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# Effect of components fineness on strength of blast furnace slag cement

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**Abstract**

The strength development of 1:1 mixes of clinker and blast furnace slag with varying fineness of components from 3000 to 6000 $cm^2/g$ has been studied. Overall results indicate that in manufacturing blast furnace slag cement (BFSC), it is not only the fineness of the clinker–slag mix but also of the individual components which govern the choice of the mix composition for a desired strength.


*Keywords:* Blast furnace slag cement; Fineness; Strength

## 1. Introduction

Recently, there has been a growing trend for the use of supplementary cementitious materials, whether natural, waste, or by-products, in the production of composite cements because of ecological, economical, and diversified product quality reasons.

Slag, a by-product of the transformation of iron ore into pig-iron in a blast furnace, is one of these materials whose use in cement manufacture goes to as far back as 1880 [1]. Since then its use has expanded because it has various advantages over other cementitious materials. Firstly, slag has a relatively constant chemical composition compared to fly ash, silica fume, pozzolanas etc. Besides, it has advantages like low heat of hydration, high sulfate and acid resistance, better workability, higher ultimate strength, etc. These properties are beneficial specialised applications such as hydroelectric dams, large bridges, power stations, metro systems, motorways, and harbours.

One of the major determinants of cement quality is its fineness. It is well known that the compressive strength of cement increases with fineness, and that cements with a narrow-size distribution have higher strength than those with a wide one [2]. In this relation, grinding of cement, particularly blended cements, has attracted interests of many researchers.

Traditionally, blast furnace slag cement (BFSC) has been produced by intergrinding cement clinker with slag in tube mills [3]. It is known that when this grinding mode is employed, it is not possible to exercise an independent control on the degree of fineness of the constituents because of mutual, complex interaction between the components with different grindabilities; in case of BFSC, the harder component slag tends to accumulate in coarse-size fractions. This results in less participation of slag in the hydration reactions and thus reduction in the strength. To compensate for this, the mix must be ground finer which is not economically feasible. A recent and more popular concept is to grind clinker and slag separately and mix them in appropriate proportions according to market requirements [4]. This mode of grinding has advantages such as lower specific energy consumption, ease of manufacture, higher addition of slag, and higher flexibility in product quality arrangements [5].

When separate grinding is practiced, a question must be asked, "Which fineness the components should be ground to compensate for the lower reactivity of slag ?" At first sight it seems logical to grind clinker finer because of its higher grindability. On the other hand, it is claimed that for the same incremental increase in fineness, slag gives higher strength development compared to clinker [3]. There is not much work done on these seemingly opposing views and the ones available in the literature are contradictory [3,6].

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Table 1
Chemical analysis of clinker and slag

| Chemical composition (%) | Clinker | Slag |
|---|---|---|
| $SiO_2$ | 20.50 | 42.29 |
| $Al_2O_3$ | 5.66 | 10.56 |
| $Fe_2O_3$ | 3.87 | 0.32 |
| CaO | 64.99 | 37.35 |
| MgO | 2.43 | 6.71 |
| $K_2O$ | 0.83 | 0.94 |
| $TiO_2$ | 0.29 | 0.45 |
| $Mn_2O_3$ | 0.06 | 1.67 |
| $P_2O_5$ | 0.09 | 0.011 |
| $Cr_2O_3$ | 0.023 | 0.012 |
| $Na_2O$ | 0.04 | 0.18 |
| Loss on ignition | 0.5 | 0.55 |
| Mineralogical composition Bogue | $C_3S$, % 65.2 | Amorphous phase |
| | $C_2S$, % 9.8 | |
| | $C_3A$, % 8.5 | |
| | $C_4AF$, % 11.8 | |

In this work, the effect of components fineness on the strength development of BFSC is investigated, also taking the specific energy consumption into consideration.

## 2. Material characterization

Chemical analysis of clinker and slag samples received from Oysa-Iskenderun cement grinding plant is given in Table 1 together with the main mineral phases calculated according to Bouge's formula. XRD patterns given in Fig. 1 confirm the presence of main mineral phases in the clinker and the presence of high-quality amorphous material in the slag.

Table 2
Results of Bond grindability tests

| Sample | Grindability (g/rev) | Work index (kW h/ton) |
|---|---|---|
| Clinker | 1.27 | 13.16 |
| 50% Slag + 50% Clinker | 0.91 | 16.90 |
| Slag | 0.77 | 19.15 |

Results of Bond grindability tests conducted on the individual components and on the mix having 50% slag are given in Table 2. As seen in the table, grindability of the mixture is not the weighed average of the component grindabilities but is even lower than the harder component slag. This conforms with the findings of other studies [7], and explains why separate grinding is preferred for the manufacture of BFSC.

## 3. Experimental work

Batch grinding tests were carried out in a standard Bond mill. Minus 3 mm feed materials, clinker and slag, were ground separately under standard mill operating conditions until they reached the desired Blaine specific surface area levels, namely 3000, 4000, 5000, and 6000 $cm^2/g$. The fineness values in 50 $cm^2/g$ neighbourhood of the desired values were accepted as nominal.

Specific energy consumption for each Blaine level was measured by a wattmeter placed in the circuit. The measured

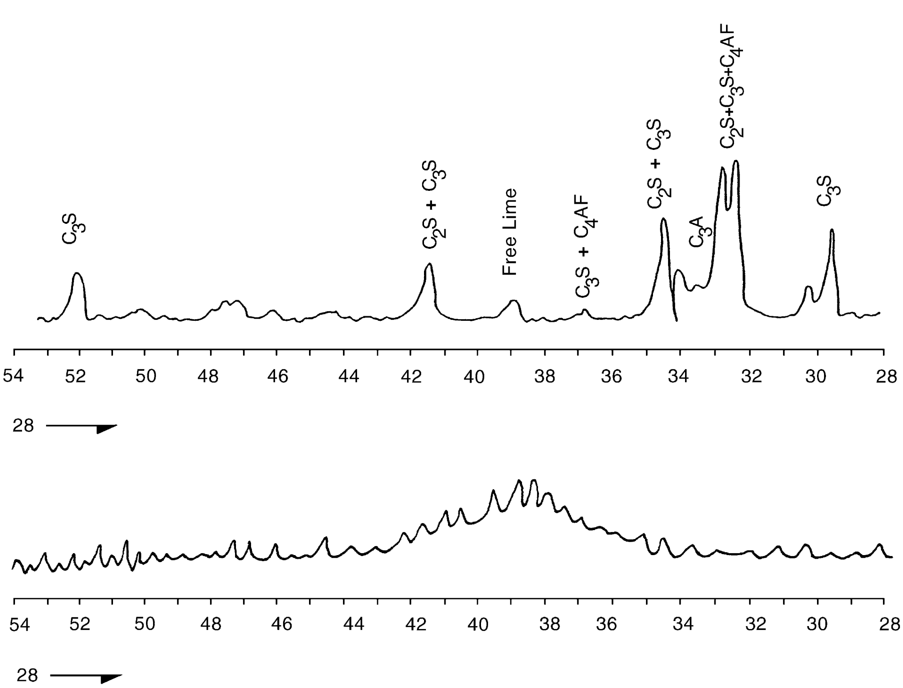


Fig. 1. XRD patterns of clinker and slag.

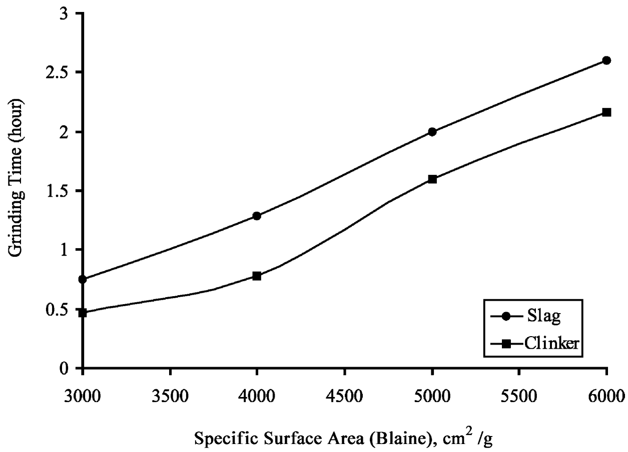


Fig. 2. Grinding times necessary to obtain desired level of fineness.

energy values were extremely high for products having 5000 and 6000 $cm^2/g$ Blaine values. This was because of the heavy coating of the materials on the mill inside the surface and on the balls. The specific energy consumed for each BFSC fineness was therefore calculated using Bond's energy law as it seemed to be a more logical approach. Relevant 80% passing sizes for the feeds and the products were determined by sieve analysis and dry mode laser diffraction analysis, respectively. However, due to agglomeration of particles, particle size measurements by dry laser diffraction method gave relatively larger distribution resulting in rather low, calculated, specific energy consumptions. No surfactants were used to avoid coating and agglomeration as they would affect the strength of cement. It is therefore suggested that the grinding times necessary to obtain a desired level of fineness should be used to help explain some points in general. They are given in Fig. 2.

2-, 7-, and 28-day compressive strengths, initial setting time, normal consistencies, and soundness values of the cements with 50% slag by weight were determined in accordance with European Standards, EN196. All the cements contain 5% gypsum as set retarder.

In EN196, compresssive strength of cements is determined on prismatic mortar specimens ($40 \times 40 \times 160$ mm) with 1:2:6 water/cement/standard sand ratio. After applying prescribed mixing and moulding procedure, mortar specimens are cured at $20 \pm 1$ °C and more than 90% relative humidity in moulds for 24 h. Then specimens are demoulded and cured under water with $20 \pm 1$ °C temperature starts. Water curing continues until 2, 7, and 28 days after mixing cements with water. For normal consistency and setting time, Vicat apparatus is used in EN196. According to the procedure, a trial cement/water mixture is prepared in a standard manner and placed in the mould. Then, a plunger of the apparatus (10 mm in diameter) is brought into contact with the top surface of the cement paste and released. The plunger has a standard weight and its penetration into the

Table 3
Physical properties, normal consistency, Le Chatelier soundness, and initial setting times

| Compressive strength($N/mm^2$) | | | | Normal consistency (%) | Le Chatelier soundness (mm) | Initial setting (min) |
|---|---|---|---|---|---|---|
| Slag surface area (Blaine) | 2 days | 7 days | 28 days | | | |
| *Control sample (3000 Clinker)* | | | | | | |
| | 24.0 | 35.0 | 46.1 | 25.0 | 0 | 170 |
| *3000 Clinker* | | | | | | |
| 3000 | 5.6 | 13.4 | 30.8 | 25.5 | 1 | 195 |
| 4000 | 5.9 | 15.2 | 35.5 | 24.5 | 1 | 200 |
| 5000 | 7.5 | 18.0 | 41.2 | 23.5 | 1 | 170 |
| 6000 | 7.5 | 18.2 | 42.6 | 22.5 | 1 | 175 |
| *4000 Clinker* | | | | | | |
| 3000 | 7.5 | 17.4 | 37.6 | 25.5 | 1 | 190 |
| 4000 | 8.9 | 19.1 | 42.3 | 24.0 | 1 | 190 |
| 5000 | 11.1 | 23.6 | 50.8 | 23.0 | 0 | 175 |
| 6000 | 12.4 | 24.7 | 52.3 | 22.5 | 1 | 175 |
| *5000 Clinker* | | | | | | |
| 3000 | 12.1 | 20.8 | 39.2 | 25.0 | 0 | 170 |
| 4000 | 14.1 | 26.3 | 50.7 | 26.0 | 0 | 180 |
| 5000 | 14.7 | 29.3 | 55.2 | 27.0 | 0 | 180 |
| 6000 | 15.2 | 29.0 | 58.0 | 27.0 | 0 | 170 |
| *6000 Clinker* | | | | | | |
| 3000 | 11.9 | 21.2 | 43.4 | 26.5 | 0 | 185 |
| 4000 | 12.5 | 24.4 | 50.7 | 27.0 | 0 | 210 |
| 5000 | 15.0 | 29.3 | 57.6 | 27.0 | 0 | 195 |
| 6000 | 15.0 | 31.9 | 58.8 | 27.0 | 0 | 190 |

paste determines the normal consistency of cement. The water/cement ratio at which the plunger penetrates the paste to a point $5 \pm 1$ mm from the bottom is recorded as normal consistency. For the determination of setting time, cement paste at normal consistency is used and penetration of standard needle of the Vicat apparatus into the paste is measured regularly with time. The time period (from mixing cement with water) required for needle penetration to a point $4 \pm 1$ mm from the bottom is determined as the initial setting time of a cement. Soundness of a cement is measured by using Le Chatelier moulds. Cement pastes at normal consistency are placed in the mould and cured under water with $20 \pm 1$ °C for 24 h. Then the sample with mould is boiled for 3 h. After boiling and cooling, expansion of the sample with the help of rods attached to the mould is measured as soundness value.

## 4. Results and discussions

The physical properties, normal consistency, Le Chatelier soundness, and initial setting times as per EN196 are given in Table 3. Evaluation of the normal consistency values reveals that at 3000 and 4000 cm$^2$/g clinker fineness, increasing slag fineness decreases the normal consistency. As normal consistency test has a high coefficient of variation, even for a single operator, further discussions on normal consistency values are not valuable.

Initial setting times for BFSC are higher than the initial setting time of the control cement as expected. Soundness figures are also in conformity with the standard.

The strength development of 1:1 mixes of clinker and slag with varying fineness of components is given in Figs. 3, 4, and 5 in terms of iso-strength curves for 2, 7, and 28 days, respectively. The curves are drawn by using the Surfer Mapping System, Version 6.01, Golden Software. As seen in the figures, it is not only the fineness of a final blend but also of individual components, which governs the choice of the mix composition for desired strength levels. Specific energy consumption of individual components should also be taken into consideration for the final choice.

The figures indicate that numerous alternative fineness combinations are possible in order to produce a mix with certain strength. In other words, following a path of an iso-strength curve, there are many different combinations of component fineness for obtaining the same strength. Likewise, for the same mix fineness (i.e., weighted mean of the component fineness), which is represented by the diagonal

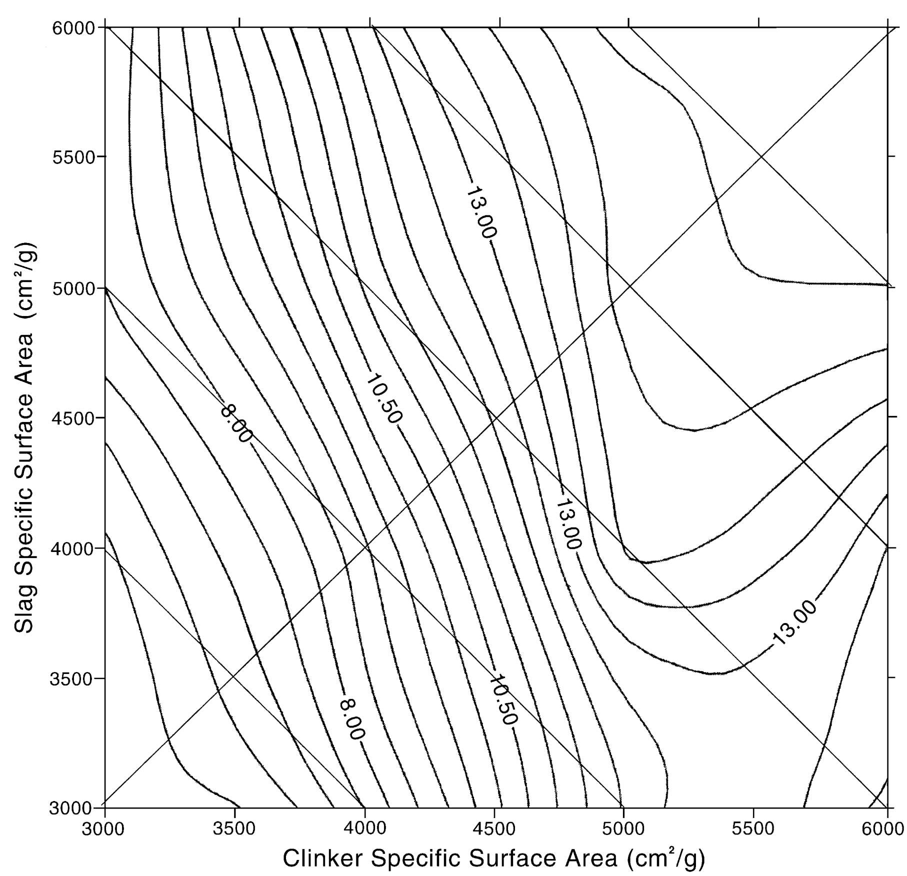


Fig. 3. Iso-strength curves for 2 days.

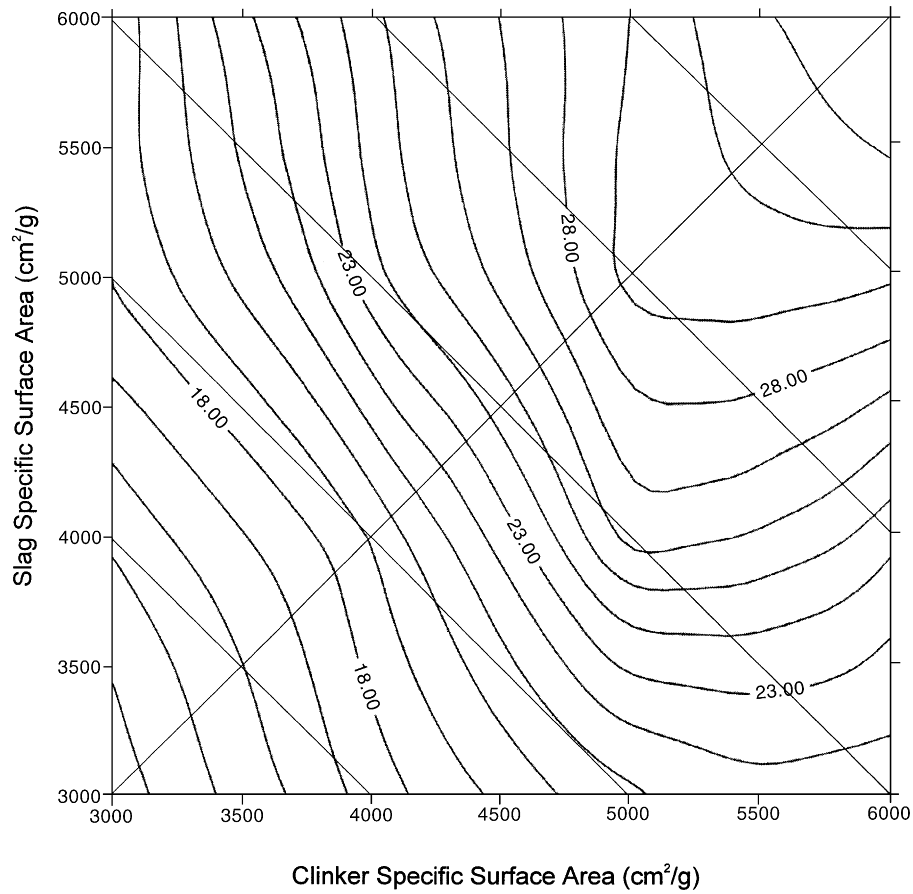


Fig. 4. Iso-strength curves for 7 days.

parallel lines on the figures, there are numerous strength values depending on the fineness levels of the components comprising the mix. On the figures, only the lines representing 3500, 4000, 4500, 5000, and 5500 $cm^2/g$ mean mix fineness are given. When these lines are divided into two at their midpoints, the below portion corresponds to higher clinker fineness than slag in the mix and vice versa. In the light of this information, considering Fig. 3 for 2-day strengths, for the same mix fineness the higher the clinker fineness, the higher the strength. As a result, it can be said that grinding clinker component to a higher fineness is more effective for regulating 2-day strength of BFSC.

To validate this conclusion on the efficiency of regulating 2-day strength by clinker fineness, numerical data in Table 3 should be evaluated. For a constant slag fineness at 4000 $cm^2/g$, increasing clinker fineness from 3000 to 4000 $cm^2/g$ gives rise to a 3 $N/mm^2$ increase in 2-day strength of the mix. Whereas, for a constant clinker fineness at 4000 $cm^2/g$, increasing slag fineness from 3000 to 4000 $cm^2/g$ brings about only 1.4 $N/mm^2$ increase. This also supports the conclusion that increasing clinker fineness is more effective on strength at 2 days.

The preference of increasing the clinker fineness for increasing 2-day strength coincides with the consideration of cost effectiveness. As given in Fig. 2, clinker grinding is less energy consuming than grinding slag as expressed by shorter grinding times required for the same fineness levels.

As seen in Fig. 4, 7-day strengths show a similar trend as of 2-day strengths up to a mix fineness level of 4500 $cm^2/g$, i.e., mixes with finer clinker than slag have higher strength. Above this fineness, grinding clinker finer than slag has no longer a beneficiary effect on strength development for this age. This may be because of the fact that slag has equally good reaction rates as that of clinker at these high fineness levels and at this relatively long curing age.

Iso-strength curves for 28 days given in Fig. 5 follow the abovementioned general trend up to about 3500 $cm^2/g$ mix fineness level, i.e., grinding clinker finer than slag is more influential on strength development. Above this fineness, the iso-strength curves have mainly parallel alignment with the diagonal lines showing the same mix fineness. This is the indication of the similar effectiveness of the component fineness on 28-day strength. At this age, activity of slag is as effective as that of clinker.

A regression program was used to determine the best regression for BFSC strength as a function of specific surface area of individual components in the mixes. The

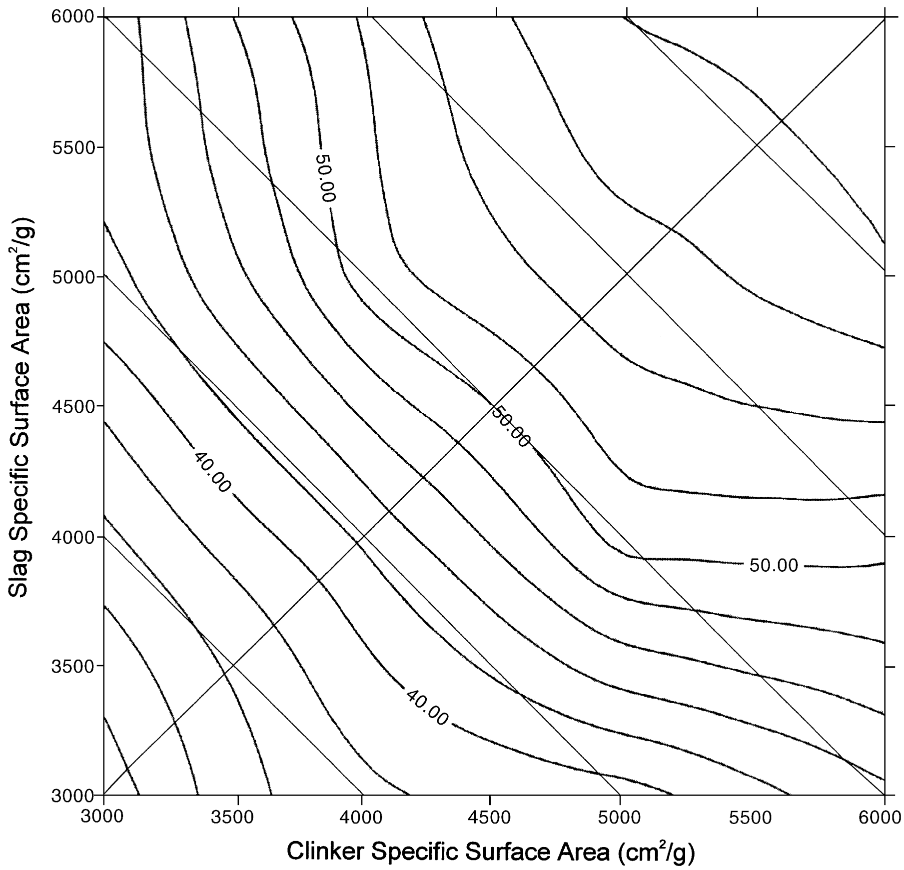


Fig. 5. Iso-strength curves for 28 days.

correlations could be expressed by the following equations for 2-, 7-, and 28-day strengths.

$$2\text{ days} = \frac{[1.88\text{CF}] + [0.64\text{SF}]}{1000}, \quad R^2 = .74$$

$$7\text{ days} = \frac{[2.91\text{CF}] + [2.23\text{SF}]}{1000}, \quad R^2 = .81$$

$$28\text{ days} = \frac{[5.05\text{CF}] + [5.36\text{SF}]}{1000}, \quad R^2 = .91$$

where CF = clinker fineness (cm$^2$/g); SF = slag fineness (cm$^2$/g).

As seen from the correlations, the regression equation predicts better results for the longer curing ages.

The original idea was to include in the study the cost effectiveness also of the preparation of the mixes having the same specific surface area from differing component fineness. Therefore, energy consumption in separate grinding of clinker and slag to different fineness was either measured or calculated from size analysis results as explained earlier. However, the results were not highly meaningful due to heavy coating of materials on balls and on mill inside the surface and also due to agglomeration of particles above the 4000-cm$^2$/g level. Nevertheless, the necessary grinding times given in Fig. 2 to obtain the same fineness of components clearly indicate that slag consumes considerably higher specific energy than clinker. When this fact is taken into account, it can be said that lower activity of slag would not be compensated by grinding it finer, but rather it should be compensated by even finer grinding of clinker, which requires less energy for the same incremental increase in specific surface area, i.e., more cost-effective. Thus, the overall conclusion can be that for the same mix fineness, it is always better to adjust the mix fineness by grinding clinker finer than slag for all age strengths.

## 5. Conclusions

Based on the results obtained below, the given general conclusions can be drawn:

- When manufacturing blended cements, it is not only the fineness of the mix but also of the individual components which govern the choice of the mix composition for a desired strength.
- In manufacturing BFSC, grinding clinker component to a higher fineness should be practiced, as it is more

effective in regulating the strength and it is also more cost-effective.

- Cost effectiveness point should further be investigated in more detail for the final choice of the mix composition, preferably with varying slag additions.

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