Journal of Zhejiang University SCIENCE
ISSN 1009-3095
http://www.zju.edu.cn/jzus
E-mail: jzus@zju.edu.cn

Reliable evaluation method of quality control for compressive strength of concrete*

CHEN Kuen-suan[1], SUNG Wen-pei[†2], SHIH Ming-hsiang[3]

([1]Department of Industrial Engineering and Management, [2]Department of Landscape Design and Management, National Chin-Yi Institute of Technology, Taiping, Taichung, Taiwan 41111, China)

([3]Department of Construction Engineering, National Kaoshiang First University of Science and Technology, Kaoshiang, Taiwan 824, China)

[†]E-mail: sung809@chinyi.ncit.edu.tw

Received July 6, 2004; revision accepted Aug. 9, 2004

Abstract: Concrete in reinforced concrete structure (RC) is generally under significant compressive stress load. To guarantee required quality and ductility, various tests have to be conducted to measure the concrete's compressive strength based on ACI (American Concrete Institute) code. Investigations of recent devastating collapses of structures around the world showed that some of the collapses directly resulted from the poor quality of the concrete. The lesson learned from these tragedies is that guaranteeing high quality of concrete is one of the most important factors ensuring the safety of the reinforced concrete structure. In order to ensure high quality of concrete, a new method for analyzing and evaluating the concrete production process is called for. In this paper, the indices of fit and stable degree are proposed as basis to evaluate the fitness and stability of concrete's compressive strength. These two indices are combined to define and evaluate the quality index of the compressive strength of concrete. Principles of statistics are used to derive the best estimators of these indices. Based on the outcome of the study, a concrete compressive strength quality control chart is proposed as a tool to help the evaluation process. Finally, a new evaluation procedure to assess the quality control capability of the individual concrete manufacturer is also proposed.

Key words: Quality index of concrete, The best estimators, Quality control chart, Evaluation criteria, Fit degree of compressive strength of concrete, Stable degree of compressive degree of concrete

doi:10.1631/jzus.2005.A0836 **Document code:** A **CLC number:** TU411

INTRODUCTION

In recent years, devastating disasters in which reinforced concrete structures collapsed have caused major loss of life and property damage around the world. Investigation of these incidents showed that the collapses were mainly due to the poor concrete quality (NCREE, 1999; SECL, 1999; Watabe, 1995). Therefore, high quality assurance in reinforced concrete (RC) structure design and manufacturing is one of the most important safety factors. To promote the reliability of structure, concrete engineers need to achieve the required compressive strength and ductility of concrete in their design.

An RC structure with sufficient ductility is capable of dealing with nonlinear deformation. It will give warning signs before its impending collapse to allow corrective actions in order to avoid major loss of life and property damage. The ductility of the RC structure is mostly influenced by the compressive strength of its concrete. In order to ensure the earthquake-resisting capability of RC structure, the ductility ratio of structure should meet the requirement prescribed by ACI code (ACI, 1983). Then, the fit compressive strength of concrete can be determined based on the ductile ratio. Generally, engineers take daily concrete samples for strength tests and evaluation of the average compressive strength of concrete prescribed by "ACI 318-95, Section 5.6: Evaluation

*Project (No. NSC92-2213-e-167-001) supported by the National Science Council, Taiwan, China

and Acceptance of Concrete" (ACI, 1983). If the compressive strength of concrete greatly exceeds the specified strength, it will seriously affect the ductile ratio of the structure. On the other hand, if the deviation of compressive strength of concrete is over the limit, it causes imbalance to the ductile ratio of structure, and adversely influence the seismic capability of the structure. So statistical methods (PCA, 1970; Kane, 1986) are used to evaluate the manufacturing capacity and quality control of manufacturers, as prescribed by "ACI 318-95, Section 5.3". First, the standard deviation is decided by at least thirty successive sets of test results of dispensed concrete prescriptions, and then the average compressive strength requirement of concrete is imposed to identify the quality control capability of a manufacturer. In the process of construction, although the dispensed prescriptions of concrete are the same, some uncertain factors may cause imbalance to the deviation of compressive strength of concrete and affect the engineering quality and the required compressive intensity and ductility of the structure. It may even cause an unexpected structure collapse. Thus, the purpose of this research is to propose a procedure and a set of criteria to evaluate the concrete quality and control capability of the concrete manufacturing processes.

Currently, many effective evaluation methods have been proposed by well-known researchers (Kane, 1986; Chan *et al*., 1988; Chou and Owen, 1989; Boyles, 1991; 1994; Pearn *et al*., 1992; Cheng, 1994; Chen, 1998a; 1998b) in various manufacturing industries. Sung *et al*.(2001) proposed a method for the production and quality control capability of steelworks. Based on his method, this study developed an evaluation method for concrete based on two indices, one for the fitness and the other for the stability degree of the compressive strength of concrete. These two indices are used to measure the concrete quality, whether it meets both the target value and the smaller deviation. Furthermore, both indices are combined to define a new index, called the index of concrete quality to simultaneously evaluate the fitness and stability degree of concrete quality. This evaluation method can be used to evaluate an individual concrete manufacturer. If there are more than two concrete manufacturers, the evaluation method will need some modification. Modification is based on statistical principles applied to derive the three estimators–probability density functions, expected values, and variance values. And the test of hypothesis is used to develop a quality control chart. These three estimators and quality control chart can then be used to objectively evaluate the quality of concrete from various concrete manufacturers. Also in this study, a new, convenient and useful evaluation procedure and a set of decision-making criteria are proposed for examining and comparing the production process and quality control capability of various concrete manufacturers. Based on the above proposed procedure and criteria, the principle for choosing the best manufacturer is established.

QUALITY INDEX OF CONCRETE

Based on the conception of ACI 318-95 Section 5.6, the compressive strength values of tested concrete cylinder, using X as symbol, are impossibly the same. Thus, X is obviously a random variable. Too much or insufficient compressive strength of concrete, can both affect the structure quality. Thus, the difference between test values X and fit value of compressive strength of concrete T should be less than d, called the maximum allowed error value. The actual compressive strength of concrete should result in tolerance interval (L, U) in which the upper specification U is from T plus d ($U=T+d$) and the lowest specification limit L is from T minus d ($L=T-d$). Consequently, when the test value exceeds the upper limit specification U or below the lowest limit specification L, the quality of concrete does not meet the specified requirement.

If X follows normal distribution in which the mean value is μ and variance value is σ^2, it denotes as $X \sim N(\mu, \sigma^2)$. When the mean value μ is closer to the fit value of compressive strength of concrete T, it indicates that the fit degree of compressive strength of concrete is higher. The index of fit degree of compressive strength of concrete is defined as follows:

$$E_{if} = (\mu - T)/d \tag{1}$$

$E_{if}>0$ ($\mu>T$) shows that the average compressive strength of concrete is greater than the fit value T based on the definition of index E_{if}. Contrarily, $E_{if}<0$

($\mu<T$) indicates that the average compressive strength of concrete is smaller than the fit value T. The quality control engineer of a concrete manufacturer should improve the quality of concrete in accordance with the values of E_{if}. If the μ values approach the fit value, it means that the fit degree is higher. Consequently, the square of the E_{if} symbol (E_{if}^2) is used to evaluate the fit degree of the compressive strength of concrete. For the variance value σ^2, lesser value of σ^2 indicates stabler quality of concrete. By means of the relationship of actual test distribution and tolerance interval, the index of stable degree of compressive strength of concrete can be defined as follows:

$$E_{is}=\sigma/d \tag{2}$$

According to the numerator of E_{is} being σ and the denominator d being a constant value, lesser E_{is} indicates that the variance value σ^2 is small. Thus, the stability degree of compressive strength of concrete is higher. When values of index E_{is} are 1, 1/2 and 1/3 under condition of $\mu=T$, the probability rates of tallied specification p% of actually tested compressive strength of concrete exceeding the uppermost and lowest specification limit is 31.73%, 4.56% and 0.27%. Obviously, lesser E_{is} indicates stable quality of compressive strength of concrete and higher rate of tallied specification p%.

In this paper, the index, proposed by Chan and Owen (1989), is used and modified as a concrete quality index. This index as well as the indices for the fit and stable degree of compressive strength of concrete is joined as a single index to evaluate the production process capability. The index is as follows:

$$E_Q=\frac{d}{\sqrt{\sigma^2+(\mu-T)^2}} \tag{3}$$

Actually during $E_Q=[(E_{is})^2+(E_{if})^2]^{-1/2}$, when E_Q is large, the two indices E_{if} and E_{is} are small, indicating that the concrete quality has qualifications of a fit and stable degree. Contrarily, a much smaller value of E_Q, owing probably to the larger E_{if} value or E_{is} value, will show that the concrete quality is undesirable. Obviously, larger index E_Q indicates better concrete quality. Otherwise, the concrete quality is undesirable. When the difference between the test value and the target value is smaller than the tolerance value d, the quality of concrete attains the required specification. Contrarily, the quality control of the concrete manufacturing process is not acceptable. Assuming that the rate of tallied specification p% can be calculated by $F(U)-F(L)$, in which $F(\cdot)$ is the cumulative function of the random variable X, on the assumption of normality, the relationship between the rate of tallied specification p% and index E_Q can be expressed as follows:

$$p\%=P(L\le X\le U\mid E_{if}=0)=P(-E_Q\le Z\le E_Q\mid \mu=T)$$
$$=[\Phi(E_Q)-\Phi(-E_Q)]=2\Phi(E_Q)-1 \tag{4}$$

where, Z is the standard normal distribution; Φ is the cumulative function of standard normal distribution.

Obviously, when the value of E_Q is larger, the rate of tallied specification p% is higher. On the other hand, when the value of E_Q is smaller, the rate of tallied specification p% is lower. Although when the value of E_{if} is equal to "0", the one-to-one relation between the rate of tallied specification p% and index E_Q does not exist. However, when index E_Q is equal to constant c, the relationship between the index E_Q and the rate of tallied specification p% can be expressed as follows:

$$p\%=\Phi\left(\frac{1+\sqrt{1/c^2-(\sigma/d)^2}}{(\sigma/d)}\right)+\Phi\left(\frac{1-\sqrt{1/c^2-(\sigma/d)^2}}{(\sigma/d)}\right)-1$$
$$=\Phi\left(1/E_{is}+\sqrt{(c\times E_{is})^{-2}-1}\right)+\Phi\left(1/E_{is}-\sqrt{(c\times E_{is})^{-2}-1}\right)-1 \tag{5}$$

where, $E_{is}\le c^{-1}$.

When $E_{is}=c^{-1}$ ($\mu=T$), then $p\%=2\Phi(E_Q)-1$. Generally, the rate of tallied specification p% is not less than $2\Phi(E_Q)-1$ ($p\%\ge 2\Phi(E_Q)-1$) for any real case of $c\ge 1$.

ESTIMATORS OF INDICES

Let X_1, ..., X_n, be a random sample taken from the test results. The symbols of n, $\bar{X} = n^{-1}\left(\sum_{i=1}^{n} X_i\right)$ and $S^2 = (n-1)^{-1}\sum_{i=1}^{n}(X_i - \bar{X})^2$, denoting respectively sample size, sample mean and sample variance, are used to evaluate mean μ and variance σ^2. The unbiased estimators of E_{is}, E_{if} and E_Q, quoted and modified from Cheng (1994-95) can be expressed as follows:

$$\hat{E}_{if} = (\bar{X} - T)/d \tag{6}$$

$$\hat{E}_{is} = S/(dc_4) \tag{7}$$

$$\hat{E}_Q = \frac{d}{\sqrt{S_n^2 + (\bar{X} - T)^2}} \tag{8}$$

where, $c_4 = \sqrt{2/(n-1)}\,\Gamma[n/2]/\Gamma[(n-1)/2]$ is a function of n (Montgomery, 1985), $S_n^2 = (n-1)S^2/n$.

Table 1 lists various c_4 values and corresponding values of sample size n.

Table 1 c_4 values and corresponding values of sample size n

n	c_4	n	c_4	n	c_4	n	c_4
2	0.7979	8	0.9650	14	0.9810	20	0.9869
3	0.8862	9	0.9693	15	0.9823	21	0.9876
4	0.9213	10	0.9727	16	0.9835	22	0.9882
5	0.9400	11	0.9754	17	0.9845	23	0.9887
6	0.9515	12	0.9776	18	0.9854	24	0.9892
7	0.9594	13	0.9794	19	0.9862	25	0.9896

Remark: $c_4 \cong 4(n-1)/(4n-3)$ for $n > 25$

Obviously, $(n-1)\{[c_4\,\hat{E}_{is}\,]/E_{is}\}^2$ is statistically chi-square distribution with $n-1$ degree of freedom based on the assumption of normality. The $\hat{E}_{if}$, obeying the mean value, is E_{if}, and the variance value is $(E_{is})^2/n$, based on the normal distribution. The quantity $(\hat{E}_Q \times E_{is})^{-2}$ obeys non-central chi-square distribution with n degree of freedom and non-centrality parameter $n(E_{if}/E_{is})^2$. Similarly, the quantity $(\hat{E}_Q / E_Q)^{-2}$ is approximately distributed as central $\{\chi_v^2 / v\}$ (Boyles, 1991), where

$$v = \frac{n(1+\lambda^2)^2}{1+2\lambda^2},\ \lambda = \frac{E_{if}}{E_{is}} \tag{9}$$

Actually, each of the two unbiased estimators $\hat{E}_{if}$ and $\hat{E}_{is}$ has qualifications of a completely sufficient statistical quantity. Therefore, these two unbiased estimators are uniformly the minimum variance unbiased estimators (UMVUE) of E_{if} and E_{is}. The estimator $\hat{E}_Q$ is the maximum likelihood estimator (MLE) of E_Q, known as the normal distribution of $\bar{X}$, S_n^2 and the maximum likelihood estimator of μ and σ, respectively. Finally, the expected value of is expressed as follows:

$$E(\hat{E}_Q) = \frac{1}{E_{is}}\sqrt{\frac{n}{2}}\sum_{j=0}^{\infty}\left(\frac{e^{-\lambda/2}(\lambda/2)^j}{j!}\frac{\Gamma[j+(n-1)/2]}{\Gamma[j+n/2]}\right) \tag{10}$$

The variances of these three estimators are derived as follows:

$$\mathrm{Var}(\hat{E}_{if}) = \left(\frac{1}{n}\right)(E_{is})^2 \tag{11}$$

$$\mathrm{Var}(\hat{E}_{is}) = \left(\frac{1-c_4^2}{c_4^2}\right)(E_{is})^2 \tag{12}$$

$$\mathrm{Var}(\hat{E}_Q) = E(\hat{E}_Q)^2 - E^2(\hat{E}_Q) \tag{13}$$

where,

$$E(\hat{E}_Q)^2 = \frac{1}{E_{is}^2}\,\frac{n}{2}\sum_{j=0}^{\infty}\left(\frac{e^{-\lambda/2}(\lambda/2)^j}{j!}\frac{2}{n+2j-2}\right) \tag{14}$$

Eqs.(11), (12) and (13) show that the variances of these three estimators are affected by the stable degree (E_{is}), indicating that the higher the stable degree of compressive strength of concrete, the smaller the variances of the three estimators. On condition that E_{is} is a constant, the more the number of samples (n), the lesser the variances of the three estimators.

EVALUATION CRITERIA FOR THE CONCRETE QUALITY

The index E_Q is an excellent tool for evaluating the quality of concrete. If the index E_Q is large enough, it indicates that the concrete manufacturer has qualifications for high-level production capability. On the other hand, if the index E_Q is small, quality control capability does not attain the requirement. However, Cheng (1994-95) pointed out that the parameters of production process are unknown. Thus, the estimated values should be obtained by means of sampling. Unfortunately, using estimated values as indices to judge the production capability may not be objective because that there may be errors existing in the sampling. Therefore, the best formulas of these three estimators, derived in this paper, are used via statistically examining hypothesis to evaluate the compressive strength of concrete for concrete manufacturers. In other words, this evaluation method is used to judge whether or not the concrete quality meets the required tolerance specification for the compressive strength.

Determination of critical value of quality

Assuming the minimum requirement for the compressive strength of concrete is E_Q>C, C is a parameter value that can be determined by actual conditions. The symbol C is the effective test requirement that can be reasonably defined by the contract and can be used to calculate the rate of unqualified p%. The concrete quality meets the requirement if E_Q is larger than C, and it does not meet the requirement if E_Q is less than or equal to C.

$$\mathrm{H}_0\text{: } E_Q \le C$$
$$\mathrm{H}_1\text{: } E_Q > C$$

If H_1, the alternative hypothesis, is recognized as irrefutable, it represents that the compressive strength of concrete quality is fine. Otherwise, if H_0, the null hypothesis is true, it symbolizes that the quality of concrete is not good. The quality control engineer to evaluate the quality of concrete from the manufacturers can use these hypotheses. The appropriate quality control plan can then be mapped out to promote the engineering quality. Actually, the best estimator $\hat{E}_Q$ of index E_Q can be obtained via sampling and used as a test statistic to evaluate whether the compressive strength of concrete attains the required specification or not. Since the quantity $(\hat{E}_Q / E_Q)^{-2}$ is approximately distributed as central χ_v^2 / v, the critical value C_0 can be determined by the following equation.

$$P(\hat{E}_Q \ge C_0 | E_Q = C) = \alpha$$
$$\Rightarrow P\left(\left(\frac{E_Q}{\hat{E}_Q} \right)^2 \le \left(\frac{E_Q}{C_0} \right)^2 \middle| EQ = C \right) = \alpha$$
$$\Rightarrow P\left(\chi_v^2 \le v \times \left(\frac{C}{C_0} \right) \right) = \alpha$$
$$\Rightarrow v \times \left(\frac{C}{C_0} \right)^2 = \chi_{\hat{v};\alpha}^2$$
$$\Rightarrow C_0 = \frac{\sqrt{v}C}{\sqrt{\chi_{\hat{v};\alpha}^2}} \tag{15}$$

where, α is the probability of rejecting a null hypothesis if the null hypothesis is true; $\chi_{\hat{v};\alpha}^2$ is the α upper percentile of chi-square distribution with v degrees of freedom.

The quantity $\hat{v}$ is the maximum likelihood estimator (MLE) of v that can be expressed as follows:

$$\overline{v} = \frac{n(1+\hat{\lambda}^2)^2}{1+2\hat{\lambda}^2}, \ \hat{\lambda} = \frac{\hat{E}_{if}}{\hat{E}_{is}} \tag{16}$$

Finally, $\hat{E}_Q = W$ is calculated. If $W \ge C_0$, the quality control capability of concrete is satisfactory. Contrarily, if $W < C_0$, it reveals that the quality control capability of the concrete manufacturer is not achieved.

Establishment of quality level control chart

A fine engineering quality means not only strict supervision during the construction stage but also a satisfactorily evaluated production process of the concrete manufacturer at the initial stage. Therefore, the quality of concrete is the most important factor affecting the engineering quality. The method of statistical inspection is best only in helping the quality control engineer to judge the concrete quality of one concrete manufacturer. This method is based on the equation of $E_Q = [(E_{is})^2 + (E_{if})^2]^{-1/2} \ge C_0$ to evaluate the quality of concrete. Nevertheless, it is unsuitable for judging and comparing the quality level of more than two concrete manufacturers at the same time. Thus, the various values of significance level C_0 is calculated based on the requirement of concrete quality (E_Q=C) and numbers of tested concrete sample n and under the consideration of various values of significance level α-risk. The E_{if} is along the horizontal axis and the E_{is} is used as the ordinate. Then, the quality control level chart of concrete suppliers is plotted in Fig.1. The following example is used to clarify this figure. When C=1.0 and

(1) Significance level α=0.1, C_0=1.654. The contour line of E_Q=1.654 is plotted based on the equation of $E_Q=[(E_{is})^2+(E_{if})^2]^{-1/2}$.

(2) If significance level α=0.01, C_0=1.283. Then, the contour line of E_Q=1.283 is plotted based on the equation of $E_Q=[(E_{is})^2+(E_{if})^2]^{-1/2}$.

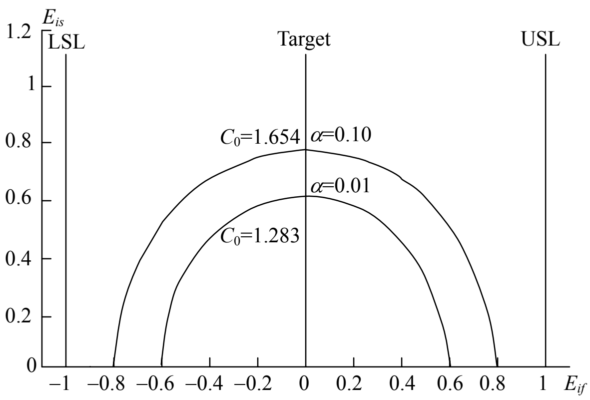

Fig.1 The quality control level chart for concrete supplier

Evaluation procedure and decision-making

In order to rapidly select fine concrete suppliers for the quality control engineer, a set of convenient, useful evaluation criteria, and decision-making method for the quality of concrete can be established, discussed as follows.

(1) Determining the C value of concrete quality level and significance level α-risk value as comparison pattern for quality.

(2) Determining the number of sample n for sampling. Calculate the values of $\hat{E}_{if}$, $\hat{E}_{is}$, $\hat{E}_Q$, $\hat{\lambda}$ and $\hat{\nu}$ based on test value of concrete cylinders.

(3) According to Eq.(15), calculate the critical value C_0 based on significance level value of α=0.10 and α=0.01, and two contour lines of E_Q=C_0 are plotted base on the equation of $E_Q=[(E_{is})^2+(E_{if})^2]^{-1/2}$.

(4) The coordinate points of $(\hat{E}_{if}, \hat{E}_{is})$, indices of concrete quality of test cylinders calculated for concrete manufacturer, can be used to plot a quality control level chart for the concrete suppliers.

(5) Using the following decision-making criteria to select fine quality concrete suppliers:

Criteria a: if the coordinate point $(\hat{E}_{if}, \hat{E}_{is})$ of the test concrete cylinder is located outside the contour line of α=0.10, it indicates that the quality of concrete is not satisfactory.

Criteria b: if the coordinate point $(\hat{E}_{if}, \hat{E}_{is})$ of the test concrete cylinder is just located on the contour line of α=0.10, it shows that the concrete quality just attains the basic requirement. To prevent the poor quality concrete of a concrete supplier from affecting the quality of construction, the changeable situation of concrete quality should be incessantly supervised.

Criteria c: if the coordinate point $(\hat{E}_{if}, \hat{E}_{is})$ of the test concrete cylinder is located between contour lines of α=0.10 and α=0.01, it indicates that the concrete quality of this manufacturer is of desirable quality.

Criteria d: if the coordinate point $(\hat{E}_{if}, \hat{E}_{is})$ of the test concrete cylinder is located inside on contour line of α=0.01, it reveals that the concrete quality of this concrete factory is very good.

Obviously, when the coordinate point $(\hat{E}_{if}, \hat{E}_{is})$ of the test concrete cylinder is closer to the center of the coordinate, it expresses that the quality for the compressive strength of concrete is better. Contrarily, if the coordinate point $(\hat{E}_{if}, \hat{E}_{is})$ of the test concrete cylinder is farther from the center of the coordinate, it indicates that the quality of concrete is undesirable. Actually, the above-mentioned evaluation procedure and decision-making criteria enable the quality control engineer not only to evaluate if the individual concrete supplier meets the basic quality requirement or not, but also to choose the fine quality concrete manufacturer based on the distance of the coordinate point of $(\hat{E}_{if}, \hat{E}_{is})$ from the center of the coordinate. For example, if the coordinate point locates between these two contour lines, it represents that the quality of the concrete meets the requirement of α=0.10. If the significance level rises to α=0.01, the quality level should obviously be improved and strengthened. With the above conclusions summarized, the quality control level chart proposed in this paper can be timely used by a quality control engineer to compare the concrete quality levels of different concrete manufacturers simultaneously. It is used as a decision-maker for selecting the best quality concrete manufacturer.

INVESTIGATION OF EXAMPLE

The quality control index of concrete quality uses the value of the index to assess whether the concrete quality meets the required fitness and stability. Therefore, the evaluation standard for concrete quality in ACI code (ACI, 1996) is used to judge the production and quality control capability of concrete manufacturers in this paper. An example is discussed below. The data for testing the compressive strength of concrete came from four different concrete manufacturers. The quality estimation formulas, evaluation procedure and decision-making criteria, proposed in this paper, are used to evaluate and explain the production process and quality control capability of concrete factories. Under the provision of ACI 318-95 Section 5.3, the target value T, the maximum allowable error value d, the upper specification limit U and the lower specification limit L are defined as follows: T=4000 psi, d=400 psi, $U=T+d$=4000+400=4400 psi and $L=T-d$=4000−400=3600 psi. The results of tests of the four concrete manufacturers, analyzed by the proposed equations, are shown in Fig.2. The comparison results are discussed below:

1. Concrete supplier 1: the SP1 point is located on the significance level α=0.10 contour line, it reveals that the quality control capability is fine. The risk level $0.01\le\alpha\le0.10$.

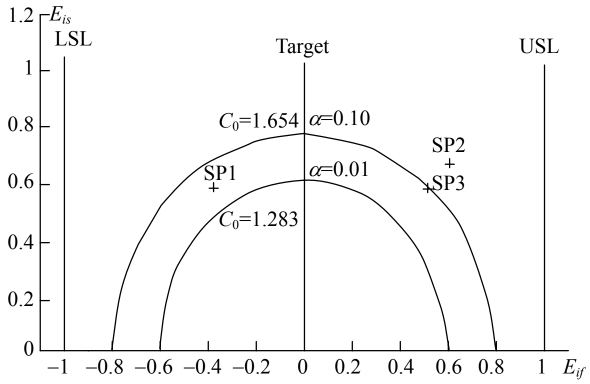

Fig.2 The comparison of four concrete suppliers

2. Concrete supplier 2: the SP2 point is situated outside the significance level α=0.10 contour line, so the risk level is too high, α>0.10, obviously indicating that the quality of concrete from concrete supplier 2 is unsatisfactory.

3. Concrete supplier 3: the SP3 point is located just on the significance level α=0.10 contour line, the concrete quality level roughly attains the quality specification of risk level, α=0.05. That is, the quality of concrete supplied by concrete supplier 3, should be supervised strictly.

4. Concrete supplier 4: the SP4 point is located in the block of the significance level α=0.05 contour line. Obviously, this concrete supplier has best quality control capability and offers the best concrete quality.

The decision-making criteria help the construction-engineering unit to select the best concrete supplier. In this paper, the decreasing order sequence of selecting concrete manufacturers is suggested as follows: SP4→SP1→SP3→SP2. The proposed procedure and decision-making criteria comprise a very good method for the engineering unit to evaluate the quality control capability of concrete factories an thus make the wisest purchase choice.

CONCLUSION

The quality of raw materials and the fitness degree and stability degree of concrete quality affect the stability of concrete structures tremendously. To ensure the quality of concrete provides adequate compressive strength to the structure, ACI code prescribes a statistical approach which, however, lacks an appropriate and convenient evaluation method to judge the fitness and stability of compressive strength of concrete. In this paper a new evaluation method is developed to objectively evaluate the fitness and stability degree of compressive strength of concrete. A statistical inference is used to create an easy, effective and reliable evaluation tool. Engineers and researchers can use this method to evaluate the fitness and stability degree of compressive strength of the concrete, be it a newly developed type or the often-used type. Further, the indices of fitness and stability based on this method can be used to plot the quality control level chart. The production level, deviation degree and the influence of various concrete manufacturers can then be evaluated easily. The improvement of process capability can be measured by the above method as well. The impact of this new method is that it provides easy calculative equations for measuring the production quality of a concrete factory. In addition, it offers a whole set of procedures for the construction industry and concrete manufacturers to evaluate the quality of concrete. It also helps the construction industries to make purchase decisions. Furthermore, it offers the concrete manufacturers an analytical method that can improve the production process and quality control capability. Thus, this analysis method is both convenient and effective.

References

ACI Committee 214, 1983. Recommended Practice for Evaluation of Compressive Test Results of Concrete (ACI 214-77, Reapproved 1983). American Concrete Institute, Detroit, U.S.A.

ACI Committee 318, 1996. Building Code Requirement for Reinforced Concrete (ACI 318-95) and Commentary-ACI 318R-95, Reported by ACI Committee 318.

Boyles, R.A., 1991. The Taguchi capability index. *Journal of Quality Technology*, **23**(1):17-26.

Boyles, R.A., 1994. Process capability with asymmetric tolerances. *Communication in Statistics–Simulation and Computation*, **23**:615-643.

Chan, L.K., Cheng, S.W., Spiring, F.A., 1988. A new measure of process capability: C_{pm}. *Journal of Quality Technology*, **20**:162-175.

Chen, K.S., 1998a. Estimation of the process incapability index. *Commun. Statist.–Theory Methods*, **27**(5):1263-1274.

Chen, K.S., 1998b. Incapability index with asymmetric tolerances. *Statistica Sinica*, **8**:253-262.

Cheng, S.W., 1994-95. Practical implementation of the process capability indices. *Quality Engineering*, **7**(2): 239-259.

Chou, Y.M., Owen, D.B., 1989. On the distribution of the estimated process capability indices. *Commun. Statist.–Theory Methods*, **18**:4549-4560.

Kane, V.E., 1986. Process capability indices. *Journal of Quality Technology*, **18**(1):41-52.

Montgomery, D.C., 1985. Introduction to Statistical Quality Control. John Wiley & Sons, New York, U.S.A.

NCREE, Taiwan, 1999. Investigation of 921 Chi-Chi Earthquake Damages.

PCA, 1970. Statistical Product Control. Publication IS172T, Portland Cement Association, Skokie, IL, U.S.A.

Pearn, W.L., Kotz, S., Johnson, K.L., 1992. Distribution and inferential properties of process capability indices. *Journal of Quality Technology*, **24**:216-231.

SECL, Taiwan, 1999. 921 Chi-Chi Earthquake Brief Report, Taipei, Taiwan.

Sung, W.P., Chen, K.S., Go, C.G., 2001. The Effective Method of Evaluation for the Quality Control of Steel Reinforcing Bar. *Advances and Applications in Statistics*, **1**(2):175-193.

Watabe, M., 1995. Lessons Learnt from Hanshin-Awaji Devastating Earthquake. Proceedings of Conference for Architecture Damage in Hanshin-Awaji Earthquake, Taipei, Taiwan, p.1-1-1-49.