Evaluation of factors influencing the compressive strength of Portland cement statistically

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Abstract. One of the most effective parameters that influence the performance of concrete is the compressive strength of cement. The chemical composition and the physical properties of Portland cement (PC) can be greatly affected the compressive strength of it. So the aim of this study is to make a statistical analysis for the effect of many factors on (3, 7, 28, and 60 day) compressive strength test results. The factors investigated include the main four compounds of cement (C\textsubscript{2}S, C\textsubscript{3}S, C\textsubscript{3}A and C\textsubscript{4}AF) in addition to (CaO, MgO, SO\textsubscript{3}, loss on ignition (LOI), insoluble residue (IR) lime saturation factor (LSF), silica modulus (SM) and alumina ratio (AR)). Furthermore fineness, unsoundness and setting time of cement were also studied. To attain the aim of the present work a statistical program “Statistica” was used for the analysis. It was found that (C\textsubscript{3}S, C\textsubscript{3}A and C\textsubscript{4}AF) compounds has a good correlation with compressive strength, while (C\textsubscript{2}S, CaO, MgO and SO\textsubscript{3}) has a negative effect especially at age of 3 days, considering that (C\textsubscript{2}S and SO\textsubscript{3}) effect became positive at 7 day age onward. The effect of (LSF and fineness) was positive on compressive strength and the effect of (LOI, IR, SM, AR, unsoundness, fineness, IST, FST) was negative.

Keywords: statistical analysis, Statistica, compressive strength, cement chemical composition.

1. Introduction
Concrete is an important structural compound being used widely in the construction industry. The reaction of cement with water leads to hardening, the setting time and strength are two of the most vital characteristics for this process. The combination of the initial mineral ingredients should have an assured composition to get an appropriate strength in compression and time of setting and after these materials passing high temperatures in the furnace and then mixing with water. C\textsubscript{3}S affected cement strength at 7 days greater than at 3 days [1]. It causes the most of the strength increment during the first 4 weeks [2]. In addition to that the strength at ages until 28 days found to be a function of the percentage of C\textsubscript{3}S in cement [1]. The content of C\textsubscript{3}S in cement is linearly related to the raise in strength between 28 days and

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6 months [1]. Increasing the age of testing the negative effect of C2S decreases [3],[4]. The point that C3A has a strength between 28 days and 6-months considered as the positive influence on the development of strength at primary days when mixes with calcium silicate. The C3A it interacts as a catalyst for the reactions of calcium silicate and contributes to the strength of cement [5]. On the other hand, the destructive reactions of C3A may be reduced by the other compounds, especially C3S and C2S and this what cause the negative effect on strength. This is based on the fact that the hydration of C3A is retarded by Ca(OH)2 liberated by the hydrolysis of C3S[2]. It is found that there is a positive result on the compressive strength by C3A up to 7 and 28 days[6], the cement strength at a certain hydration time increases with the C3A content to a maximum of 14% C3A [7]. Opposing to another results concluded that there is a negative effect on O.P.C by C3A at 7 and 28 days of strength [3].

The C4AF produces the highest vital strength of all compounds, then closely by C3S [8]. C4AF contributes positively to the compressive strength of cement at 12 hours accelerated curing, 3, 7, and 28 days normal curing [4]. Contrary to another research that found a negative effect of C4AF on O.P.C. at the ages of 24 hours accelerated curing, 3, 7, and 28 days normal curing [3]. At different ages and up to 60 days the insoluble residue has a negative impact on compressive strength [9].

Increasing in MgO drops concrete compressive strength nonlinearly at what time other aspects are in their low or high level whereas increasing MgO has a various impact on the initial setting time at great and small level fascination of the other aspects [10].

2. Data collection:
The experimental data includes the physical and chemical analysis of the collected samples from seven different cement factories in Iraq, Indian cement, and Kuwaiti cement. Forty different cement samples testing data, (26) of them were ordinary Portland cement while the other (14) samples were sulphate resisting Portland cement. The compliance of cements was done according to the Iraqi standard specification (IQS No.5 : 1984) for the chemical analysis and physical properties specified in this standard.

3. Statistical Analysis:
The statistical analysis implemented by using the statistical program (Statistica) and the factors (as individuals) that studied in the present study were (C2S, C3S, C3A and C4AF) in addition to (CaO, MgO, SO3, loss on ignition, insoluble residue, silica modulus and alumina ratio). Furthermore, fineness, unsoundness and setting time of cement were also studied.

In this study, nonlinear estimation was adopted to be exactly appropriate for forecasting the dependent variable "compressive strength of Portland cement" from factors influencing strength which include the chemical and physical characteristics of cement (as independent variables). The nonlinear "nonlinear regression” prediction is a global fitting technique which will appraisal every gender of connection among a dependents (or response variables), and a list of independent variables. Broadly, all regression models may be put as (Stat Soft 2003):

\[ Y = F(x_1, x_2, \ldots, x_n) \]

In the phrase above, the expression F(x...) refers that y, the dependent or response variable, is a function of the x’s, that is, the independent variables.

Then the model is accurately evaluated to examine if the underlying hypothesis of the examination seem reasonable by applying it to data from different source other than data produced from this study. If the suppositions appeared righteous, the scientific or engineering problems that encouraged the modeling work can be answered by the model (Engineering Statistic Hand book-II).
4. Results and discussion

4.1. Effect of main compounds on cement compressive strength

The relationship and regressions that had been obtained between C$_3$S and Portland cement compressive strength at 3, 7, 28 and 60 days are shown in Figure (1). It is clear from statistical analysis that the correlation between C$_3$S content and compressive strength was significant and this compound (C$_3$S) has a positive influence on cement compressive strength for the four ages of testing but this influence was more noticeable at early ages especially at 7 days. The reason for this may be due to the greatest and fastest strength development of this compound.

![Figure 1](image1.png)

**Figure 1.** Relationship between C$_3$S and 3, 7, 28, and 60 days of Portland Cement Compressive Strengths.

Figure (2) shows the relationship and regressions that had been obtained between C$_2$S and Portland cement compressive strength. It is clear from that figure that C$_2$S has negative effect on compressive strength at early age (3 days) but this negative effect decreased with time which means enhancing the percentage of the reactive amount of this compound. The effect of aluminates (C$_3$A and C$_4$AF) on cement compressive strength was lower than silicate and this clear in Figures (3 and 4) respectively. This may be due to the retardation of C$_3$A hydration due to liberation of Ca(OH)$_2$ from the hydrolysis of C$_3$S which will produce a protective coating on the surfaces of unhydrated C$_3$A grains. This result was in the same line of Alexander [7] but in contrary with Osbaeck[10] who found a negative effect of C$_3$A on 7 and 28 days compressive strength. Osbaeck [11] attributed his results to reason that the hydration products of C$_3$A are metastable where they suffer changes in their physical structures which will be reflected in destructive effects on cement strength.
Figure 2. Relationship between C₃S and 3, 7, 28, and 60 days of Portland Cement Compressive Strengths.

Figure 3. Relationship between C₃A and 3, 7, 28, and 60 days Compressive Strengths of Portland Cement.

Figure 4. Relationship between C₄AF and 3, 7, 28, and 60 days of Portland Cement Compressive Strengths.
4.2. Effect of minor compounds on cement compressive strength

The relationships and regression models between the minor compounds and the 3, 7, 28 and 60 days cement compressive strength are shown in Figures (5 to 7). From these figures it can be seen that the compressive strength of cement is negatively influenced by the increase in MgO and SO₃.

![Figure 5](image)

**Figure 5.** Relationship between MgO and 3, 7, 28, and 60 days of Portland Cement Compressive Strengths.

For MgO effect, this reduction in strength may be due to the slow reaction of periclase crystals while for SO₃ effect this reduction in strength slightly decrease with increasing curing age and this because at this age enough hydration products have been formed mostly due to the hydration of silicates which were able to reduce the role of harmful effect of SO₃ on the cement.

![Figure 6](image)

**Figure 6.** Relationship between Free CaO(%) and 3, 7, 28, and 60 days of Portland Cement Compressive Strengths.
4.3. Effect of Loss on Ignition (L.O.I), Insoluble Residue (I.R), Alumina Ratio (A.R), Silica Modulus (S.M) and Unsoundness on cement compressive strength

The effect of (L.O.I), (I.R), (A.R), (S.M) and unsoundness on 3, 7, 28 and 60 days compressive strength are shown in Figures (8 to 12). It can be seen from these figures that the abovementioned variables had a negative or untouchable effect on cement compressive strength and this is obvious from the weak correlation. Figure (12) shows the influence of unsoundness “expressed by the percentage of expansion”, the presence of Free CaO, MgO and SO\textsubscript{3} is the main reason for this reduction in cement strength.

**Figure 7.** Relationship between SO\textsubscript{3} and 3, 7, 28, and 60 days of Portland Cement Compressive Strengths.

**Figure 8.** Relationship between Loss on Ignition (%) and 3, 7, 28, and 60 days of Portland Cement Compressive Strengths.
Figure 9. Relationship between Insoluble Residue(%) and 3, 7, 28, and 60 days of Portland Cement Compressive Strengths.

Figure 10. Relationship between Alumina Ratio and 3, 7, 28, and 60 days of Portland Cement Compressive Strengths.
Figure 11. Relationship between Silica Modulus and 3, 7, 28, and 60 days of Portland Cement Compressive Strengths.

Figure 12. Relationship between Unsoundness(%) and 3, 7, 28, and 60 days of Portland Cement Compressive Strengths.

4.4. Effect of fineness on cement compressive strength
It is quite clear that the fineness of cement is of fundamental importance in studying the hydration and strength of cement. Figure (13) illustrated the relationship between fineness of cement “expressed as blain specific surface (m²/kg)” and cement strength. The positive influence of fineness is obvious in Figure (13) but this positive effect was at different levels and the greatest important effect was at 7 days ”as it had the highest correlation” then this positive
effect decreased at later ages and the main reason may be due to the prolonged curing (28 and 60 days) allowed more cement to hydrate thus reducing the effect of fineness.

4.5. Effect of Initial and Final Setting Time on cement compressive strength

The relationship between Initial Setting Time (IST) and Final Setting Time (FST) and cement compressive strength is shown in Figures (14 and 15). It can be seen from these figures that both (IST) and (FST) had a negative effect on cement strength especially at 3 and 7 days age.

**Figure 13.** Relationship between Specific Surface Area of Cement (m²/kg) and 3, 7, 28, and 60 days of Portland Cement Compressive Strengths.

**Figure 14.** Relationship between Initial Setting Time (minute) and 3, 7, 28, and 60 days of Portland Cement Compressive Strengths.
Figure 15. Relationship between Final Setting Time (minute) and 3, 7, 28, and 60 days of Portland Cement Compressive Strengths.

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