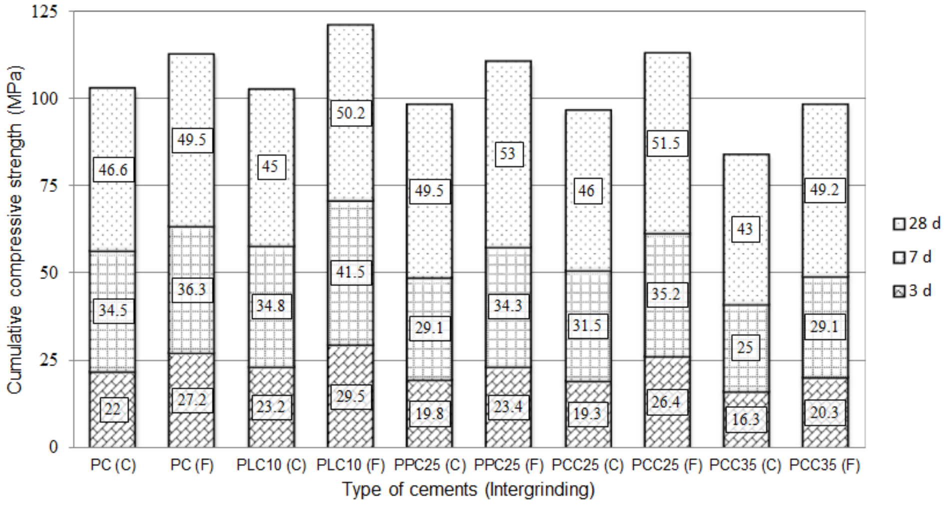
c) Compressive strength

Figure 3 shows the compressive strength values at 3, 7, and 28 days for blended cements and reference portland cements. As expected, the compressive strength values of all mortar specimens increased with curing time and increasing fineness of cements. For example, as shown in this Figure, the 28 days compressive strength for PCC25 (FI) was 12% higher than that of PCC25 (CI).

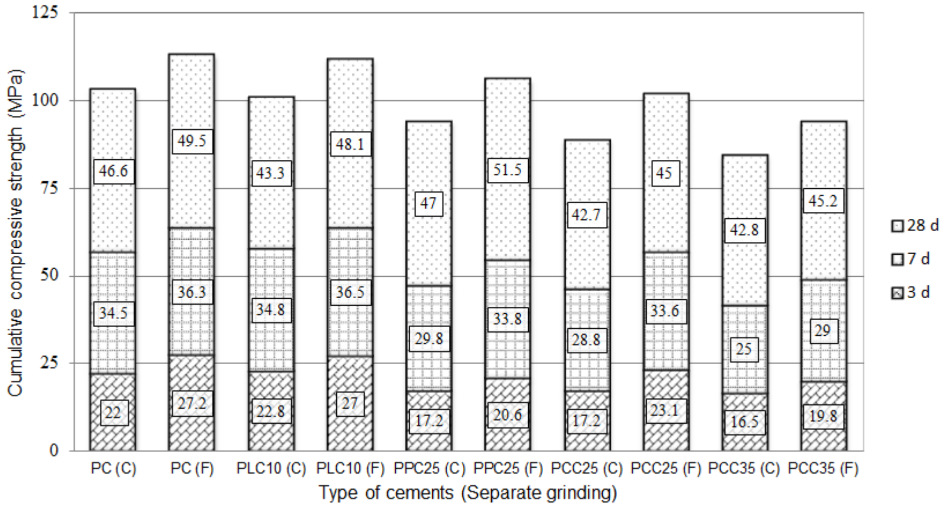
Also, for a similar residue on the 45µm sieve, the compressive strength of the mortars prepared with interground cement was generally higher than those prepared with separately ground cements. The higher compressive strength of the interground cement was due to its more beneficial PSD and higher homogeneity. From Fig. 3, it can be seen that the average compressive strength of the separately ground blended cement specimens at 28 days was lower by about 6% than that of the interground ones.

It is known that in mortars containing limestone or natural pozzolans, the compressive strength decreases with increasing amount of these supplementary materials. The reduction in compressive strength is attributed to a clinker dilution effect. The dilution effect is a consequence of replacing a part of cement with the same quantity of SCM. Ramezanianpour et al. [12] have shown that in PLC, up to 10% limestone replacement does not result in a significant reduction. In this study, PLC mortars containing 10% limestone have higher compressive strength than the PC mortars. This increase can be attributed to the filler effect and heterogeneous nucleation of limestone that counteract the dilution effect.

In mortars containing Trass, the compressive strength is less than that of PC up to 7 days. However, due to the relatively high pozzolanic activity of Trass from 7 to 28 days, the compressive strength of mortars increases, so that at 28 days, the compressive strength is higher in some of the cements (PPC25 and PCC25) than the PC.



(a) PC, PLC, PPC, and PCC produced by intergrinding



(b) PC and PLC, PPC, and PCC produced by separate grinding
Fig. 3. Compressive strength for PC, PLC, PPC, and PCC

4. CONCLUSION

The following conclusions can be drawn from the results obtained in this investigation:

- In general, for achieving the same percentage of 45-µm residue, intergrinding materials is less energy-demanding than separate grinding, especially for producing finer materials. Also, the negative effect of limestone on energy consumption is eliminated by incorporation of Trass in the mix.
- Generally, for a similar percentage of 45-µm residue, all blended cements had finer PSD and higher Blaine fineness compared to the PC, which was due to the effect of interactions between components.
- In coarser cements, adding both limestone and Trass helped with grinding, and the grindability of multi-component mixture was better than that of PC. But in finer cements, due to limestone particles agglomeration, only adding Trass helped with grinding. In other words, the negative effect of agglomeration phenomenon on grinding process was less apparent when cement was coarser.
- The blended cements indicated satisfactory compressive strength, especially at later ages, and compressive strength of the mortars prepared with interground cement was generally higher than those prepared with separately ground cements.

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