Received: 18 April 2022, Accepted: 15 July 2022, Published: 30 September 2022, Publisher: UTP Press, Creative Commons: CC BY 4.0

OPTIMIZATION OF RAW MIX DESIGN OF CLINKER PRODUCTION: A CASE STUDY IN CEMENT INDUSTRY

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ABSTRACT

Raw mix design refers to the raw materials' quantitative proportions to achieve clinker with the desired chemical and mineralogical composition. The existing method used to formulate the raw mix design is based on iterative laboratory trials, which is time-consuming and heavily relies on the chemist's experience. Considering the negative environmental impacts, optimizing the raw mix design has become one of the major concerns among the cement players. Thus, the objective of this research is to optimize raw mix design with minimum cost while satisfying the critical clinker quality control targets. This study explored the Linear Programming (LP) model to achieve the objective. A Series of mathematical modeling was developed to relate the decision variables, raw mix and fuel mix design and the clinker chemistry. Bogue calculation is then applied to correlate the oxides from both raw mix and fuel mix to the phase content of C_3S, C_2S, C_3A and C_4AF in the clinker. The ratio of the clinker phases would be Lime Saturation Factor (LSF), Silica Ratio (SR) and Alumina Modulus (AM), which are used to determine the quality of the clinker, were defined as the main constraint. Limitation in the plant design, such as the number of dosing weighers, is also considered programming constraint. A case study was performed with eight types of raw materials consisting of Limestone, clay, sand, alternate material and additives to evaluate the LP model. Based on the GRG Nonlinear LP simulation, the optimized raw mix design was achieved at the cost of RM 6.845 per tonne composed of, 85.03% of Limestone, 0.9% of Clay 1, 12.6% of Alternate Material 1 and 1.47% of Additive 2. The obtained results prove that the developed LP model can minimize the raw material cost save analysis time, and provide flexibility in the raw material selection process without the need for actual trials.

Keywords: *Linear programming, raw mix design optimization, clinker production, cement chemistry*

INTRODUCTION

The cement manufacturing process is typically energy extensive and consumes many natural resources [1]. The cement industry alone accounts for 5% of the global CO_2 emission (i.e. 1 tonne of Portland cement releases 0.95 tons of CO_2 to the environment) [2]. Such huge emission mainly comes from the calcination process of limestone ($CaCO_3 \rightarrow CaO + CO_2$) and partly from the combustion of carbon-based fuel [3]. Several international treaties, such as Kyoto Protocol and Paris Agreement, have identified the cement industry as one of the alarming sectors and urged players to adopt green strategies such as raw material optimization and utilization of alternate fuel [2],[4],[5]. The cement production process also accounts for 30%-40% of the global energy consumption, partially due to heavy machineries' operation to crush raw material and grind cement into fine powder [6]. Gauging the adverse impact of the cement industry on global sustainability and considering the soaring economic pressure due to the recent pandemic, optimizing the raw mix design has become a primary concern. Focusing on sustainability is one of the strategies to opt for alternate raw materials, such as industrial wastes or by-products, to reduce the proportion of conventional materials in the raw mix design [7]-[8]. In that sense, a reliable mathematical model is needed to achieve raw mix design quickly at the lowest cost by considering a wide range of raw materials, clinkering process and quality targets [9].

The cement production processes start with quarrying and then grinding raw materials such as limestone, clay, sand and other additives to fine powder, called kiln feed, which is then heated to a sintering temperature up to 1450°C in a cement kiln to produce clinker [10]. The clinker nodules are then grounded with gypsum and other material in a cement mill to form cement. The continuous production of high-quality clinker is only possible if the raw mix design possesses optimum chemical composition of lime, silica, alumina, iron oxide, magnesium oxide and alkalis extracted from various types of raw material such as limestone, clay and sand [11]. Major clinker components are CaO, SiO_2, Al_2O_3 and Fe_2O_3, which account for more than 95% of weight composition, and the remaining are composed of MgO, TiO_2, P_2O_5 and alkalis that exist as compound form [12]. Technically, at least four to five or even more types of raw materials with different compositions of minerals that will be formulated together to achieve the specified clinker compositions.

Prior research [13] indicated that laboratory analysis to assess the acceptable range of clinker quality possesses a long analysis time, which ranges from three to four hours. As a result of the long-delayed analysis, any deviation in the clinker quality will result in the rejection or recycling of the formed clinker [14]. This situation reiterates the importance of achieving a consistent raw mix design that primarily influences the clinker quality and productivity. Clinker quality is also partially influenced by the type of fuel used [15], such as coal and petroleum coke, that contain similar oxides, which further complicates the raw mix design formulation. Hence, this research paper will focus on ways to optimize the raw mix design formulation. This study will explore the application of the linear programming method, which will integrate raw mix design compositions with all critical parameters that influence clinker chemistry at the lowest possible cost.

Linear Programming (LP) Application

LP is a method that merges several variables based on a linear function of objective function while simultaneously satisfying a group of restrictions [16]. This technique effectively makes optimum use of resources and offers viable solutions in the presence of different constraints beyond the problem [17]. Recent research [18] has illustrated the use of LP to correlate the relationship between raw mix chemistry and clinker chemistry regardless of multiple constraints. The construction of the LP model can be divided into three basic components as follows:

1. Express the objective functions in terms of decision variables to optimize the optimality criterion. (i.e. cost of raw material).
2. Identify the decision variables (i.e. the proportion of limestone and so on) and establish a mathematical solution to relate them to the clinker phases. The decision variables shall be continuous, controllable and non-negative values.
3. Outline all the constraints, such as the clinker quality targets, feed control parameters and dosing weigher capacity. The outcome of the LP must satisfy all the described constraints.

Objective Functions and Decision Variables

The raw mix design predominantly comprises of limestone, sand, clay mixture and other additives. Firstly, each raw material sample must be collected and analysed using X-Ray Fluorescence to determine the chemical composition on a periodical basis. Table 1 shows the list of eight types of raw materials that need to be considered in this LP formulation, the chemistry of each raw material and the cost (per tonne). These chemical composition values will be used in the mathematical modeling to relate to the clinker chemistry in the upcoming sections.

This study aims to determine the raw mix proportioning with the minimum cost; hence the objective function can be expressed as:

$$Minimum\ Cost = \sum_{i=1}^{8} C_i X_i \quad (1)$$

where C_i = cost/ton, X_i = material type.

The decision variables that the LP will compute are stated below:

X_1 = Limestone (%wt) to dose in Raw Mix
X_2 = Sand (%wt) to dose in Raw Mix

Table 1 Cost and chemistry of raw material

Variables	Weight Percentage (%wt)					Cost/ton
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	
Limestone, X_1	(SiO_2)X1	(Al_2O_3)X1	(Fe_2O_3)X1	(CaO)X1	(MgO)X1	C_1
Sand, X_2	(SiO_2)X2	(Al_2O_3)X2	(Fe_2O_3)X2	(CaO)X2	(MgO)X2	C_2
Clay 1, X_3	(SiO_2)X3	(Al_2O_3)X3	(Fe_2O_3)X3	(CaO)X3	(MgO)X3	C_3
Clay 2, X_4	(SiO_2)X4	(Al_2O_3)X4	(Fe_2O_3)X4	(CaO)X4	(MgO)X4	C_4
Alternate Material 1, X_5	(SiO_2)X5	(Al_2O_3)X5	(Fe_2O_3)X5	(CaO)X5	(MgO)X5	C_5
Alternate Material 1, X_6	(SiO_2)X6	(Al_2O_3)X6	(Fe_2O_3)X6	(CaO)X6	(MgO)X6	C_6
Additive 1, X_7	(SiO_2)X7	(Al_2O_3)X7	(Fe_2O_3)X7	(CaO)X7	(MgO)X7	C_7
Additive 2, X_8	(SiO_2)X8	(Al_2O_3)X8	(Fe_2O_3)X8	(CaO)X8	(MgO)X8	C_8

X_3 = Clay Type 1 (%wt) to dose in Raw Mix
X_4 = Clay Type 2 (%wt) to dose in Raw Mix
X_5 = Alternate Material 1 (%wt) to dose in Raw Mix
X_6 = Alternate Material 2 (%wt) to dose in Raw Mix
X_7 = Additive 1 (%wt) to dose in of Raw Mix
X_8 = Additive 2 (%wt) to dose in of Raw Mix

METHODOLOGY

Determination of Fuel Ash Absorption and Free Lime in the Burning Stage (Input)

Coal combustion in the kiln produces ash [19]. It is crucial to determine the amount of coal ash absorption into the clinker as the remaining portion needs to fill up by raw mix design. The lab can identify the fuel ash chemistry and absorption rate by X-Ray Fluorescence (XRF) and Bomb Calorimeter testing. In this report, the fuel ash absorption in the clinker is assumed as 0.6% for calculation. The composition of the Coal ash and the weight percentage is shown in Table 2.

The next burning parameter to consider is the free lime percentage in the kiln operation, which is influenced by many factors like burnability and upstream process [20]. The free lime (CaO) will not combine any oxides, which leads to undesirable effects such as fluctuating setting time, difficulty grinding clinker, and reduced cement strength [12]. In this report, it is assumed that free lime (FCaO) content in the clinker is 1.5% which will be used in Equation 13 to determine one of the clinker chemistries.

Table 2 Coal ash chemistry and weight percentage

Coal Ash Composition		Weight Pct. (wt%)
Silica	SiO_2	(SiO_2)Ash
Lime	CaO	(CaO)Ash
Ferrite	Fe_2O_3	(Fe_2O_3)Ash
Alumina	Al_2O_3	(Al_2O_3)Ash
Magnesium Oxide	MgO	(MgO)Ash
Sulphur trioxide	SO_3	(SO_3)Ash

Formulation of Raw Mix Design in Linear Programming

Since the coal ash absorption rate was specified at 0.6% earlier, the remaining 99.4% of clinker chemistry will be contributed by raw mix design. The sum of individual oxides content contributed by each decision variable is expressed from equated as:

$$(X_1)(CaO)X1 + (X_2)(CaO)X2 + (X_3)(CaO)X3 + \ldots + (X_8)(CaO)X8 = (CaO)\mathrm{RM} \quad (2)$$

$$(X_1)(SiO_2)X1 + (X_2)(SiO_2)X2 + (X_3)(SiO_2)X3 + \ldots + (X_8)(SiO_2)X8 = (SiO_2)\mathrm{RM} \quad (3)$$

$$(X_1)(Fe_2O_3)X1 + (X_2)(Fe_2O_3)X2 + (X_3)(Fe_2O_3)X3 + \ldots + (X_8)(Fe_2O_3)X8 = (Fe_2O_3)\mathrm{RM} \quad (4)$$

$$(X_1)(Al_2O_3)X1 + (X_2)(Al_2O_3)X2 + (X_3)(Al_2O_3)X3 + \ldots + (X_8)(Al_2O_3)X8 = (Al_2O_3)\mathrm{RM} \quad (5)$$

$$(X_1)(MgO)X1 + (X_2)(MgO)X2 + (X_3)(MgO)X3 + \ldots + (X_8)(MgO)X8 = (MgO)\mathrm{RM} \quad (6)$$

The theoretical conversion from raw mix chemistry to clinker chemistry can be done by multiplying it by the Loss on Ignition (LOI) factor. The LOI can be determined by test in a laboratory furnace [21] and in this report, the loss on ignition (by percentage) is determined to be 35%. Then, the multiplication factor is calculated to be 1.538 by utilizing the formula as in formula as:

$$LOI\ Factor = \frac{1}{1 - \left(\frac{LOI}{100}\right)} \quad (7)$$

Finally, the contribution of oxides of both raw mix and fuel mix that transforms into clinker phases are equated as:

$$\left[(CaO)_{\mathrm{RM}} \times Loss\ Factor \times \frac{99.4}{100}\right] + \left[(CaO)_{ASH} \times \frac{0.6}{100}\right] = (CaO)_{CKR} \quad (8)$$

$$\left[(SiO)_{\mathrm{RM}} \times Loss\ Factor \times \frac{99.4}{100}\right] + \left[(siO)_{ASH} \times \frac{0.6}{100}\right] = (SiO_2)_{CKR} \quad (9)$$

$$\left[(Fe_2O_3)_{\mathrm{RM}} \times Loss\ Factor \times \frac{99.4}{100}\right] + \left[(Fe_2O_3)_{ASH} \times \frac{0.6}{100}\right] = (Fe_2O_3)_{CKR} \quad (10)$$

$$\left[(Al_2O_3)_{\mathrm{RM}} \times Loss\ Factor \times \frac{99.4}{100}\right] + \left[(Al_2O_3)_{ASH} \times \frac{0.6}{100}\right] = (Al_2O_3)_{CKR} \quad (11)$$

$$\left[(MgO)_{\mathrm{RM}} \times Loss\ Factor \times \frac{99.4}{100}\right] + \left[(MgO)_{ASH} \times \frac{0.6}{100}\right] = (MgO)_{CKR} \quad (12)$$

Clinker Chemistry (Constraint)

Portland cement clinker mainly consists of four crystalline phases, namely alite (C_3S), belite (C_2S), tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF) in close interpenetrating association [20]. C,S,A and F in the clinker phase represent as CaO, SiO_2, Al_2O_3 and Fe_2O_3, respectively. Apart from that, the clinker also contains a small proportion of voids or pores where the free lime and periclase (free MgO) are present without combining with other phases [12]. The common composition of clinker phases and its properties are discussed in Table 3.

The main clinker phase compositions are then estimated through the application of Bogue Calculation [22] by utilizing the oxides as expressed in formulas as:

$$C_3S = 4.07((CaO)_{CKR} - FCaO) - 7.60(SiO_2)_{CKR} - 6.72\,(Al_2O_3)_{CKR} - 1.43(Fe_2O_3)_{CKR} - 2.85(SO_3)_{ASH} \quad (13)$$

$$C_2S = 2.87(SiO_2)_{CKR} - 0.754C_3S \quad (14)$$

$$C_3A = 2.65(Al_2O_3)_{CKR} - 1.69\,(Fe_2O_3)_{CKR} \quad (15)$$

$$C_4AF = 3.04(Fe_2O_3)_{CKR} \quad (16)$$

Table 3 Clinker phases and its properties

Designation	Formula	Average Content (%wt.)	Properties in Cement
Tricalcium silicate (Alite)	3CaO.SiO_2 (C_3S)	60	High initial and final strength (main)
Dicalcium Silicate (Belite)	2CaO.SiO_2 (C_2S)	15	Slow hydration and good final strength
Tricalcium aluminate	3CaO. Al_2O_3 (C_3A)	11	Rapid hydration, volume expansion, good early strength
Tetracalcium aluminoferrite	4CaO. Al_2O_3. Fe_2O_3 (C_4AF)	8	Gives cement colour
Free lime	FCao	≤ 2	Reduced strength, increased setting time (undesirable)
Free Magnesium Oxide	MgO	≤ 3	Develops volume expansion and cracks (undesirable)

(*Source:* Kohlhaas & Labahn [20])

Table 4 Constraints in linear programming

Constraint	Phase Contents (%wt.)
C_3S	55-65
$C_3S + C_2S$	≥72
C_3A	7-9
C_3AF	Not constraint
$C_3S + C_2S + C_3A + C_3AF + (MgO)_{CKR} + FCaO$	≤100
$(MgO)_{CKR}$	2.5-3.3

(*Source:* Kohlhaas & Labahn [20])

The aim of this section is to ensure the phase contents (by weight percentage) in the clinker are achieved within acceptable limits. Table 4 highlights the expected limit of clinker phases which serves as the constraints to meet by the decision variable in Linear Programming.

Feed Parameter Control (Constraint)

Prior research [23] outlined the Lime Saturation Factor (LSF), Silica Ratio (SR) and Alumina Modulus (AM) are some of the critical clinker quality targets and can be estimated by using formulas as:

$$LSF = \frac{100(CaO)_{CRK}}{2.8(SiO_2)_{CRK} + 1.18(Al_2O_3)_{CRK} + 0.65(Fe_2O_3)_{CRK}} \quad (17)$$

$$SR = \frac{(SiO_2)_{CRK}}{(Al_2O_3)_{CRK} + (Fe_2O_3)_{CRK}} \quad (18)$$

$$AM = \frac{(Al_2O_3)_{CRK}}{(Fe_2O_3)_{CRK}} \quad (19)$$

The LSF corresponds to the ratio of CaO to the other main oxides, which controls the ratio of alite to belite in the clinker. In addition, the silica ratio represents the proportion of SiO_2 to the total of Fe_2O_3 and Al_2O_3 that determines the burnability of the clinker by reducing liquid phase content [11]. On the other hand, the alumina modulus is the ratio of Al_2O_3 to Fe_2O_3, which evaluates the composition of the liquid phase in the clinker. Table 5 shows the list of constraints and the allowable limit for LSF, SR and AM as established in the LP for the decision variable to satisfy.

Table 5 Constraints in linear programming [11]

Constraint	Allowable Range
LSR	96-98
SR	2.2-2.4
AM	1.5-2.5

Feeding Weigher Capacity (Constraint)

Besides clinker chemistry, it is also compulsory to analyse the maximum dosing capacity of the raw mix feeding system, which varies from each manufacturing facility. As for this case study, the raw materials are stored in four hoppers, as shown in Figure 1, which feeds material to the individual conveyor belt weigher and eventually to the feed conveyor belt. The proportion of the raw material is controlled by the variable speed of the conveyor belt weigher, which is adjusted based on the raw mix design.

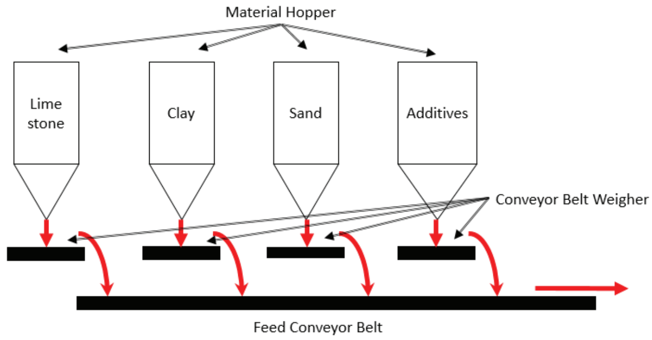

Figure 1 Raw mix feeding system

This report defines the weigher maximum capacity for each raw material as shown in Table 6. Note that clay and alternate material will be stored in the same hopper and shares the same weigher and the maximum limit is 0.2 (20% of the total feed). If the total design feed is 500 tph, and then the clay weigher is capable to feed maximum at the rate of 100 tph.

Table 6 Weigher capacity constraints in linear programming

Constraint	Decision Variables	Limit
Limestone Weigher	X_1	1
Clay + Alternate Material Weigher	$X_3 + X_4 + X_5 + X_6 + X_7$	0.2
Sand Weigher	X_2	0.016
Additives Weigher	X_8	0.04

RESULT AND DISCUSSION

Table 7 shows the actual chemistry composition of both raw mix and fuel mix with the clinker chemistry contribution rate of 99.4% and 0.6% respectively. The types of clay, alternate material and additive used in the raw mix varies from plant to plant and this information is kept confidential.

Table 7 Actual chemistry composition of raw mix and fuel mix

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Cost (RM)
Raw Mix Proportion (99.4%)						
Limestone	4.75	1.29	0.64	49.52	2.45	5.00
Sand	91.92	4.11	0.39	0.29	0.09	32.00
Clay 1	23.29	16.43	58.05	0.16	0.13	49.00
Clay 2	82.03	19.43	11.76	0.31	0.09	16.80
Alt Material 1	67.09	15.42	2.49	0.56	0.09	13.05
Alt Material 2	71.24	22.01	2.79	0.23	0.98	28.00
Additive 1	81.79	4.24	1.81	3.36	0.27	8.99
Additive 2	28.33	5.38	57.25	0.32	0.97	15.40
Fuel Mix (0.6%)						
Coal + Petcoke	46.510	21.290	6.390	5.990	1.010	N/A

Table 8 refers to the remaining information that need to be defined in the LP which associated with the mathematical calculation to convert raw mix and fuel chemistry into clinker chemistry as explained earlier in Equations 8 to 12.

Table 8 LOI, Multiplication Factor and Free Lime Content

Parameters	Values
LOI (in %)	35%
Factor	1.538
(SO3)CLK	1.548
Free Lime	1.50%

Based on the GRG Nonlinear LP simulation, the minimum cost of raw mix design is determined to be RM 6.845 per tonne. The calculated raw mix design consists of 85.03% of Limestone, 0.9% of Clay 1, 12.6% of Alternate Material 1 and 1.47% of Additive 2 as listed in Table 9.

Table 8 Computed raw mix design

Decision Variable	Description	Raw Mix Proportion	Proportions in %
X1	Limestone	0.8503	85.03
X2	Sand	0.0000	0.00
X3	Clay 1	0.0090	0.90
X4	Clay 2	0.0000	0.00
X5	Alt Material 1	0.1260	12.60
X6	Alt Material 2	0.0000	0.00
X7	Additive 1	0.0000	0.00
X8	Additive 2	0.0147	1.47

The simulated raw mix proportion satisfied all the constraints as portrayed in Table 10.

Table 9 Computed result of constraints

Constraint Parameter	Target	Result
C_3S	55-65 wt%	56.85 wt%
C_3A	7-9 wt%	7.81 wt%
$C_3S + C_2S$	≥72 wt%	72.82 wt%
$C_3S + C_2S + C_3A + C_4AF + Fcao + MgO$	≤100 wt%	95.77 wt%
MgO	2.5-3.3 wt%	3.23 wt%
LSF	96-98	98.00
SR	2.2-2.4	2.40
A/F	1.5-2.5	1.50
Limestone Weigher	≤1	0.85
Clay Weigher	≤0.2	0.13
Sand weigher	≤0.016	0.00
Additive Weigher	≤0.04	0.01
Sum of all raw material	1	1.00

On average, a typical cement plant produces 1.5 to 2 million tonnes of cement annually. At this scale, accurate representation of raw material use with the linear programming saves huge amount of cost compared to the conventional method. This approach able to design the raw mix based on minimum cost which could not possible even by multiple laboratory trials. This approach also saves immense amount of analysis time that were used to estimate the raw mix proportion each time the new batch of raw materials arrived. Other than that, it is also useful in terms of production planning to estimate the inventory management to plan on the amount of raw material to hold within the plant because longer storage can degrade the material quality due to surrounding environment such as moisture and temperature. The use of the LP tool to determine the raw mix design also provides other intangible benefit such as employee empowerment. The job of estimating raw mix design that previously managed by senior person can be now shifted to lab technicians with this tool. A clear procedure or SOP and sufficient trainings will do for a technician to compute raw mix in the LP. In addition, the developed LP model also can be used to test alternatives when sourcing for new sustainable material or fuel in the future.

However, the result presented by the LP will only be valid as long the chemistry of the raw mix and fuel remains unchanged, which is very challenging to maintain. This is because the raw material or the fuel chemistry is analyzed based on random sampling that does not represent the whole pile. Thus, it is critical to introduce more sophisticated analyzers that can justify the chemical properties more accurately.

CONCLUSION

This study has demonstrated that the optimisation of raw mix design of clinker production, which will lead to high potential financial gains, can be achieved with the application of linear programming (LP) approach. With the application of LP, quality personnel can evaluate a series of raw mix design based on the expected clinker chemistry faster and cheaper compared to traditional laboratory analysis, then conveniently propose significant improvements in the process to generate better profit and drive sustainable operation. To further enhance the accuracy of the model, to take into consideration on variations in the composition, it is recommended to conduct further in-depth studies and collaboration with the cement plant, as the current proposed model assumes unchanged chemistry of raw materials mix and fuel, which is not always the case.

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