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Effect of chemical composition of clinker on grinding energy requirement

M. Tokyay *

Civil Engineering Department, Middle East Technical University, 06531 Ankara, Turkey

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Abstract

Fifteen commercial Portland cement clinker samples with a wide range of chemical compositions were subjected to grinding tests and relationships between grinding energy requirement attained specific surface areas and various chemical parameters were found. Regression analyses of the test results revealed that the energy–fineness relationship is exponential, and grinding energy is correlated with Al_2O_3, free CaO, liquid phase contents, silica moduli, and $(C_3S + C_2S)/(C_3A + C_4AF)$ ratios of the clinkers.

Keywords: Clinker; Grinding; Fineness

About 30% of the energy required to produce one ton of cement is consumed in grinding. It is a significant percentage of the total cost of cement. The energy consumption in the cement mills varies between 16.5 to 63.5 kWh/ton with an average of 36kWh/ton [1]. There are numerous factors affecting the energy consumption during clinker grinding. Clinker hardness imparts a wide variation to grindability. The hardest clinker takes about 80% more power than the softest one [2]. Furthermore, different fineness requirements result in higher energy consumption. Clinker grindability is the measure of the ability of a clinker to resist grinding forces. It is used to estimate the energy requirement for grinding the clinker to a given fineness. There are several different laboratory testing methods developed for determining the grindability of clinkers. The commonly used methods for this purpose are determination of (a) the energy requirement of the mill to produce a cement with a specified fineness, (b) revolutions of the mill necessary to produce a cement with specified fineness, (c) specific surface area of the ground clinker for a specified energy consumption of the mill, and (d) amount of ground clinker passing a specified sieve (usually 75 μm) per mill revolution.

Several investigations have been carried out to correlate the chemical and mineralogical compositions of clinkers with the grinding energy requirement. According to Duda [3], grindability increases with decreasing silica ratio and with increasing alumina (Al_2O_3) and iron oxide (Fe_2O_3) contents. A high C_3S content results in increased grindability, whereas a high C_2S content reduces grindability. The more liquid phase there is, the lower is the grindability of the clinker [3]. It also was shown by Gouda [2] that C_3A content and amount of liquid phase of clinkers play an important role in increasing the required energy consumption for a specified fineness. A similar conclusion for the effect of C_3A content was reached by Frigione et al. [4], who also found that higher C_4AF, K_2O, and MgO contents result in energy savings. Higher free lime contents of the clinkers were found to help grinding [5,6]. Besides the chemical and mineralogical compositions of the clinkers, microstructure, as affected by the cooling process, plays a significant role in grinding. Air-quenched clinkers were found to be more grindable than those cooled by planetaries [6].

This paper attempts to develop a mathematical relationship between the grinding energy consumption and attained specific surface area of Portland cement clinkers, irrespective of the production process. Furthermore, the effects of compound compositions of the clinkers on grindability were investigated. For this purpose, clinker samples obtained from 15 different cement plants in Turkey were used.

1. Experimental

The chemical and potential compound compositions of the clinkers used in this study are listed in Table 1. Grinding was carried out in a laboratory ball mill with 20-kg capacity. Size distribution of the mill charge is given in Table 2. Grinding was stopped at predefined time intervals to determine the specific surface area of the ground clinker. Blaine fineness values were determined according to ASTM C204.

*Tel.: 90-312-210-2430; Fax: 90-312-210-1262; E-mail: mtokyay@rorqual.cc.metu.edu.tr.

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Table 1
Chemical and mineralogical compositions of the clinkers

Clinker no.	Chemical composition (%)										Potential compound composition (%)			
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Free CaO	LOI	C_3S	C_2S	C_3A	C_4AF
1	19.46	6.01	3.57	65.16	2.14	1.42	0.81	0.08	0.15	1.17	71.89	1.56	9.89	10.86
2	21.92	6.09	2.69	65.64	2.13	0.21	0.46	0.06	0.22	0.72	55.87	20.70	11.59	8.19
3	20.60	5.73	3.02	64.91	2.60	1.06	0.57	0.34	0.26	1.12	64.88	10.12	10.07	9.19
4	20.91	4.68	4.47	65.21	1.74	1.28	0.78	0.42	0.67	0.28	68.72	8.11	4.84	13.60
5	21.23	5.02	3.71	66.30	0.79	0.49	0.55	0.24	0.28	1.50	69.53	8.41	7.03	11.29
6	20.46	6.00	3.44	65.32	1.78	1.02	0.81	0.17	0.31	0.85	65.19	9.48	10.08	10.47
7	20.38	5.25	2.90	65.42	2.01	1.39	0.68	0.16	0.68	0.75	72.02	4.10	9.01	8.82
8	20.05	6.12	3.25	65.70	2.35	1.10	0.68	0.14	1.56	0.52	69.32	5.19	10.72	9.89
9	21.11	5.42	3.26	66.07	1.63	0.92	0.65	0.08	1.19	0.51	67.46	9.63	8.85	9.92
10	22.07	3.98	4.41	64.52	1.39	2.03	0.68	0.20	0.31	0.26	61.88	16.59	3.09	13.42
11	20.68	4.98	3.98	65.50	1.69	1.67	0.65	0.12	0.46	0.46	70.33	6.23	6.46	12.11
12	20.51	5.94	3.13	66.07	1.36	0.30	0.80	0.29	0.11	1.44	68.71	6.96	10.45	9.52
13	20.87	6.24	2.65	65.01	1.48	1.26	1.03	0.64	0.49	0.65	60.33	14.31	12.05	8.06
14	19.72	6.12	3.22	64.69	3.24	0.63	0.70	0.33	0.13	1.06	67.76	5.42	10.77	9.80
15	21.17	6.23	2.86	65.51	0.7	0.41	0.78	0.40	0.11	0.70	59.86	15.54	11.67	8.70

2. Results and discussion

The overall relationship between the Blaine specific surface area and the corresponding energy consumption is given in Fig. 1. The values given are the average of three tests each. The relationship between the energy consumption and the specific surface area can be represented by the exponential function given in Eq. (1):

$$P = Ae^{BS} \tag{1}$$

where P is the energy consumption in kWh/ton, S is the Blaine specific surface area in cm^2/g divided by 1000, and A and B are constants depending on the clinker composition. The constants for different clinkers used in this investigation are given in Table 3.

The correlations between constants A and B and the chemical parameters of the clinkers stated in the literature as affecting energy consumption during clinker grinding have been determined. The parameters used, their best relationships with A and B, and corresponding correlation coefficients are given in Table 4. As seen from the table, fair correlations between the constants and Al_2O_3, free CaO contents, silica modulus (SM), liquid phase (L_p), and ratio of silicates to fluxes [$(C_3S + C_2S)/C_3A + C_4AF$)] exist. Discussion of the effects of these five parameters on grinding energy consumption follows.

Table 2
Mill charge used

Chamber	Charge dimensions (mm)	Charge weight (kg)
I (spherical charge)	30	5
	40	20
	50	40
	60	35
II (cylindrical charge)	10 × 10	2
	12 × 12	9
	16 × 16	25
	19 × 19	36
	22 × 22	28

2.1. Effect of alumina content of clinkers on grinding energy

The relationship between the Al_2O_3 contents of the clinkers used in this investigation and the grinding energy consumption calculated by using the constants A and B given in Table 4 is shown in Fig. 2 for three different specific surface areas (2800, 3400, and 4000 cm^2/g). The overall relationship (solid line) indicates that grinding energy requirement decreases with increasing Al_2O_3. However, an interesting feature of Fig. 2 is that there occurs almost no change in energy requirement up to Al_2O_3 contents around 6% and then it decreases sharply (dashed line). The reduction in energy requirement with increasing alumina contents over 6% becomes more pronounced as the fineness increases.

2.2. Effect of free lime content of clinkers on grinding energy

The relationship between the free lime contents of the clinkers used in this investigation and the grinding energy

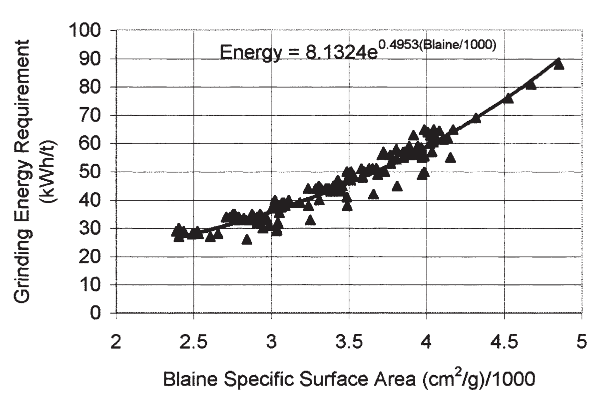

Fig. 1. Overall relationship between fineness and corresponding power consumption obtained for the clinkers used in this investigation.

Table 3
Constants A and B of the energy consumption–Blaine fineness relationship

Clinker	A	B
1	6.040	0.5788
2	7.387	0.5312
3	8.623	0.4987
4	7.142	0.5552
5	7.376	0.5245
6	7.004	0.5465
7	8.833	0.4760
8	8.555	0.5083
9	11.069	0.4161
10	10.055	0.4470
11	7.984	0.5110
12	6.190	0.5640
13	5.260	0.5648
14	5.368	0.5855
15	6.614	0.5418

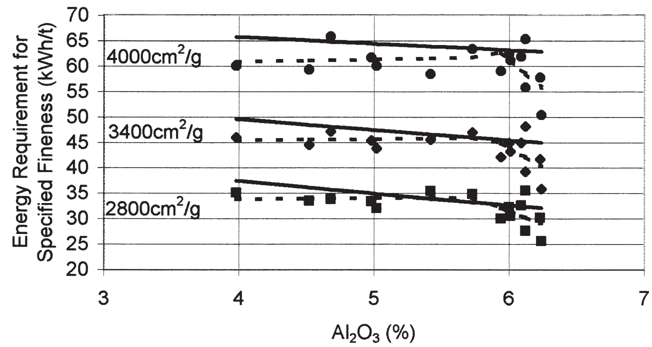

Fig. 2. Relationship between alumina content of the clinkers and grinding energy requirement for specified fineness.

consumption calculated by using the constants A and B given in Table 4 is shown in Fig. 3 for three different specific surface areas (2800, 3400, and 4000 cm^2/g). The overall relationship (solid line) indicates that grinding energy requirement increases logarithmically with increasing free CaO.

2.3. Effect of SM of clinkers on grinding energy

The relationship between the SM of the clinkers used in this investigation and the grinding energy consumption calculated by using the constants A and B given in Table 4 is shown in Fig. 4 for three different specific surface areas (2800, 3400, and 4000 cm^2/g). The relationship between grinding energy requirement and SM can be described by a second-order polynomial (solid line). The extremum points of the polynomial where the energy requirement is maximum decrease linearly with increasing fineness (2.71, 2.48, and 2.27 for 2800, 3400, and 4000 cm^2/g, respectively). However, for specific surface areas around 3000cm^2/g, the curve can be approximated as a line where the energy requirement increases with increasing SM.

2.4. Effect of L_p content of clinkers on grinding energy

The L_p contents for 1400°C were calculated for the clinkers. It is stated in the literature that as the L_p content increases grindability decreases [2,4]. However, the decrease in grindability also is related with the rate of clinker cooling. With faster cooling rates, the L_p forms more glass, thus increasing the strength of the clinker [4]. In this investigation, it was not possible to determine the cooling rates of the clinkers. The relationship between the L_p contents of the clinkers used in this investigation and the grinding energy consumption calculated by using the constants A and B given in Table 4 is shown in Fig. 5 for three different specific surface areas (2800, 3400, and 4000 cm^2/g). The relationship between grinding energy requirement and L_p content can be described by a second-order polynomial (solid

Table 4
Relationships between the chemical parameters of the clinkers and constants A and B of the exponential equation

Parameter	A	R_A	B	R_B
SiO_2	$0.0026(SiO_2)^{2.62}$	0.422	$-0.66\ln(SiO_2) + 2.55$	0.477
Al_2O_3	$20.61e^{-0.18\,Al_2O_3}$	0.576	$0.04\,Al_2O_3 + 0.31$	0.538
MgO	$-1.02(MgO)^2 + 3.67(MgO) + 4.66$	0.366	$0.025(MgO)^2 - 0.084(MgO) + 0.583$	0.341
K_2O	$13.78e^{-0.88K_2O}$	0.554	$0.16\,K_2O + 0.41$	0.438
Na_2O	$8.85e^{-0.73\,Na_2O}$	0.542	$0.13\,Na_2O + 0.49$	0.419
Total alkalies	$11.84e^{-0.49(alkali)}$	0.609	$0.09(alkali) + 0.44$	0.476
SO_3	$1.15(SO_3) + 6.41$	0.365	$-0.025(SO_3)^2 + 0.019(SO_3) + 0.536$	0.383
LOI	$-1.47\ln(LOI) + 7.06$	0.474	$0.04\ln(LOI) + 0.54$	0.446
Free CaO	$1.2\ln(fCaO) + 8.89$	0.599	$-0.03\ln(fCaO) + 0.49$	0.575
HM	$138.29(HM)^2 - 613.09(HM) + 686.75$	0.326	$-4.76(HM)^2 + 21.12(HM) - 22.87$	0.384
SM	$5.76(SM) - 5.82$	0.579	$-0.2(SM) + 0.98$	0.678
AM	$11.23e^{-0.25(AM)}$	0.504	$0.07\ln(AM) + 0.49$	0.421
Liquid phase (at 1400°C)	$-0.81L_p + 26.81$	0.640	$0.026L_p - 0.103$	0.711
C_3A	$10.75e^{-0.04\,C_3A}$	0.537	$8.4 \times 10^{-3}\,C_3A + 0.45$	0.480
C_4AF	$2.33\,(C_4AF)^{0.5}$	0.367	$0.74(C_4AF)^{-0.15}$	0.243
$(C_3S + C_2S)/(C_3A + C_4AF)$	$1.007[(C_3S + C_2S)/(C_3A + C_4AF)]^{1.46}$	0.628	$-0.345\ln[(C_3S + C_2S)/(C_3A + C_4AF)] + 0.99$	0.660
C_3S/C_2S	$2.1 \times 10^{-3}(C_3S/C_2S)^2 - 0.15(C_3S/C_2S) + 8.47$	0.426	$-7 \times 10^{-5}(C_3S/C_2S)^2 + 5.5 \times 10^{-3}\,(C_3S/C_2S) + 0.49$	0.522
C_3A/C_4AF	$9.59e^{-0.28\,C_3A/C_4AF}$	0.504	$0.04\ln(C_3A/C_4AF) + 0.53$	0.419

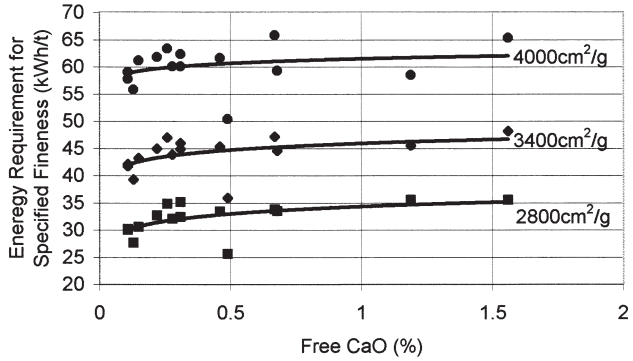

Fig. 3. Relationship between free lime content of the clinkers and grinding energy requirement for specified fineness.

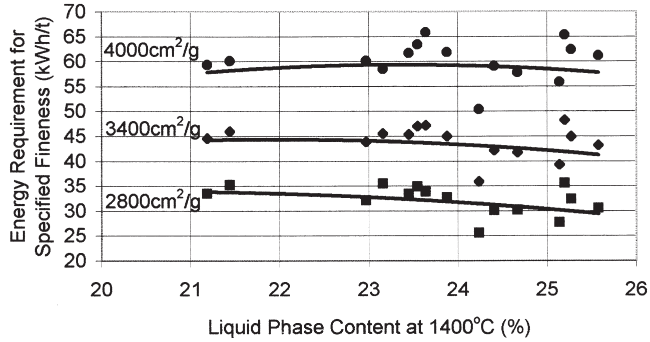

Fig. 5. Relationship between liquid phase contents of the clinkers and grinding energy requirement for specified fineness.

line). The extremum points of the polynomial where the energy requirement is maximum increase linearly with increasing fineness (20.22, 21.89, and 23.35 for 2800, 3400, and 4000 cm^2/g, respectively). However, for Blaine finenesses around 3000 cm^2/g, the relationship between grinding energy and L_p content can be approximated as a line where energy decreases with increasing L_p.

2.5. Effect of $(C_3S + C_2S)/(C_3A + C_4AF)$ of clinkers on grinding energy

The ratio of the silicates $(C_3S + C_2S)$ to the fluxes $(C_3A + C_4AF)$ is stated to decrease with increasing work index of the clinkers [2]. The relationship between the ratios of silicates to fluxes of the clinkers used in this investigation and the grinding energy consumption calculated by using the constants A and B given in Table 4 is shown in Fig. 6 for three different specific surface areas (2800, 3400, and 4000 cm^2/g). The overall relationship (solid line) indicates that grinding energy requirement reduces with increasing ratio. However, an interesting feature of Fig. 6 is that there occurs almost no change in energy requirement for the ratio values >4. For values <4, the relationship assumes a parabolic shape (dashed line). For a ratio of 3.70, the grinding energy is minimum. The energy trough becomes deeper as the required fineness increases.

3. Conclusions

This study was performed on 15 commercial clinkers showing a wide range of chemical compositions. Among 18 different chemical parameters that were stated in previous research (2–4) to affect the grindability of clinkers, alumina content, free lime content, SM, L_p content, and ratio of silicates to fluxes were found to correlate fairly with grinding energy requirement. However, it should be noted that the effects of these parameters also depend on numerous other chemical, mineralogical, and physical properties of the clinkers. The following conclusions were drawn from the results of this investigation:

1. The relationship between the grinding energy consumption and the specific surface area attained can be represented by an exponential function. The constants of the exponential function depend on the chemical composition of the clinkers.
2. Energy requirement for a specified fineness of the ground clinker decreases with increasing Al_2O_3 content. The reduction is more pronounced for alumina contents above a certain value, which was found to be about 6% in this investigation.
3. The relationship between grinding energy requirement and free lime content of the clinker is logarithmic, where energy increases with increasing free lime content.

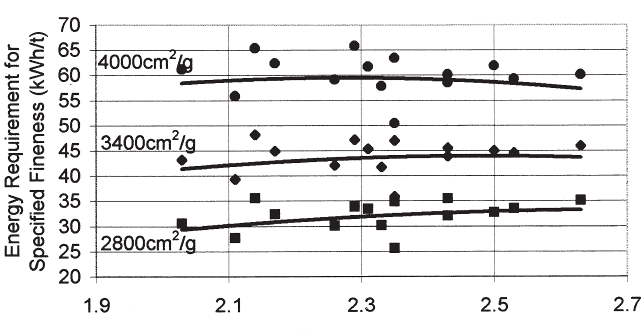

Fig. 4. Relationship between silica moduli of the clinkers and grinding energy requirement for specified fineness.

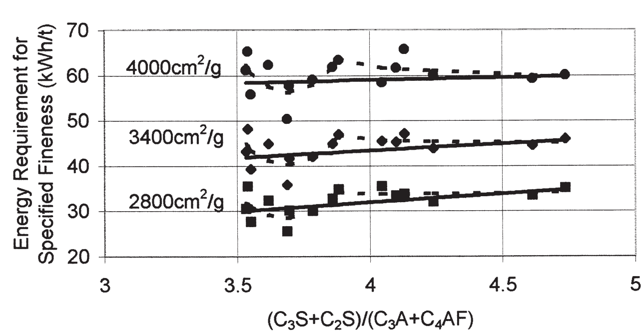

Fig. 6. Relationship between ratios of silicates to fluxes of the clinkers and grinding energy requirement for specified fineness.

4. Grinding energy is related with SM and L_p contents of the clinkers by second-order polynomial equations. For the general range of SM (1.9–3.2), energy requirement can be accepted to increase linearly with increasing SM, for fineness values around 3000cm^2/g (Blaine). Similarly, energy requirement decreases with increasing L_p content for fineness values around 3000cm^2/g (Blaine).
5. Energy requirement for a specified fineness of the ground clinker increases with increasing ratio of silicates to fluxes. However, in this investigation, it was observed that there is a parabolic relationship between this ratio and energy requirement up to 4, and minimum energy is attained at 3.70. For ratios >4, a slight decrease in energy is obtained with increasing ratio.
6. Thus it can be stated that a reasonable amount of energy savings can be obtained by careful adjustment of the chemical composition of the kiln feed.

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