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Influence of fineness of fly ash on the aggregate pelletization process

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Abstract

One of the main issues associated with fly ash is the variation in the fineness of fly ash produced within a plant and between thermal power plants, due to the variation in the quality of coal used and the production technique adopted in which pelletization of fly ash becomes complex. In this paper, the influence of fineness of fly ash is studied by collecting typical samples of fly ash from two thermal power plants. Significance of the factors influencing the pelletization of fly ash was statistically determined by adopting 2^4 with eight run and 2^5 with sixteen run fractional factorial design for fly ash with fineness of 414 m^2/kg and 257 m^2/kg, respectively. Finer fly ash exhibits higher pelletization efficiency as compared to coarser fly ash. Addition of clay binders like bentonite and kaolinite enhanced the pelletization efficiency of coarser fly ash. Amount of binder content and moisture content varies with type of binder used (with fly ash having a fineness of 257 m^2/kg), which is attributed to the difference in plasticity index. Addition of clay binder changes the relative influence of pelletization factors.

Keywords: Fly ash; Fineness; Aggregate; Pelletization; Bentonite; Kaolinite

1. Introduction

Tremendous environmental problems posed by large-scale dumping of fly ash brought the research focus towards high volume utilization of fly ash in concrete. Though effective measures have been taken in utilizing fly ash by the construction industry in various forms (such as cement replacement or addition in concrete, production of pozzolanic cement, brick and block manufacturing, embankment filling and soil stabilization), still a large amount of material remains unutilized. Increasing attention in the recent years of converting fly ash into a value added product like aggregate offers greater potential for its high volume utilization, thereby reduces use of depleting natural weight aggregates [1,2]. This artificial aggregate can be produced by adopting established techniques like pelletization or compaction. Pelletization is the process of consolidating finer moisturized particles into larger solid material without application of external force and the resultant product is light in weight due to the presence of pores. The pellets formed attains sufficient strength by the force generated by itself inside the mixer [3–5]. In the compaction technique, external force is applied, which makes the aggregates relatively denser and stronger compared to those of pelletized aggregate [6]. Amongst several types of pelletizers used in metallurgical industry, disc pelletizer is popular as it facilitates production of aggregates of various size fraction and the operation requires less space. Baykal and Doven [4] reported that the pelletization of fly ash aggregate was influenced by grain size distribution of raw material, wettability and moisture content and mechanical factors like speed and angle of disc or drum. Inter-grinding of coarser particles is reported to enhance pelletization [3]. Tay et al. [7] studied production of sintered coarse aggregates by pelletizing wastewater sludge. An earlier study by the authors concluded that (i) for a given moisture content, the use of fly ash with a fineness of 452 m^2/kg resulted in an increase in average size of

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aggregate as compared to fly ash with fineness of 340 m^2/kg [8], and (ii) coarser fly ash requires higher moisture content to produce a particular size fraction of aggregate. Further, to improve the strength and water absorption of aggregate, binders like cement, lime and bentonite were added [9].

One of the main issues associated with fly ash is the variation in the fineness of fly ash produced within the same and between thermal power plants due to the variation in the quality of coal used and the production technique adopted [2]. As the process of pelletization becomes complex with changes in fineness of fly ash, an in depth study is essential.

2. Materials and methodology

2.1. Materials

This paper focuses on the influence of fineness of fly ash using two typical samples of fly ash, one relatively coarser than the other, having chemical composition as in Table 1. Sample-1 and Sample-2 were conforming to Class C and Class F, respectively (ASTM C 618-91) [10].

As the objective of the present study is to produce coarse aggregate, the pelletization efficiency, expressed in percentage mass of aggregate of size greater than 4.75 mm produced as against the quantity of fly ash used, is used as a basis for evaluating the experimental results. A disc pelletizer with provision for adjusting and controlling the inclination of the disc (between 0° and 65° at $2\frac{1}{2}^{\circ}$ interval) and vary the speed (between 10 and 100 rpm with 1 rpm accuracy) has been used. To ensure the uniform distribution of moisture into the fly ash, a water sprayer accompanied with the air compressor has been attached to the pelletizer. Two kilogram of dry sample was observed to be optimum for effective production of aggregate.

First stage feasibility study using these two samples of fly ash indicates that (i) pelletization of fly ash with a fineness of 414 m^2/kg resulted in almost entire material being converted into aggregate and (ii) use of fly ash with a fineness of 257 m^2/kg, resulted in only 12% of the raw material forming into aggregate, and the aggregates were weak to even withstand the handling stresses. In order to enhance the pelletizability of coarser fly ash, as grinding involves considerable additional handling and energy, the option of binders has been considered in this study. As binders like cement and lime disintegrates during sintering [9], commercially available bentonite and kaolinite clay with plasticity index (difference of moisture content between liquid and plastic limits) values of 370% and 35%, respectively, were tried as binders for this coarser fly ash.

As a second stage, a study on the influence of dosage of binders on the pelletization efficiency was made by a trail and error process, wherein for each dosage of binder the water content was varied to produce maximum pelletization efficiency at a given dosage was determined. Table 2 exhibits that the type of clay binder determines its dosage required, i.e., when 4% bentonite was added to Class F fly ash, the pelletization efficiency was increased to 48%, whereas only 29% efficiency was obtained for the same percentage of kaolinite. A maximum of 98% pelletization efficiency was obtained at a dosage of 14% with bentonite. An increase in dosage of bentonite beyond this level resulted in sticking of pellets to each other leading to formation of muddy balls, which was attributed to high plasticity index of bentonite (i.e., 370%). However, for the same percentage of kaolinite content, an efficiency of 68% was observed. The maximum efficiency of pelletization achieved

Table 1
Chemical composition of fly ash

Properties	Compounds in percent by mass			
	Sample-1	Sample-2	Bentonite	Kaolinite
Type of fly ash (conforming to ASTM C618 [10])	Class-F	Class-C	–	–
Specific gravity	2.10	2.64	2.65	2.57
Fineness (m^2/kg)	257	414	–	16,000
Silicon dioxide (SiO_2) (%)	63.60	31.62	37.84	45
Calcium oxide (CaO) (%)	1.57	17.17	0.83	0.06
Alumina (Al_2O_3) (%)	28.19	30.11	17.94	38
Ferric oxide (Fe_2O_3) (%)	2.99	8.94	11.09	0.60
Magnesia (MgO) (%)	0.54	3.71	1.39	0.07
Titanium oxide (TiO_2) (%)	–	–	0.077	0.55
Sodium oxide (Na_2O) (%)	0.05	0.74	2.97	0.15
Potassium oxide (K_2O) (%)	0.003	0.10	0.09	0.10
Sulphuric anhydride (SO_3) (%)	0.26	5.72	–	–
Manganese oxide (MnO) (%)	0.03	0.02	–	–
Loss on ignition (%)	0.85	3.18	19.73	14.5

Table 2
Influence of binders on pelletization efficiency of fly ash with a fineness = 257 m^2/kg

Binder content (%)	Pelletization efficiency (%) with binder	
	Bentonite	Kaolinite
4	48	29
6	67	32
8	76	40
10	81	54
12	90	63
14	98	68
16	–	75
18	–	80
20	–	84
22	–	86
24	–	90
26	–	93
28	–	96
30	–	98

was only at 30% kaolinite content, due to its low plasticity index (i.e., 35%). Lesser amount of bentonite requirement may be attributed to higher expansive nature of three-layer montmorillonite structure in the bentonite.

2.2. Experimental programme

As pelletization is a multivariable process in which several factors affect the characteristics of aggregates produced [11], the application of statistical experimental design techniques [12] was used to identify the relative influence of significant factors on the pelletization process. The lower and higher limits of other factors were identified by similar experimental trials (lower limit – below which the pelletization efficiency was very low, and the upper limit – above which muddy balls were formed) as shown in Table 3. Even though the dosage of these two binders

Table 3
Factors and its range considered for the production process of aggregate

Factors	Fly ash-C	Fly ash-F + bentonite	Fly ash-F + kaolinite
Mechanical factors			
Angle (°)	35–55	35–55	35–55
Speed (rpm)	35–55	35–55	35–55
Duration (min)	13–15	8–16	8–16
Physical factors			
Binder content (%)	–	6–14	10–30
Moisture content (%)	30–31	33–35	23–25

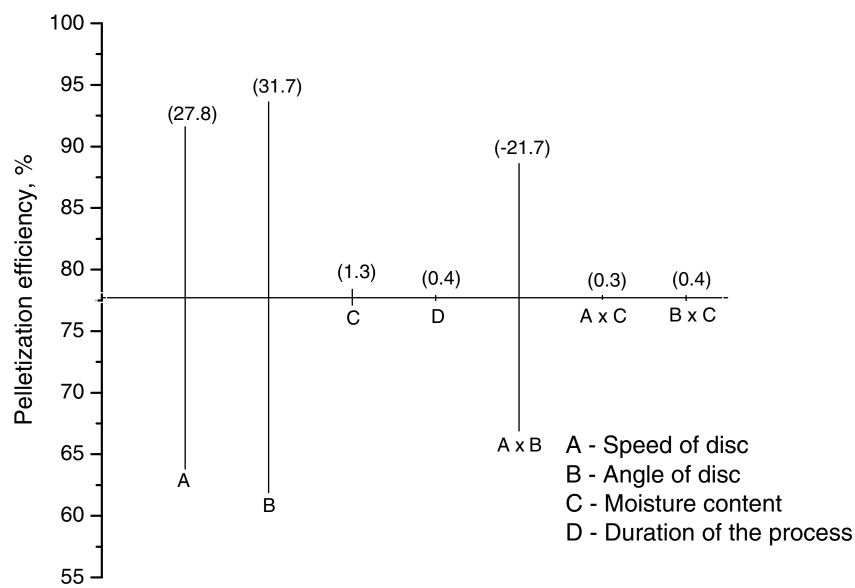

Fig. 1. Estimated effects of factors on pelletization efficiency of fly ash with a fineness of 414 m^2/kg.

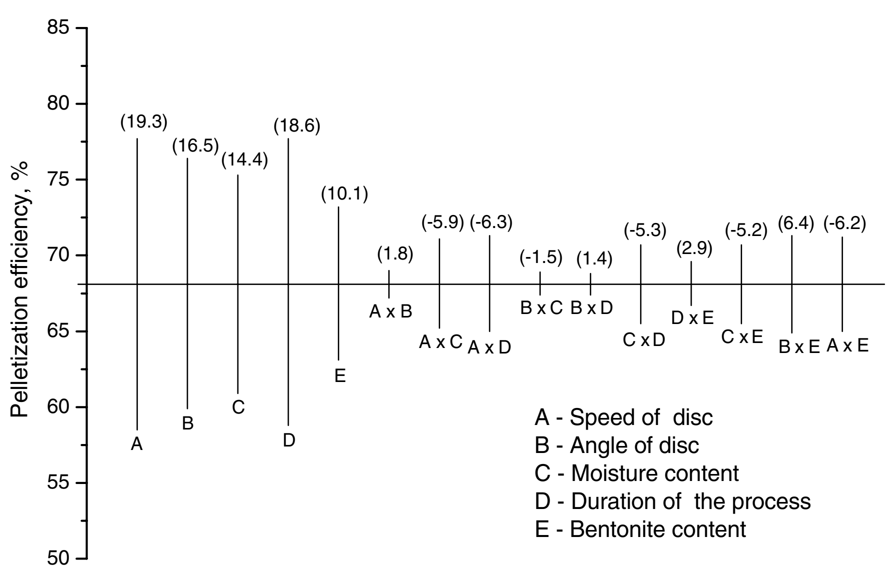

Fig. 2. Estimated effects of factors on pelletization efficiency of fly ash with a fineness of 257 m^2/kg and bentonite binder.

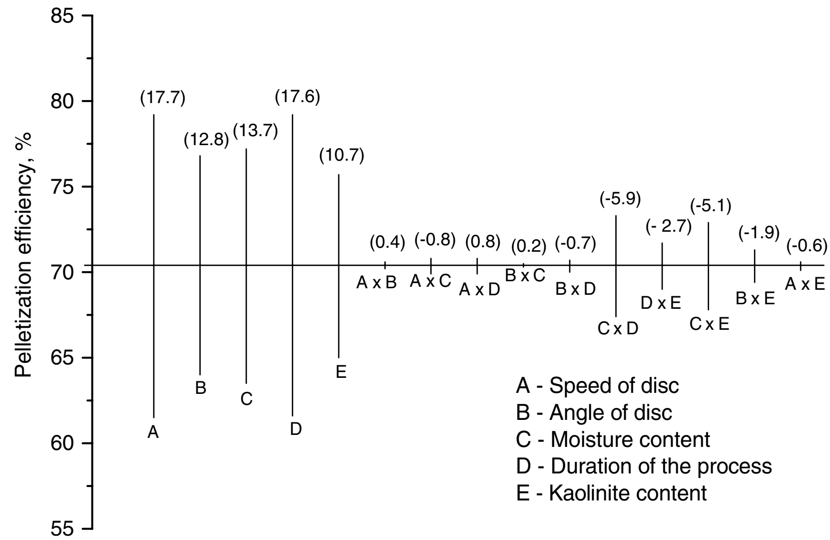

Fig. 3. Estimated effects of factors on pelletization efficiency of fly ash with a fineness of 257 m^2/kg and kaolinite.

have been determined based on maximum pelletization efficiency, in order to ascertain their interaction with other parameters of pelletization the following experimental design was done.

2.3. Experimental design and analysis

As fly ash with a fineness of 414 m^2/kg could be pelletized without any binders, a 2^4 with eight run fractional factorial design was adopted. With the need to include binders for the pelletization of fly ash with a fineness of 257 m^2/kg, a 2^5 with 16 run fractional factorial design was adopted to avoid confounding effect due to increase in the number of factors. The response tables are presented in Appendix Tables A.1–A.3. To visualize the relative influence of factors on the response, a range analysis was done. The effect of the factors were calculated by the difference between the mean of the factor's high level to low level and presented in Figs. 1–3. "Estimated squares" was determined by squaring these "effects". Analysis of variance (ANOVA) was also carried out for determining the significance of the factors and interaction effects. *F*-statistics for each factors and interaction effects was determined by the ratio of sum of estimated squares to "No effects" (number of lower magnitude interaction effects) as shown in the Tables 4–6. The *F*-statistics value for factors and interaction effects was compared with standard *F*-statistics value for the assumed degree of freedom (one for main and significant interaction effects) [12].

Table 4
Analysis of variance for pelletization efficiency of fly ash with a fineness of 414 m^2/kg

Factor	Estimate squared, E^2	DoF	*F*-statistic
A: Speed of pelletizer	772.84	1	5944.82
B: Angle of pelletizer	1004.89	1	7729.92
C: Moisture content	1.69	1	13.00
D: Duration of pelletization	0.16	1	1.23
A × B	470.89	1	3622.23
No effect	0.13	2	

Table 5
Analysis of variance for efficiency of fly ash with a fineness of 257 m^2/kg and bentonite

Factor	Estimate squared, E^2	DoF	*F*-statistic
A: Speed of pelletizer	368.64	1	175.54
B: Angle of pelletizer	272.25	1	129.64
C: Moisture content	207.36	1	98.74
D: Duration of pelletization	345.96	1	164.74
E: Bentonite content	102.01	1	48.58
A × B	3.24	1	1.54
A × C	34.81	1	16.58
A × D	39.69	1	18.90
C × D	28.09	1	13.38
D × E	8.41	1	4.00
C × E	27.04	1	12.88
B × E	40.96	1	19.50
A × E	38.44	1	18.30
No effect	2.11	2	

Table 6
Analysis of variance for efficiency of fly ash with a fineness of 257 m^2/kg and kaolinite

Factor	Estimate squared, E^2	DoF	*F*-statistic
A: Speed of pelletizer	313.29	1	803.31
B: Angle of pelletizer	163.84	1	420.10
C: Moisture content	187.69	1	481.26
D: Duration of pelletization	309.76	1	794.26
E: Kaolinite content	114.49	1	293.56
C × D	34.81	1	89.26
D × E	7.29	1	18.69
C × E	26.01	1	66.69
B × E	3.61	1	9.26
No effect	0.39	6	

3. Discussion of results

3.1. Aggregates produced using fly ash with a fineness of 414 m^2/kg

Fig. 1 shows the variation of the factors and interaction effects on the pelletization efficiency of aggregate produced using fly ash with a fineness of 414 m^2/kg.

It is observed that speed and angle of the disc are the main factors significantly affecting the pelletization efficiency. At lower angle, as a consequence of reduced balling path, bridging of moisturized particle for pellet formation is reduced leading to lower pelletization efficiency. However, when the angle increases, the length of balling path increases and pellet growth is enhanced which results in increased efficiency. At lower speed of the disc, the pellet growth is restricted due to reduced centrifugal force. Moisture content and duration of the process are not significantly affecting the efficiency as compared to speed and angle of the disc. Insignificant effect of both these factors is due to the narrow range of the factors. Higher influence of interaction effect between speed and angle of the disc, indicate that a longer balling path and optimal centrifugal force combination is essential for achieving higher pelletization efficiency.

ANOVA results in Table 4 exhibits that the calculated F-statistics for the main effects viz., speed, angle and the interaction effect between speed and angle are significantly higher as compared to standard F-statistics value for 95% confidence interval (i.e., standard F-statistics value for 95% confidence interval with two DoF is 18.51). It is seen that the calculated F-statistics value for moisture content, duration of the process and other two interaction effects are less than 18.51, which shows their insignificance on the pelletization efficiency. It can be concluded that speed and angle of the disc and interaction effect between speed and angle are the predominant factors affecting the pelletization efficiency of fly ash with a fineness of 414 m^2/kg.

3.2. Aggregate produced with fly ash with a fineness of 257 m^2/kg with bentonite binder

Unlike above, all the main factors viz., speed, duration, angle, moisture and bentonite contents affect the pelletization efficiency significantly (Fig. 2). As the binder becomes essential due to lower fineness of fly ash, the process demands higher duration and moisture content for achieving enhancing pelletization efficiency. The explanation is drawn from the observation made by Kawatra and Ripke [13], based on iron ore–bentonite pelletization. With the addition of moisture (i) alkali present in the three-layer montmorillonite of bentonite hydrates and expands, (ii) expanded montmorillonite layer slip each other and forms fibre due to the tumbling force produced inside the disc, and (iii) ball growth is enhanced by the fibres covering the material to be pelletized [13].

At lower moisture content and duration of pelletization, the ball growth was restrained due to the incomplete hydration and expansion of montmorillonite, resulting in lower efficiency. As the moisture content and duration increases, fibre forming mechanism of montmorillonite for ball growth is activated and results in increased efficiency.

It is seen from Table 5 that all the main effects F-statistics value is greater than standard F-statistics value (18.51) and shows their significance on the response. It is observed from the Fig. 2 that several interaction effects appears to be influencing the pelletization efficiency. However, the ANOVA results in the Table 6 shows that for 95% confidence interval, F-statistics for interaction effects viz., between speed and duration, angle and bentonite content are greater than standard F-statistics value (i.e., 18.51). Significance of these interaction effects indicate that higher angle and speed for longer balling path, higher bentonite content to compensate for lower fineness of fly ash and prolonged duration for activating the fibre formation, are required for increasing the pelletization efficiency of fly ash with a fineness 257 m^2/kg with bentonite as a binder.

3.3. Aggregate produced using fly ash with a fineness of 257 m^2/kg and kaolinite binder

Fig. 3 shows that the speed and duration of the process affects the efficiency relatively higher as compared to other main effects viz., moisture content, angle and kaolinite content. Unlike the bentonite, as kaolinite is a non-expansive clay [14], having a two-layered structure [15], does not expand under moisture, due to the absence of hydration alkalis such as sodium and potassium. Addition of kaolinite to the fly ash with a fineness of 257 m^2/kg, improves the efficiency due to the increase in fines content. Due to this non-expansive nature, higher amount of kaolinite (i.e., 30%) is needed to achieve maximum pelletization efficiency. It is an important observation that moisture requirement varies with type of binder, which may be attributed to the difference in the plasticity index. The calculated F-statistics presented in Table 6 indicate that all the main effects are significantly higher than the standard F-statistics value (18.51) for 95% confidence interval. The calculated F-statistics for interaction effects between moisture content and duration, moisture content ant kaolinite content, and duration and kaolinite content are higher than standard F-statistics value.

3.4. Gradation of fly ash aggregates

Fig. 4 presents the gradation of fly ash aggregates obtained when the pelletization factors for both the three types of fly ash aggregates were at the significant level. These aggregates do not satisfy the grading requirements of ASTM C 330-98 [16]. This points out to the need for an optimization study to identify factor levels that produce aggregates of desired grading requirements.

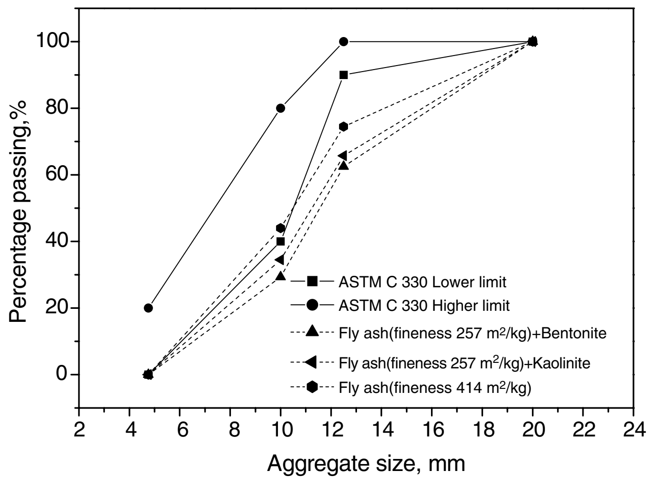

Fig. 4. Comparison of aggregate grading obtained with ASTM grading requirements.

4. Conclusions

The following conclusions are applicable for the range of parameters considered and the materials used in this study.

1. Finer fly ash (fineness of 414 m^2/kg) does not require any binder for achieving maximum pelletization efficiency.
2. Use of fly ash with a fineness of 257 m^2/kg exhibit lower pelletization efficiency of only 12%. Addition of clay binders (bentonite or kaolinite) significantly improved the pelletization efficiency up to 98%.
3. For achieving maximum pelletization efficiency, the dosage level of binders and moisture content varies with type of binder used, which is attributed to the difference in plasticity index of clay binders. For achieving maximum pelletization efficiency, lower dosage level (14%) of bentonite is attributed to the presence of expansive montmorillonite structure in bentonite.
4. Statistically designed experiments showed that only angle and speed significantly influence the pelletization of fly ash with fineness of 414 m^2/kg, whereas for fly ash with fineness of 257 m^2/kg and different binders, all the main factors significantly influence the pelletization process.
5. Addition of clay binder changes the relative influence of different pelletization factors, which points out to the need for further in depth optimization studies.

Appendix A

See (Tables A.1–A.3).

Table A.1
Response table for pelletization efficiency fly ash with a fineness of 414 m^2/kg

Run	Efficiency (%)	A: Speed (rpm)		B: Angle (°)		C: Moisture content (%)		A × B		A × C		B × C		D: Duration (min)	
		35	55	35	55	30	31							13	15
		1	2	1	2	1	2	1	2	1	2	1	2	1	2
1	36.6	36.6	*	36.6	*	36.6	*	*	36.6	*	36.6	*	36.6	36.6	*
2	37.6	37.6	*	37.6	*	*	37.6	*	37.6	37.6	*	37.6	*	*	37.6
3	90	90	*	*	90	90	*	90	*	*	90	90	*	*	90
4	91	91	*	*	91	*	91	91	*	91	*	*	91	91	*
5	86.2	*	86.2	86.2	*	86.2	*	86.2	*	86.2	*	*	86.2	*	86.2
6	87	*	87	87	*	*	87	87	*	*	87	87	*	87	*
7	95.4	*	95.4	*	95.4	95.4	*	*	95.4	95.4	*	95.4	*	95.4	*
8	97.9	*	97.9	*	97.9	*	97.9	*	97.9	*	97.9	*	97.9	*	97.9
Total	621.7	255.2	366.5	247.4	374.3	308.2	313.5	354.2	267.5	310.2	311.5	310	311.7	309.9	311.7
No. of values	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Mean	77.7	63.8	91.6	61.9	93.6	77.1	78.4	88.6	66.9	77.6	77.9	77.5	77.9	77.5	77.9
Effect		27.8		31.7		1.3		−21.7		0.3		0.4		0.4	

Table A.2
Response table for pelletization efficiency: fly ash having a fineness of 257 m^2/kg with bentonite as binder

Run	Efficiency (%)	A: Speed (rpm)		B: Angle (°)		C: Moisture content (%)		D: Duration (min)		AB		AC		AD		BC	
		35	55	35	55	33	35	8	16	1	2	1	2	1	2	1	2
		1	2	1	2	1	2	1	2								
1	32	32	*	32	*	32	*	32	*	*	32	*	32	*	32	*	32
2	45.6	45.6	*	45.6	*	45.6	*	*	45.6	*	45.6	*	45.6	45.6	*	*	45.6
3	52	52	*	52	*	*	52	52	*	*	52	52	*	*	52	52	*
4	75	75	*	75	*	*	75	*	75	*	75	75	*	75	*	75	*
5	28.2	28.2	*	*	28.2	28.2	*	28.2	*	28.2	*	*	28.2	*	28.2	28.2	*
6	87.6	87.6	*	*	87.6	87.6	*	*	87.6	87.6	*	*	87.6	87.6	*	87.6	*
7	72	72	*	*	72	*	72	72	*	72	*	72	*	*	72	*	72
8	75.6	75.6	*	*	75.6	*	75.6	*	75.6	75.6	*	75.6	*	75.6	*	*	75.6
9	55.6	*	55.6	55.6	*	55.6	*	55.6	*	55.6	*	55.6	*	55.6	*	*	55.6
10	74.5	*	74.5	74.5	*	74.5	*	*	74.5	74.5	*	74.5	*	*	74.5	*	74.5
11	65.5	*	65.5	65.5	*	*	65.5	65.5	*	65.5	*	*	65.5	65.5	*	65.5	*
12	78.8	*	78.8	78.8	*	*	78.8	*	78.8	78.8	*	*	78.8	*	78.8	78.8	*
13	80.2	*	80.2	*	80.2	80.2	*	80.2	*	*	80.2	80.2	*	80.2	*	80.2	*
14	83.6	*	83.6	*	83.6	83.6	*	*	83.6	*	83.6	83.6	*	*	83.6	83.6	*
15	85.1	*	85.1	*	85.1	*	85.1	85.1	*	*	85.1	*	85.1	85.1	*	*	85.1
16	98.5	*	98.5	*	98.5	*	98.5	*	98.5	*	98.5	*	98.5	*	98.5	*	98.5
Total	1090	468	622	479	611	487	603	471	619	538	552	569	521	570	520	551	539
No. of values	16	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Mean	68.1	58.5	77.7	59.9	76.4	60.9	75.3	58.8	77.4	67.2	69	71.1	65.2	71.3	65	68.9	67.4
Effect		19.2		16.5		14.4		18.6		1.8		−5.9		−6.3		−1.5	

Run	Efficiency (%)	BD		CD		DE		CE		BE		AE		E: Bentonite content (%)	
		1	2	1	2	1	2	1	2	1	2	1	2	6	14
														1	2
1	32	*	32	*	32	32	*	32	*	32	*	32	*	*	32
2	45.6	45.6	*	45.6	*	45.6	*	*	45.6	*	45.6	*	45.6	45.6	*
3	52	*	52	52	*	*	52	52	*	*	52	*	52	52	*
4	75	75	*	*	75	*	75	*	75	75	*	75	*	*	75
5	28.2	28.2	*	*	28.2	*	28.2	*	28.2	28.2	*	*	28.2	28.2	*
6	87.6	*	87.6	87.6	*	*	87.6	87.6	*	*	87.6	87.6	*	*	87.6
7	72	72	*	72	*	72	*	*	72	*	72	72	*	*	72
8	75.6	*	75.6	*	75.6	75.6	*	75.6	*	75.6	*	*	75.6	75.6	*
9	55.6	*	55.6	*	55.6	*	55.6	*	55.6	*	55.6	55.6	*	55.6	*
10	74.5	74.5	*	74.5	*	*	74.5	74.5	*	74.5	*	*	74.5	*	74.5
11	65.5	*	65.5	65.5	*	65.5	*	*	65.5	65.5	*	*	65.5	*	65.5
12	78.8	78.8	*	*	78.8	78.8	*	78.8	*	*	78.8	78.8	*	78.8	*
13	80.2	80.2	*	*	80.2	80.2	*	80.2	*	*	80.2	*	80.2	*	80.2
14	83.6	*	83.6	83.6	*	83.6	*	*	83.6	83.6	*	83.6	*	83.6	*
15	98.5	85.1	*	85.1	*	*	85.1	85.1	*	85.1	*	85.1	*	85.1	*
16	*	98.5	*	98.5	*	98.5	*	98.5	*	98.5	*	98.5	*	98.5	
Total	1126	539	550	566	524	533	557	566	524	520	570	570	520	505	585
No. of values	16	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Mean	68.1	67.4	68.8	70.7	65.5	66.7	69.6	70.7	65.5	64.9	71.3	71.2	65	63.1	73.2
Effect		1.4		−5.3		2.9		−5.2		6.4		−6.2		10.1	

Table A.3
Response table for pelletization efficiency: fly ash having a fineness of 257 m^2/kg with kaolinite as binder

Run	Efficiency (%)	A: Speed (rpm)		B: Angle (°)		C: Moisture content (%)		D: Duration (min)		AB		AC		AD		BC	
		35	55	35	55	23	25	8	16	1	2	1	2	1	2	1	2
		1	2	1	2	1	2	1	2								
1	46.9	46.9	*	46.9	*	46.9	*	46.9	*	*	46.9	*	46.9	*	46.9	*	46.9
2	52	52	*	52	*	52	*	*	52	*	52	*	52	52	*	*	52
3	51.2	51.2	*	51.2	*	*	51.2	51.2	*	*	51.2	51.2	*	*	51.2	51.2	*
4	71	71	*	71	*	*	71	*	71	*	71	71	*	71	*	71	*
5	40.8	40.8	*	*	40.8	40.8	*	40.8	*	40.8	*	*	40.8	*	40.8	40.8	*
6	77.1	77.1	*	*	77.1	77.1	*	*	77.1	77.1	*	*	77.1	77.1	*	77.1	*
7	73.5	73.5	*	*	73.5	*	73.5	73.5	*	73.5	*	73.5	*	*	73.5	*	73.5
8	79.4	79.4	*	*	79.4	*	79.4	*	79.4	79.4	*	79.4	*	79.4	*	*	79.4
9	43.8	*	43.8	43.8	*	43.8	*	43.8	*	43.8	*	43.8	*	43.8	*	*	43.8
10	86	*	86	86	*	86	*	*	86	86	*	86	*	*	86	*	86
11	77.2	*	77.2	77.2	*	*	77.2	77.2	*	77.2	*	*	77.2	77.2	*	77.2	*
12	83.5	*	83.5	83.5	*	*	83.5	*	83.5	83.5	*	*	83.5	*	83.5	83.5	*
13	75.5	*	75.5	*	75.5	75.5	*	75.5	*	*	75.5	75.5	*	75.5	*	75.5	*
14	85.8	*	85.8	*	85.8	85.8	*	*	85.8	*	85.8	85.8	*	*	85.8	85.8	*
15	83.5	*	83.5	*	83.5	*	83.5	83.5	*	*	83.5	*	83.5	83.5	*	*	83.5
16	98.5	*	98.5	*	98.5	*	98.5	*	98.5	*	98.5	*	98.5	*	98.5	*	98.5
Total	1126	492	624	512	614	508	618	492	633	561	564	566	560	560	566	562	564
No. of values	16	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Mean	70.4	61.5	79.2	64	76.8	63.5	77.2	61.6	79.2	70.2	70.6	70.8	69.9	69.9	70.8	70.3	70.5
Effect		17.7		12.8		13.7		17.6		0.4		−0.8		0.8		0.2	

Run	Efficiency	BD		CD		DE		CE		BE		AE		E : Kaolinite content (%)	
		1	2	1	2	1	2	1	2	1	2	1	2	6	14
														1	2
1	46.9	*	46.9	*	46.9	46.9	*	46.9	*	46.9	*	46.9	*	*	46.9
2	52	52	*	52	*	52	*	*	52	*	52	*	52	52	*
3	51.2	*	51.2	51.2	*	*	51.2	51.2	*	*	51.2	*	51.2	51.2	*
4	71	71	*	*	71	*	71	*	71	71	*	71	*	*	71
5	40.8	40.8	*	*	40.8	*	40.8	*	40.8	40.8	*	*	40.8	40.8	*
6	77.1	*	77.1	77.1	*	*	77.1	77.1	*	*	77.1	77.1	*	*	77.1
7	73.5	73.5	*	73.5	*	73.5	*	*	73.5	*	73.5	73.5	*	*	73.5
8	79.4	*	79.4	*	79.4	79.4	*	79.4	*	79.4	*	*	79.4	79.4	*
9	43.8	*	43.8	*	43.8	*	43.8	*	43.8	*	43.8	43.8	*	43.8	*
10	86	86	*	86	*	*	86	86	*	86	*	*	86	*	86
11	77.2	*	77.2	77.2	*	77.2	*	*	77.2	77.2	*	*	77.2	*	77.2
12	83.5	83.5	*	*	83.5	83.5	*	83.5	*	*	83.5	83.5	*	83.5	*
13	75.5	75.5	*	*	75.5	75.5	*	75.5	*	*	75.5	*	75.5	*	75.5
14	85.8	*	85.8	85.8	*	85.8	*	*	85.8	85.8	*	85.8	*	85.8	*
15	83.5	83.5	*	83.5	*	*	83.5	83.5	*	83.5	*	83.5	*	83.5	*
16	98.5	*	98.5	*	98.5	*	98.5	*	98.5	*	98.5	*	98.5	*	98.5
Total	1126	566	560	586	539	574	552	583	543	571	555	565	561	520	606
No. of values	16	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Mean	70.4	70.7	70	73.3	67.4	71.7	69	72.9	67.8	71.3	69.4	70.6	70.1	65	75.7
Effect		−0.7		−5.9		−2.7		−5.1		−1.9		−0.6		10.7	

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