Final Report

on

Study No. 64-02-2

OURI No. 1483

STATISTICAL QUALITY CONTROL OF PORTLAND CEMENT CONCRETE PAVEMENTS

Prepared by

Joakim G. Laguros, Associate Professor
School of Civil Engineering and Environmental Sciences
College of Engineering
University of Oklahoma
Norman, Oklahoma

Submitted to

OKLAHOMA DEPARTMENT OF HIGHWAYS
and
DEPARTMENT OF TRANSPORTATION
Federal Highway Administration
Bureau of Public Roads

From the

UNIVERSITY OF OKLAHOMA RESEARCH INSTITUTE
Norman, Oklahoma
June, 1968

ACKNOWLEDGMENTS

This study was conducted by the School of Civil Engineering and Environmental Sciences, College of Engineering, at the University of Oklahoma. The study was jointly funded by the Oklahoma Department of Highways and the Bureau of Public Roads, Federal Highway Administration, Department of Transportation. The support given by these organizations is gratefully acknowledged. The opinions, findings, conclusions, and recommendations expressed in this report are those of the author and not necessarily those of the funding agencies.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

Figure		Page

SUMMARY

The scope of this investigation was to study statistically the process of preparing concrete for Portland cement concrete pavements and to compare the data with the specifications in use. It encompassed the measurement of properties of the constituents of concrete, namely, coarse aggregate, fine aggregate, and cement; the determination of the properties of the finished concrete, namely slump, air content, compressive strength, and amount of cement in the cured concrete; and the measurement of the thickness of the concrete pavement.

This investigation was conducted in three phases. The first phase consisted of selecting three different concrete paving projects in Oklahoma which were subjected to a statistically based extensive sampling. The second phase included the laboratory or field testing of the samples collected for the determination of certain physical properties pertinent to concrete characterization. In the third phase, the data obtained from property determinations were statistically analyzed. Also, the mean values (average values) of the properties of concrete and its constituent materials were compared with the job specifications.

On the basis of the data collected, the following conclusions/recommendations were reached:

1. The mean values indicated that, in general, the specification provisions were met.
2. The sampling plan as applied to these projects was excessive and, therefore, it is not recommended that it be applied to this extent in concrete paving projects because it would not be economically feasible. However, the number of samples for any specific job should be based on the Random Numbers (Table 2) and also on economic considerations.
3. Acceptance and rejection should be arrived at only on the basis of statistical evaluation.
4. Samples of concrete constituents should be taken as early as possible in the concrete-production process.
5. Testing and control criteria should be revised to be commensurate with the statistically treated data.
6. Some tests should be revised to provide control and/or corrective measures during construction as soon as possible.
7. The specifications should be revised to become more meaningful by including the upper and lower control limits in addition to the mean values, thus recognizing that there are certain inevitable and characteristic variations in materials and construction. It is reasonable to assign $x \pm 2\sigma$ values to the upper and lower control limits.

8. Some control tests should be discontinued, some retained, and others retained with modifications as shown below:

Item	Characteristic	Recommendation
Pavement	Thickness	Retain as used in this study
Plastic Concrete	Slump	Retain
	Air Content	Retain
Cured Concrete	Cylinder Strength	Discontinue
	Cement Content	Discontinue; try a field test
Coarse Aggregate	Grading	Retain
	Durability	Retain; use quarry test
	Passing No. 200	Retain
	Deleterious Material	Retain (visual)
	Los Angeles Loss	Discontinue
Fine Aggregate	Grading	Retain
	Fineness Modulus	Retain
	Passing No. 200	Retain
	Sand Equivalent	Retain
Cement	Alkali Content	Discontinue
	Strength	Discontinue
	Air Content	Discontinue

9. More research is needed in the area of concrete-manufacturing process. Specifically, it is necessary to study and implement by a simulation approach control policies for large-scale concrete production which uses granular raw materials. This can possibly be done by modeling specific operations and statistically fitting the various parameters. It is envisioned that such a study would not only reveal the feasibility of various techniques, but would make possible the delineation of various factors and conditions which lead to a product of desirable and higher quality.

STATISTICAL QUALITY CONTROL OF PORTLAND CEMENT CONCRETE PAVEMENTS

CHAPTER I

INTRODUCTION

Ever since highway engineers started laying concrete pavements, they have been concerned with the quality of concrete and its constituents, namely, aggregate, cement, and water. Years of research and experimentation have resulted in specification limits for the acceptance of concrete highway materials and the final product--concrete. However, in spite of tight controls, failures of concrete pavements have not been uncommon. While these failures may be attributed to a number of reasons, such as foundation failures, and unanticipated heavy traffic conditions, the quality of concrete should not be excluded. Therefore, it becomes necessary to look at the quality of concrete from a critical vantage point and compare it with the specification limits used to produce that concrete.

Current specifications are basically of three types:

1. 100 percent compliance with a definite limit, including prescribed tolerances.

2. The specification which bases acceptance on the set of conditions described by the term "to the satisfaction of the engineer."

3. The specification which states definite limits, but indicates substantial compliance.

The existence of variations in test results of concrete has long been recognized. Only qualitative knowledge about these variations, however, is available. To quantify these, it is imperative to study the variances of the component parts, such as variance in the materials themselves, variance due to sampling procedures, and testing variance. Only then, is it possible to specify tolerance limits.

The problem, then, becomes one of incorporating into the specifications realistic tolerances because it is well accepted today that 100 percent compliance with specification limits is impossible. Thus, the need arises for a modification. Because highway construction involves large quantities of different materials, it seems natural to approach the problem of modification from a statistical point of view. The fundamental statistical parameters, i.e., arithmetic mean, variance, type of distribution, and shape of the distribution curve, must be evaluated not only on the finished product but also on the constituents.

It was with these general objectives in mind that the present study was undertaken. More specifically, the primary purpose was to establish mathematically the quality of concrete obtained when certain given specifications were followed. Implied in the study was the general idea that both the component parts and the finished product were acceptable to the buyer or had met existing specifications.

CHAPTER II

REVIEW OF LITERATURE

Statistical quality control has been used in industry for quite some time because it is the only effective and practical method of screening mass production. In addition, it has been used rather successfully in space projects where high reliability is required. Statistical quality control methods have been proven to be both a powerful detection tool and necessary on almost every production line.

The first action toward the adoption of quality control methods in the concrete industry occurred in the late 1920's. At that time, concrete was considered of value only when it was heavy. Control tests were conducted to determine only its unit weight. Because no specifications were known at that time, the practice was to use any kind of debris, gravel, or stones to produce concrete (9, 10). The statistical approach to the problem was introduced during the 1940's, and revisions to the specifications were suggested by A. M. Fruedenthal (9). The reactions to the new approach were mixed.

At the beginning of the 1950's, a committee on the quality control of concrete in the field was appointed in England (11). This committee reviewed all the aspects of concrete production and gave its recommendation with respect to the methods of improving quality and techniques of testing. The great achievement of this committee was the adoption of statistical concepts to better understand the nature of the variation in concrete production. The compression test was chosen for acceptance testing. The normal distribution was shown applicable in the concrete industry, particularly for the cylinder strength distribution. Confidence level was set at 5 percent (11, 12).

Simultaneously in the United States, concrete control was improved through new testing methods for consistency and air content (13, 14, 15). In Germany, the nature of variation in concrete production with special reference to the building industry was studied (16, 17, 18). The theory of "the weakest link" was adopted and the normal distribution was recognized as the governing type of frequency distribution in concrete. Confidence level was set at 5 percent.

The first official action in adopting the statistical approach to quality control of concrete in the United States was taken in 1955 by the ACI Committee 214 (19). Criteria were established and rational specifications for structural concrete were recommended. The highlights of this report are as follows:

1. The recognition and identification of sources of variations in concrete production.

2. The realization that variations in testing techniques are components of the overall variations.

3. The acceptance of normal distribution representing the frequency distribution in concrete production.

4. The development of concrete control standards which are still in use.

5. The adoption of statistical quality control charts as control techniques.

6. The acceptability of a maximum of 10 percent off specification.

The response to the report was very enthusiastic; however, the characteristics of the frequency distribution were, and still are, in dispute. The log normal distribution was advocated by O. G. Julian and Freudenthal (19). Their argument was that extreme values fit the log normal distribution better than the normal distribution. A different response to the publications of ACI Committee 214 came from R. Shalon and R. C. Reinitz, who accepted the log normal distribution, where a higher arithmetic mean is required to keep the 10 percent off specification (19). The use of normal distribution of the individual values, however, is justified whenever the coefficient of variation is less than 10 percent.

A report on the application of statistical quality control methods to the highway industry was first published by E. A. Nur (31), who advocated extensive use of statistical concepts in specification writing and acceptance sampling. His opinion is that 20 percent off specification should be acceptable on the grounds that:

1. Materials undergo further distribution after testing and concentration of weak spots is not likely to happen.

2. High safety factors are incorporated in the highway design.

He had realized that the so-called engineering judgment, used so often was one of the main sources of variability existing in highway construction, coupled with segregation problems (20). As a civil engineer experienced in controlling big constructions, his observations were quite valuable and served as starting points for realistic specification writing. He also adopted the normal distribution as a basis for the quality control work.

E. A. Nur considered a realistic picture of concrete produced under normal control, one in which the coefficient of variation, V, is 20 to 25 percent, and defined a good concrete as one with a coefficient of variation, V, of 15 percent (based on data from the Bureau of Reclamation) (21). He based his analysis for the minimum strength acceptable on the following assumptions:

1. Most of the specifications define 3000[1] pounds per square inch as the minimum acceptable.

2. Coefficient of variation is normally 20 percent.

3. Normal average strength is 3500[2] pounds per square inch.

   Using the normal distribution theory, he arrived at 24 percent of the concrete strength to be below the 3000 pound per square inch specified.

4. Concrete currently used is good.

Agencies such as the Bureau of Reclamation and the California Department of Water Resources have been using similar approaches to specifications rather successfully for some time (21). This relatively new approach has been applied successfully to highway construction on the Garden State Parkway in New Jersey and on the Illinois Toll Road (22). Finland, for example, where the practice of quality control was introduced and accepted almost 20 years ago, adopted the normal distribution and 16.7 percent off specification (23). Israel adopted the log normal distribution with 10 percent off specification (24). At the present time, the acceptance sampling is based on the unequality

$$\frac{\bar{x} - K}{R} \geqslant r_1 \quad \text{Region of acceptance} \qquad 2\text{-}1$$

$$\frac{\bar{x} - K}{R} < r_2 \quad \text{Region of rejection} \qquad 2\text{-}2$$

where $\bar{x}$, R are samples mean, and range, respectively. r_1, r_2, are taken from the Finish specification table. Furthermore, Finland has incorporated economical parameters in the statistical formulation (23).

Only a few reports on quality control of concrete components have been published. The report by Miller-Warden Associates (7) concerns mainly the effect of different stockpiling on the aggregate segregation and distribution.

---

[1] Curing period not specified.

[2] Curing period not specified.

A segregation index was developed (S_g) where:

$$S_g = \sigma o^2 / \sigma b^2$$

where σo^2 = overall variance 2-3

σb^2 = within-batch variance.

These criteria can be used for control of segregation and development of specification with respect to segregation.

Criteria for surface area were also developed and designated as $\bar{A}$:

where $\bar{A}$ = percent passing of (1 1/2") + percent passing (3/4") + . . . + percent passing No. 200. 2-4

The effect of different stockpiling methods was studied and reported by M. E. Volin and B. Park (25) on the problems which involved sampling and testing of aggregate for deleterious material. In the hypergeometric distribution the probability P of the event or attribute X is given by:

$$P(X) = \frac{\binom{M}{X}\binom{N-M}{n-x}}{\binom{N}{n}} \qquad 2\text{-}5$$

where: N = population size

n = sample size

M = deleterious individuals in the population

The Poisson distribution is simpler and is given by:

$$P(X) = e^{-\mu} \cdot \frac{\mu^x}{X!} \qquad 2\text{-}6$$

where μ = mean or variance.

Good fit to normal distribution was found through testing, and it has been accepted as a tool for practical purposes in instances of semi-infinite population as encountered in aggregate stockpiling. Splitting, which is a part of every standard aggregate test, was found to be an important source of variation.

During the past decade, a considerable volume of work has been published on the statistical approach to quality control of concrete (6, 8, 22, 27, 28, 29, 30, 32, 34), however, reports on field applications of the theory of quality control are infrequent (26, 35, 36).

Nationally, extensive research sponsored by the Bureau of Public Roads and local highway departments has been conducted for some time. Preliminary reports have been released which proved again that the new approach was needed, and it was of practical use (26,27).

CHAPTER III

QUALITY CONTROL-THEORY

3.1 General

It is well recognized that variability is a natural part of every production process and that tests and measurements involve variability.

Variability is merely fluctuation in the product randomly distributed. The necessity to reach certain quality levels ih the final product required that some methods of inspection will be used to assure that the required quality is produced, to reject objectional defective products, and to detect assignable variation whenever something is wrong in the production process.

Three methods of inspection are in use:

1. Screening.
2. Lot-by-lot inspection.
3. Process inspection.

3.2 Screening

Screening is defined as 100 percent inspection, which means that every unit of the product is inspected. Sometimes screening is the only method to assure that every item meets the required standards. This is usually dictated by the function and degree of criticality of the product and, of course, by economical consideration. An example of criticality is when a product determines life or death of a patient, or a vital part upon which the functioning of an entire assembly depends. In the production of highway materials, the screening is uneconomical and practically impossible because most of the concrete tests used today are destructive tests and the inspection would result in 100 percent destruction of the product.

3.3 Lot-by-Lot Inspection

Lot-by-lot inspection was invented to reduce the high cost of screening. The size of the lot is usually based on practical and economical considerations. The lot can be defined as a collection of units of product. In the production of highway materials, the lot can be the daily product of concrete, stockpile of aggregate, or a truckload of cement. A relatively small number of samples is checked and a decision of acceptance or rejection of the lot is made. The limitation of this prodedure is that the samples do not always give a true picture of the entire lot from which they have been selected. This gives rise to two types of errors.

Type I Error -- The null hypothesis is rejected when it should be accepted. The loss is to the producer (contractor).

Type II Error -- The null hypothesis is accepted when it should be rejected. The loss is to the consumer (public).

In attempting to reach a decision, it is useful to make assumptions or guesses about the population involved. Such assumptions, which may or may not be true, are called statistical hypotheses and, in general, are statements about the probability distributions of the populations.

The null hypothesis, denoted by H_o, is the type of hypothesis which assumes that the population has inherently the parameters (μ_1) and (σ), arithmetic mean and standard deviation, respectively.

The alternative hypothesis, H_1, is the one which assumes that the population arithmetic mean is μ_2, the standard deviation is σ, and they are related to each other by:

$$\bar{x}_p = \mu = \frac{1}{N} \sum_{i=1}^{N} x_i \quad \text{(parameter)} \qquad 3\text{-}1$$

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \mu)^2} \quad \text{(parameter)} \qquad 3\text{-}2$$

$$\hat{\sigma} = S = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{X})^2} \quad \text{(statistics)} \qquad 3\text{-}3$$

where: n = number of observations

N = number of observations in population

x_i = variable

S = sample standard deviation

Parameters (μ ,σ) are true values of a given population, statistics ($\bar{x}$, s) are used as an estimate to the parameters, and are determined from computation made on samples. The reliability of the estimate is a function of the sample size (n).

Modern statistics of mathematical probability help the inspector by furnishing him with ready-made sampling plans that guarantee a minimum amount of inspection for a maximum amount of protection against sampling errors. A sampling plan is required; otherwise, there will be too much or not enough inspection and the results are excessive costs or ineffective control.

The chance of making an error when rejecting an acceptable population is called the level of significance of the test denoted by α. In practice, α has the values 5 percent or 1 percent, although other values are used. For example, if α = 5 percent is specified, the hypothesis will be rejected five percent of the time when it should be accepted.

3.4 Process Inspection

Process inspection is actually a continuous inspection of the equipment methods of operation. The purpose of the occasional-pieces inspection is to discover defective products, where and when they occur, and to take corrective action immediately.

The process is concerned with all causes of defective work that may result from an operator, operation, equipment, or raw material. The limitations, however, are that the inspector is so busy that a considerable amount of the defective material may slip through between the inspector's visits.

3.5 Control Chart System

The control chart system seems to be the most important achievement is statistical in quality control, and it can be used easily. Basically, it is a graphical means to detect quickly when something is wrong or is about to go wrong with the process. The quality control charts are capable of detecting any variation greater than the random fluctuation which is inevitable and allowable. Normally, quality control is a part of the producer's duties.

In quality control and acceptance sampling, a product may be judged by attributes or variables. The attributes method involves merely a decision as to whether an item is acceptable or defective, while the variable method involves taking and recording measurements. The second method seems to be more suitable to the highway-materials field.

Quality control charts can be based on three different production variables:

1. The standard deviation of the samples, S.
2. The range within which the samples fall, R.
3. The average of the samples, $\bar{x}$.

Method No. 3 is used in this report; the use of methods 1 and 2 is basically the same.

In setting the graphical form of quality control charts, 25 or more samples have to be taken at random to obtain a good estimate for the population parameters. The statistics $\bar{x}$ and s will never have exactly the same values as the parameters (3).

$$P\,(\bar{x} = \mu / N = \infty) = \frac{1}{\infty} = 0 \qquad 3\text{-}4$$

A range around the parameters can be determined, however, with a certain confidence level, such as:

$$P\,(\bar{x} - u_{\alpha}\hat{\sigma}\, n^{-1/2} \leq \mu \leq \bar{x} + u_{\alpha}\,\sigma\, n^{-1/2}) = 1 - \alpha \qquad 3\text{-}5$$

This expression may be written in a more compact form as follows:

$$P\,(\mu = \bar{x} \pm u_{\alpha}\hat{\sigma}\, n^{-1/2}) = 1 - \alpha \qquad 3\text{-}6$$

where: $\bar{x}$ = sample mean
n = sample size
$\hat{\sigma}$ = population standard deviation
μ = population mean
u is a standard variable defined as U: (0, 1); $u = g(x) = \frac{x-\mu}{\hat{\sigma}}$
$\dot{N}$ designates population with normal distribution

An example of a quality control chart is given in Figure 1. The parameters are assumed to be known, and it is also assumed that the population is distributed normally.

In Figure 1, which depicts standard quality control (Q.C.) chart, test No. 6 falls outside the control limits. The chance to obtain this result when the process is under control is about 5 percent. The trend shown by points 4 and 5, however, is an indication that something went wrong in the process and too much air has been incorporated into the concrete. Preventive action should have been taken immediately after test No. 5.

The quality control can be with two side control limits or only one side control limit, depending on the inspector's interest in the product. For example, in the instance of air content or slump, it is desirable that the product be between two specified values because values higher or lower than those specified will produce unacceptable and defective material. The control limits, however, will guide the producer in his effort to meet the requirements.

With cylinder compressive strength, one is mainly concerned with the limiting lower value, and any material above this value is acceptable. The producer will try, however, to keep his average quality as low as possible as long as he meets the required quality, and by doing so save on cement.

Once the specification limits and percent defectives are set (based on engineering decision), the producer will try to meet the requirements with minimum cost involved so that, naturally, producers with low variability in production will be able to offer lower prices in their respective bids.

Because testing will be done on small-size samples usually, there is always a chance for sampling error and a special allowance is needed. If such an allowance is not made, tests will be rejected because the average of samples reading happens to be poorer than the process average. Practical allowance is one which involves maximum risk of making an error of two or three times out of 100 because of sampling fluctuations. Actually, the chance of rejection is smaller because the quality of the lot will be usually good and not a borderline case.

The factor used in making this allowance for sampling errors is given by:

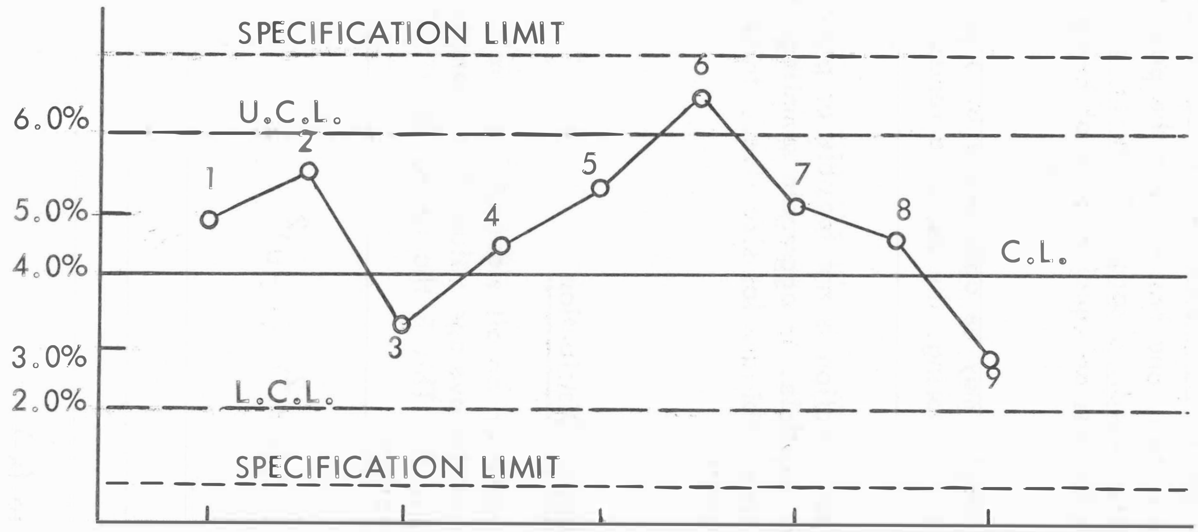
$$\frac{2\sigma_1}{(n)^{1/2}}$$

and

$$\text{L.C.L.} = \text{Lower specification limit} + \left(3.1\sigma - 2\frac{\sigma}{\sqrt{n}}\right)$$

$$\text{U.C.L.} = \text{Upper specification limit} - \left(3.1\sigma - 2\frac{\sigma}{\sqrt{n}}\right).$$

CONTROL OF AIR CONTENT IN CONCRETE



Sample Number

U.C.L. - Upper Control Limit
L.C.L. - Lower Control Limit
C.L. - Central Line ($\bar{x}$)
U.C.L. $= \bar{x} + 2\sigma$
L.C.L. $= \bar{x} - 2\sigma$

95% confidence level

Figure 1. Quality Control Chart for Air Content in Concrete

In the last instance, control limits are developed from established specification limits.

Quality control is effective only if the following requirements are met:

1. Random sampling.
2. Normal distribution of material.

To make valid statistical inference on the parameters of the population, which are usually unknown from the sample statistics, one has to meet the probability theory requirements for randomness. In other words, a sample is chosen in such a manner that every individual in the population has an equal chance of being chosen for the sample.

One way in which representative samples may be obtained is by a process called random sampling. To achieve random sampling, the use of a random numbers table is necessary.

In many instances where true random selection is not feasible or practical, an adequate substitute can be found. For example, in aggregate sampling, the random sampling plan is usually based on some arbitrary lot size (i.e., truck load, etc.) rather than on all the incoming materials.

3.6 Normal Distribution

Any production process will show variation on all sides of a central value. Usually, the distribution is symmetrical around the average value of the samples and has a typical bell shape as shown in Figure 2. This is the normal distribution, or Gaussian distribution defined by the function:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \; e^{(-1/2\sigma^2)(x-u)^2} \qquad 3\text{-}7$$

where: u, σ are the parameters
$\pi = 3.14159\ldots$
$e = 2.71828\ldots$

By integration of $f(x)$ from $(-\infty)$ to (x_o),

$$F(x) = \underline{P}(x \leq x_o) = \frac{1}{(2\pi\sigma^2)^{1/2}} \int_{-\infty}^{x_o} e^{-\frac{(x-u)^2}{2\sigma^2}} \, dx.$$

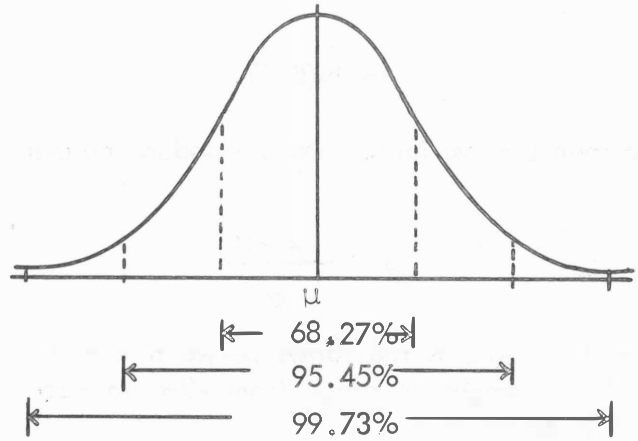


Figure 2. Normal Distribution Curve

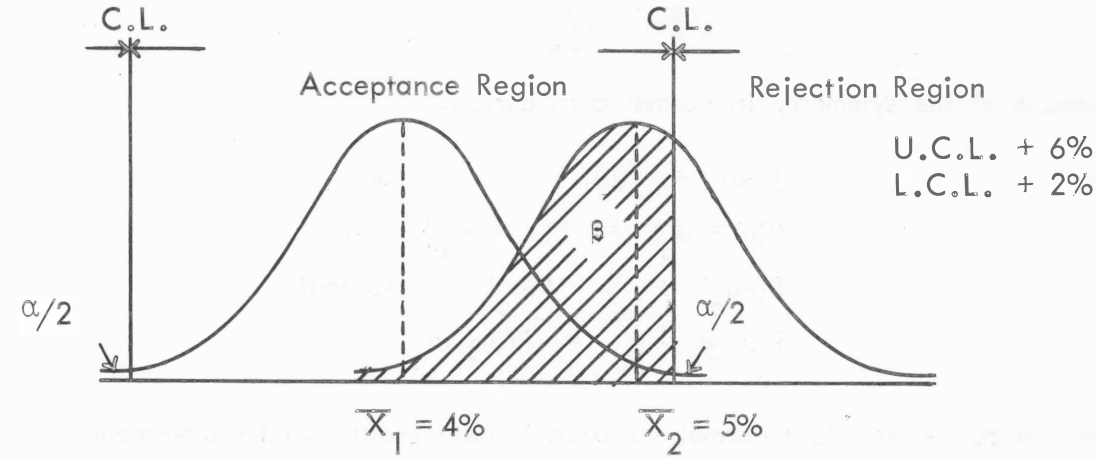


Figure 3. Air Content - Error Type II

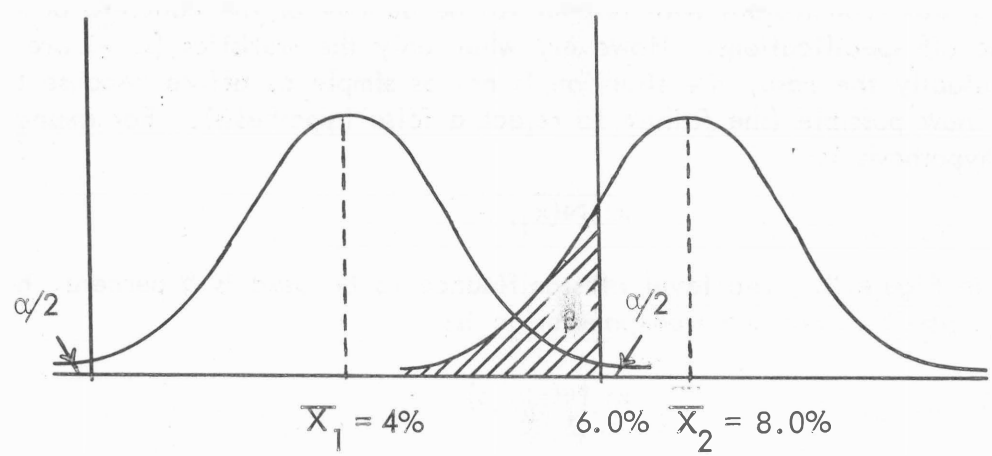


Figure 4. Air Content Distribution - Error Type II

In other words, F(x) is the chance the normal variable x will assume the value $x \leq x_o$. To simplify computations, a standard normal variable is adopted and designated as:

$$u: N(0, 1)$$

It is possible to transform any variable into a standard normal variable as follows:

$$u = \frac{x - \mu}{\sigma}$$

The physical interpretation of u is the range between x and μ expressed by the standard deviation. For example, a range from -2σ to $+2\sigma$ covers 95 percent of the population and u equals two

$$F(u) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} e^{-(u^{2}/2)} du \qquad 3\text{-}8$$

Because of the symmetry in normal distribution,

$$f(-u) = f(u) \qquad \text{or}$$

$$P(u = u_o) = P(u = -u_o) \qquad \text{and}$$

$$F(-u_o) = 1 - F(u_o) \qquad \text{so that} \qquad 3\text{-}9$$

$$P(u \leq -u_o = P(u \geq u_o) \qquad 3\text{-}10$$

The use of the standard normal variable is very useful, and ready-made tables are available (2,3,5).

In every instance where the specifications and the parameters are known, it is possible to draw conclusions with respect to the quality of the concrete or the percentage off specifications. However, when only the statistics (s, $\bar{x}$) are known, which is usually the case, the situation is not as simple as before because Error type II is now possible (the failure to reject a false hypothesis). For example, the null hypothesis is:

$$x: N(\bar{x}_1, s)$$

as shown in Figure 3. The level of significance to be used is 5 percent, however, it is possible that the true population is:

$$x: N(\bar{x}_2, s).$$

Still, there is a chance of β percent that a random sample will be from the acceptance region and the null hypothesis will be accepted when it should be rejected (Error type II). In this instance, translating the statistical language to everyday language, the null hypothesis is that a batch of concrete has 95 percent of its air-content values in the acceptance region, x: N ($\bar{x}_1$ = 4 percent, s = 1 percent), and acceptance test is made from the actual batch which is

$$x: N\,(X2 = 5 \text{ percent},\ x = 1 \text{ percent})\ .$$

There is a chance of 84.1 percent that the sample will be taken from the acceptance region and the batch will be accepted (Error type II). At the beginning, the assumption was that 95 percent of the batch is good; therefore, the loss is to the consumer, or the public, when acceptance of such a poor material is made.

When the distribution of air content in the batch moves further on to the right, assume $\bar{x}$ = 6 percent, s = 1 percent, the chance to make Error type II is smaller, β = 50 percent, and we may accept poor concrete 50 percent of the time. When the batch air-content distribution statistics are $\bar{x}$ = 8 percent, s = 1 percent, the chance that such a batch will be accepted is only β = 2.5 percent as shown in Figure 4.

It is apparent that control chart methods, like all sampling methods, involve sampling risk. Reduction of the risk can be done through increasing the number of samples. Usually, this involves a compromise between the additional cost of sampling and testing on one hand and the saving resulting from the improvement in the average quality of the product on the other hand. Operation characteristics for 15 percent and 10 percent defective materials are represented in Appendix E.

The number of samples to be taken is (based on economic consideration) (28):

$$n = \sqrt[3]{\frac{V \cdot s_\Delta : \hat{\sigma}^2}{2c \cdot \Delta}} \qquad 3\text{-}11$$

where: n = optimum number of samples

V = volume of concrete to be checked and improved, a lot (cubic feet)

$\hat{\sigma}$ = standard deviation, = s. (pounds per square inch)

c = cost per sampling and testing of sample ($)

Δ = the improvement in the average quality of the characteristic (pounds per square inch)

s_Δs = the improvement in the characteristic in one cubic foot, expressed in $

Example: Daily production of concrete - 30,000 cubic feet

$Lot = V = 30,000$ cubic feet

$\hat{\sigma} = s = 600$ pounds per square inch

$c = \$5.0$

$\$ = 0.01$ dollars per cubic foot

$\Delta = 50$ pounds per square inch/cubic feet

From the above data, the required number of samples is given by:

$$n = \sqrt[3]{\frac{(30,000)\ (0.01)\ (600)}{(2)\ (5.0)\ (50)}} = 5.2 \text{ samples}$$

which, translated, means using five samples daily.

It has been already mentioned that with highway materials, 100 percent inspection is impossible. A method has to be adopted by means of which the inspector will be able to draw conclusions with respect to rejection or acceptance of the materials with a certain known assurance that his decisions are correct. It seems that variable inspection is preferable for most practical purposes because it provides the detailed measurements that are so valuable in judging whether or not production conforms to specifications. Therefore, the use of variable sampling is a predominant practice in the highway field.

Practically, acceptance sampling will be based on:

1. Acceptance quality level of defective material, which will be determined on the basis of the specifications in existence and the local experience.

2. Sampling risk desire.

Q_U or Q_L will be determined in the field based on the following equations:

$$Q_U = (U_s - \bar{x}) / s \qquad 3\text{-}12$$

$$Q_L = (\bar{x} - L_s) / s \qquad 3\text{-}13$$

$\bar{x}$ = sample average

s = sample standard deviation

U_s = upper specification limit

L_s = lower specification limit

Q_L = acceptability lower ratio

Q_U = acceptability upper ratio

The table in Appendix F should be consulted for acceptance.

CHAPTER IV

METHOD OF INVESTIGATION

Statistical concepts cover a very large area. Their application, however, to a specific problem may be limited by the very constraints of the problem. To arrive at such a stage, it is imperative to draw from information relative to the distribution characteristics of the materials involved. More specifically, for PCC pavements, the following must be studied:

1. The overall variance existing in the various components of concrete and the type of distributions.

2. The components of the overall variance, $\hat{\sigma}_T$, attributed to testing $\hat{\sigma}_t$, sampling, $\hat{\sigma}_s$, and inherent variability resulting from the process capability of the producer, $\hat{\sigma}_a$, so that $\hat{\sigma}_T^2 = \hat{\sigma}_a^2 + \hat{\sigma}_t^2 + \hat{\sigma}_s^2$.

3. The present sampling and testing procedures.

4. The practicality of present specifications and any possible changes.

Moreover, in concrete one experiences a unique complication because its components have an overall variance of their own. Rather than getting involved in attempting to establish relationships between variances of concrete and its components, highway engineers circumvent the difficulty by testing the components and the finished product separately and comparing measurements to standard specifications established for the components and for the finished product. The standard procedure for the acceptability of both the components and the product has been based on the mathematical description of the measurements expressed in terms of the arithmetic average or mean values. As long as these values fall within a range stipulated by the specifications, the item is acceptable; this, in effect, means that a surficial emphasis has been attached to variability.

Field Problems

To test the applicability of the statistical concepts, three different pavement projects in Oklahoma were selected. In this report, the projects are identified as Project I, Project II, and Project III, respectively. In Projects II and III, slip-form pavers with electronically guided systems were used. The base in all three projects was a hot sand-asphalt mix which had previously been placed by conventional methods. All three projects were continued long enough to permit adequate sampling. The contractor in each instance was different, and so were the sources of his materials. To keep the operator effect constant, both the field and laboratory testing crews were kept the same throughout the entire projects. The properties tested are indicated in Table 1. Where testing of the finished product (concrete) was involved, a set of 50 stations was selected to sample for slump and air content, and another set to sample for concrete cylinder preparation. As shown in Figure 5, no two stations coincided and their selection was based on the standard random talbe (Table 2).

Aggregate materials were sampled from the stockpiles at the central plant. At the bin site, the dry aggregate was weighed and the cement added. This mix was hauled by mixer drum trucks to the construction site, where the concrete was prepared and placed. Because random stations could not be set at the plant, it was assumed that the aggregate materials were being processed from the stockpile into the bins at a continuous and uniform rate. At specified intervals of time, samples were taken at a point in the stockpile nearest the bins. This, in effect, meant that timewise random stations were used.

The cement was sampled from the cement truck at the aggregate bin site before being added to the mixer at intervals of time following the procedure outlined for the aggregates.

TABLE 1

PROPERTIES OF PCC PAVEMENT TESTED

Item	Characteristic	Laboratory Test Designation
Pavement	[a]Thickness	----
Plastic Concrete	[a]Slump	T119-64
	[a]Air Content	T152-63
Cured Concrete	Cement Content	T178-56
	Cylinder Compressive Strength	T22-60
Coarse Aggregate	Grading	M80-61
	Durability	[b]California 229-C
	Passing No. 200	T11-60
	Deleterious Materials	M80-51
	Los Angeles Loss	T96-60
Fine Aggregate	Grading	M6-51
	Fineness Modulus	M6-51
	Passing No. 200	M6-51
	Sand Equivalent	[b]California 217-E
Cement	Alkali Content	M85-49
	Strength	M85-60
	Air Content	M85-60

[a]On-site testing; the rest laboratory tests.

[b]Ref. 44.
AASHO (8) or the equivalent ASTM testing procedures used.

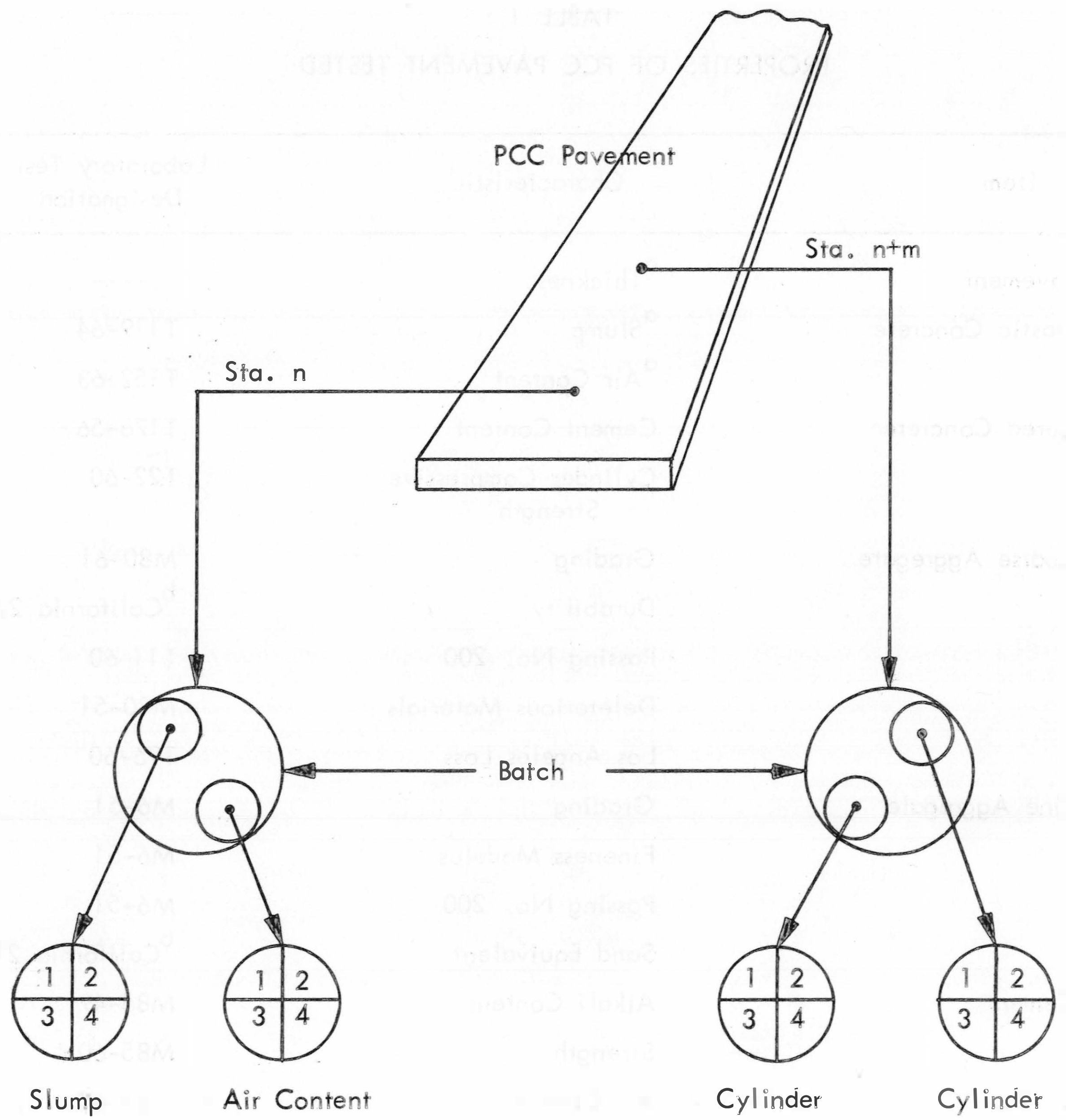


Figure 5. Random Sampling of Fresh Concrete

TABLE 2

RANDOM NUMBERS

51772	74640	42331	29044	46621	62898	93582	04186	19640	87056
24033	23491	83587	06568	21960	21387	76105	10863	97453	90581
45939	60173	52078	25424	11645	55870	56974	37428	93507	94271
30586	02133	75797	45406	31041	86707	12973	17169	88116	42187
03585	79353	81938	82322	96799	85659	36081	50884	14070	74950
64937	03355	95863	20790	65304	55189	00745	65253	11822	15804
15630	64759	51135	98527	62586	41889	25439	88036	24034	67283
09448	56301	57683	30277	94623	85418	68829	06652	41982	49159
21631	91157	77331	60710	52290	16835	48653	71590	16159	14676
91097	17480	29414	06829	87843	28195	27279	47152	35683	47280
50532	25496	95652	42457	73547	76552	50020	24819	52984	76168
07136	40876	79971	54195	25708	51817	36732	72484	94923	75936
27989	64728	10744	08396	56242	90985	28868	99431	50995	20507
85184	73949	36601	46253	00477	25234	09908	36574	72139	70185
54398	21154	97810	36764	32869	11785	55261	59009	38714	38723
65544	34371	09591	07839	58892	92843	72828	91341	84821	63886
08263	65952	85762	64236	39238	18776	84303	99247	46149	03229
39817	67906	48236	16057	81812	15815	63700	85915	19219	45943
62257	04077	79443	95203	02479	30763	92486	54083	23631	05825
53298	90276	62545	21944	16530	03878	07516	95715	02526	33537

CHAPTER V

PRESENTATION OF DATA

The accumulated data from each observation and for each project were run on the computer for the determination of the various statistical parameters which appear in tables 3, 4, and 5. The computer program for the IBM 360/40 is given in Appendix A. For each characteristic tested, three relationships are drawn: the goodness-of-fit curve, the frequency distribution curve, and the quality control chart. Appendixes B, C, and D contain the graphs for Projects I, II, and III, respectively.

5.1 Pavement Thickness

Pavement thickness is an important factor in the design of concrete pavements, and it is considered a part of the acceptance testing program by the Oklahoma Department of Highways, which has developed a payment scale based on thickness measurements. Using a set of straight edges, a thin metal rod was pushed into the freshly placed and finished concrete. Every precaution was exercised to ensure that the metal rod touched the base. Then, the metal rod was pulled out, the depth of insertion indicated on the metal rod measured thus yielding the pavement thickness. It may be argued that this method, as opposed to the core-extraction method of hardened concrete, does not take into consideration the shrinkage that may be expected as the result of hardening. While this is true, it should be emphasized that the amount of shrinkage is extremely small and, for all practical purposes and given the conditions of concrete pavement construction, has very little significance, if any. On the other hand, the method used in this study presents the advantage that corrective measures, whenever necessary, can be effected immediately irrespective of the method used in placing concrete. In addition, the core-extraction method yields the possibility of a paradox whereby the agency (i.e., the Highway Department) controls or supervises indirectly the thickness during construction, but it reserves the right to penalize the contractor later on the ground of insufficient thickness, using as a basis the thickness data of the concrete cores.

The random observations yielded results which indicate satisfactory pavement thickness for Projects II and III, and safe, but uneconomical, for Project I. This may be attributed to the fact that in Projects II and III a slip-form paver was used. The tolerance permitted in pavement thickness is within one-fourth of an inch, less that of the design or prescribed thickness, based on average values. A comparison of the data between Project II and Project III clearly demonstrates the fallacy of

TABLE 3

STATISTICAL PARAMETERS FOR THE PCC PAVEMENT FOR PROJECT I

Item	Characteristics	Number of Observations n	Testing Variance σ_t^2	Sampling Variance σ_s^2	Material Variance σ_a^2	Overall Variance σ_T^2	Overall Std. Dev. σ_T	Arithmetic Mean $\bar{x}$	Specification Provision
Pavement	Thickness, in.	72	----	----	----	0.09	0.3	8.5	8.0 in.
Plastic Concrete	Slump, in.	184	0.16	0.04	0.26	0.46	0.68	2.44	0.5-3.5 in.
	Air Content, %	188	0.08	0.12	0.47	0.67	0.82	4.6	3-6%
Cured Concrete	Cylinder Strength, psi	200	424,640	27,818	0	452,458	673	4288	none
	Cement Content of Hardened Concrete, %	48	27.1	0	14.4	41.5	6.44	101.19	none
Coarse Aggregate	Grading, % Passing 2 1/2-in.	200	All samples finer than 2 1/2 inches in diameter - 100%						
	2-in.	200	59.0	0.0	0.0	59.0	7.7	98.7	95-100%
	1 1/2-in.	200	98.5	0.0	3.4	101.9	10.1	89.7	70-95%
	1-in.	200	94.1	43.7	135.4	273.2	16.5	61.7	50-85%
	3/4-in.	200	82.3	70.2	140.9	293.4	17.1	43.4	none
	1/2-in.	200	51.2	56.7	97.3	205.2	14.3	25.5	15-40%
	3/8-in.	200	28.3	29.6	60.9	118.8	10.9	16.2	none
	No. 4	200	2.5	1.8	2.8	7.1	2.7	3.2	0-5%
	Durability	150	5.8	3.1	0.0	8.9	3.0	77.3	none
	Passing #200, %	200	0.5	0.1	0.1	0.7	0.8	1.2	2% max.

Table 3 (continued)

Item	Characteristics	Number of Observations n	Testing Variance σ_t^2	Sampling Variance σ_s^2	Material Variance σ_a^2	Overall Variance σ_T^2	Overall Std. Dev. σ_T	Arithmetic Mean $\bar{\bar{x}}$	Specification Provision
Coarse Aggregate (cont'd).	Los Angeles Loss, %	163	7.5	0.0	2.0	9.5	3.1	23.9	40% max.
	Deleterious Material	200	Visual observation indicated complete absence of deleterious materials						
Fine Aggregate	Grading, % Passing 3/8-in.	200	All samples finer than 3/8 inches in diameter						100%
	No. 4	200	0.5	0.0	0.0	0.5	0.7	98.9	95-100%
	No. 8	200	1.2	0.0	13.3	14.5	3.8	79.6	none
	No. 16	200	2.5	1.0	2.8	6.3	2.5	62.5	45-85%
	No. 30	200	10.3	0.5	2.5	13.3	3.6	45.5	none
	No. 50	200	3.0	0.4	3.2	6.6	2.6	22.3	5-30%
	No. 100	200	0.6	0.0	0.2	0.8	0.9	4.3	0-7%
	Fineness Modulus	194	0.003	.001	0.007	0.011	0.107	2.86	none
	% Passing No. 200	194	0.52	0.0	1.01	1.53	1.24	4.34	3% max.
	Sand Equivalent	198	2.6	.3	2.8	5.7	2.4	87.8	none
Cement	Compressive Strength, psi	48	19302.67	2684.35	12175.7	34151	184.83	949.42	none
	Air Content	50	0.03	0.01	0.54	0.58	0.77	4.0	none
	Alkali Content	48	0.0012	0.0003	0.0004	0.0019	.043	.245	none

TABLE 4

STATISTICAL PARAMETERS FOR THE PCC PAVEMENT FOR PROJECT II

Item	Characteristics	Number of Observations n	Testing Variance $\hat{\sigma}_t^2$	Sampling Variance $\hat{\sigma}_s^2$	Material Variance $\hat{\sigma}_a^2$	Overall Variance $\hat{\sigma}_T^2$	Overall Std. Dev. $\hat{\sigma}_T$	Arithmetic Mean $\bar{X}$	Specification Provision
Pavement	Thickness, in.	95	----	----	----	0.01	0.1	8.9	9.0 in.
Plastic Concrete	Slump, in.	200	0.13	0.02	0.45	0.60	0.8	1.5	0.5-3.5 in.
	Air Content, %	200	0.08	0.12	0.46	0.66	0.8	4.6	3-6%
Cured Concrete	Cylinder Strength, psi	200	264,694	0.0	254,840	519,534	721	3804	none
	Cement Content of Hardened Concrete, %	48	14.40	0.0	7.99	22.39	4.73	101.73	none
Coarse Aggregate	Grading, % Passing 2 1/2-in.	200	All samples finer than 2 1/2 inches						100%
	2-in.	200	2.7	0.4	0.0	3.1	1.7	97.9	95-100%
	1 1/2-in.	200	26.4	17.9	29.4	73.7	8.6	94.2	70-95%
	1-in.	200	69.2	50.4	68.7	188.3	13.7	62.1	50-85%
	3/4-in.	200	64.6	44.1	47.3	156.0	12.5	45.4	none
	1/2-in.	200	33.5	20.5	19.6	73.6	8.6	20.8	15-40%
	3/8-in.	200	14.1	6.7	12.4	33.2	5.8	9.3	none
	No. 4	200	1.1	0.5	1.6	3.2	1.8	2.2	0-5%
	Durability	156	37.5	3.0	21.9	62.4	7.9	63.3	none
	Passing No. 200, %	180	1.90	0.41	.16	2.47	1.57	1.66	2% max.
	Loss Angeles Loss, %	192	12.2	0.1	5.4	17.7	4.2	29.2	40% max.

Table 4 (continued)

Item	Characteristics	Number of Observations n	Testing Variance σ_t^2	Sampling Variance σ_s^2	Material Variance σ_a^2	Overall Variance σ_T^2	Overall Std. Dev. σ_T	Arithmetic Mean $\overline{X}$	Specification Provision
Coarse Aggregate (cont'd.)	Deleterious Material	200	Visual observation indicated complete absence of deleterious material						
Fine Aggregate	Grading, % Passing 3/8-in.	---	All samples finer than 3/8 inch						100%
	No. 4	200	0.1	0.0	0.1	0.2	0.5	98.7	95-100%
	No. 8	200	0.9	0.3	0.5	1.7	1.3	93.6	none
	No. 16	200	1.4	0.7	2.8	4.9	2.2	80.2	45-85%
	No. 30	200	6.7	0.8	19.0	26.5	5.1	54.6	none
	No. 50	200	4.0	0.0	10.9	14.9	3.9	12.3	5-30%
	No. 100	200	0.1	0.0	0.2	.3	0.6	1.2	0-7%
	Fineness Modulus	203	0.009	0.001	0.012	0.022	0.15	2.60	none
	% Passing No. 200	204	0.18	0.06	0.25	0.49	0.7	1.09	3.0% max.
	Sand Equivalent	200	0.7	0.0	0.1	0.8	0.9	97.6	none
Cement	Comp. Strength, psi	48	56124	7460	13687	77271	277.98	883.88	none
	Air Content, %	44	---	---	---	1.52	1.23	4.84	none
	Alkali Content	48	0.0030	.0003	0.0	0.0033	0.057	0.593	none

TABLE 5

STATISTICAL PARAMETERS FOR THE PCC PAVEMENT FOR PROJECT III

Item	Characteristics	Number of Observations n	Testing Variance σ_t^2	Sampling Variance σ_s^2	Material Variance σ_a^2	Overall Variance σ_T^2	Overall Std. Dev. σ_T	Arithmetic Mean $\overline{X}$	Specification Provision
Pavement	Thickness, in.	100	----	----	----	0.2	0.4	9.0	9
Plastic Concrete	Slump, in.	200	.25	.09	.46	.80	.89	2.76	0.5-3.5 in.
	Air Content, %	200	.08	.04	.14	.26	0.5	4.7	3-6%
Cured Concrete	Compressive Strength, psi	200	153486	1868	439308	594662	771	4238	none
	Cement Content of Hardened Concrete, %	48	22.0	0.63	6.3	28.95	5.38	101.75	none
Coarse Aggregate	Grade, % Passing 1 1/2-in.	200	All samples finer than 1 1/2 inches						100%
	1-in.	200	18.04	3.56	184.05	205.65	14.3	91.1	50-85%
	3/4-in.	200	49.4	37.1	292.5	379	19.5	61.3	none
	1/2-in.	200	45.0	50.7	269.6	365.31	19.1	28.2	15-40%
	3/8-in.	200	29.5	20.9	110.1	160.5	12.7	14.9	none
	No. 4	200	3.4	1.6	1.6	6.6	2.6	1.9	0-5%
	Durability	200	16.0	0.0	141.5	157.5	12.6	83.6	none
	Passing No. 200, %	200	0.11	.06	0.17	0.34	0.58	0.94	2% max.
	Los Angeles Loss, %	200	2.32	.31	12.9	15.5	3.9	24.7	40% max.

Table 5 (continued)

Item	Characteristics	Number of Observations n	Testing Variance σ_t^2	Sampling Variance σ_s^2	Material Variance σ_a^2	Overall Variance σ_T^2	Overall Std. Dev. σ_T	Arithmetic Mean $\overline{X}$	Specification Provision
Fine Aggregate	Grade, % Passing 3/8-in.	200	All samples finer than 3/8 inches						100%
	No. 4	200	0.55	0.0	192.6	193.2	13.9	97.1	95-100%
	No. 8	200	1.06	0.0	173.3	174.4	13.2	91.8	none
	No. 16	200	29.07	0.95	116.9	146.8	12.1	74.2	45-85%
	No. 30	200	25.9	5.8	58.0	89.7	9.5	45.9	none
	No. 50	200	5.1	0.14	13.3	18.5	4.3	17.9	5-30%
	No. 100	200	0.71	0.0	0.74	1.5	1.2	3.4	0-7%
	Fineness Modulus	200	0.01	0.001	0.146	0.157	0.400	2.56	none
	% Passing No. 200	200	1.6	0.0	1.7	3.3	1.81	4.22	3% max.
	Sand Equivalent	200	6.05	1.57	129.9	137.5	11.7	72.9	none
Cement	Compressive Strength, psi	48	19590	0.0	4506	24096	155	859	none
	Air Content, %	48	0.10	.0006	.002	0.103	.32	5.05	none
	Alkali Content	48	.0004	0.0	.0002	.0006	.03	0.22	none

average-values philosophy. In Project II, the specified thickness was 9.0 inches, the arithmetic mean 8.9 inches, and the standard deviation 0.1 inch. In Project III, the corresponding values were 9.0 inches, 9.0 inches, and 0.4 inch. Thus, on the basis of average values, Project III is better than Project II, but the standard deviation values indicate that this may not be true.

5.2 Slump

The water-cement ratio has long been recognized as a critical factor in the strength and workability of concrete, and these two properties are said to be reflected in the slump test. Field observations in this study led to the formulation of causes in variations as:

1. Inherent variation in the operation of the water-feeding system.
2. Position of the mixer.
3. Variation in the amount of dry material introduced into the mixer.
4. Variations in the moisture content of sand.
5. Addition of water by the construction crew to produce a more workable mix.

It was observed that when very dry or very wet concrete was produced, the reaction of the field inspector was usually to change the water setting rather than to reject the batch.

The analysis of the data obtained from 50 randomly selected stations, for each project, indicated that the results fit the log normal distribution better rather than the normal distribution. At each station, four observations were made and a point in the quality control chart represents the average of the four observations, thus giving a total of 200. Furthermore, the chart depicts the upper control limit (UCL) and the lower control limit (LCL), based on both single and average values (observations). Those based on average observations gave numerical values equal to the arithmetic mean, $\bar{x}$, $\pm$ the standard deviation, σ. This was obtained from $\bar{x} \pm \frac{2\sigma}{\sqrt{n}}$, where the number of observations, n, equals 4. It was observed that, unless the batch was very wet, the reproducibility was fairly good.

The test is quick and requires a small amount of concrete. However, immediate identification of the factors conducive to an off-specification slump is not possible because of their variety. In all three projects, the arithmetic mean value was within the specification. However, in Project III, the relatively high mean of 2.76 inches, combined with the standard deviation of 0.89, would lead to the opinion that there were times when the slump was larger than the specified upper limit.

5.3 Air Content

The use of air-entraining agents enhances the durability of concrete, but air content above a certain level reduces the strength of concrete. The main sources of variation may be attributed to:

1. Lack of reproducibility in the mixer operation.
2. Variable volume of mixer operation.
3. Variation in mixing time.

While the Department of Highways specifies a mixing time (1 1/2 minutes for mixers less than 21 cubic feet per batch and a minimum of one minute for mixers with a capacity of 21 cubic feet or greater), it is questionable that these times were strictly adhered to. As a result of improper or too much mixing, the concrete yielded variable concentration of the air content in the batch.

The air content of plastic concrete was measured employing a 1/4 cubic foot standard air meter. Using 50 stations and four measurements per station, a total of 200 observations were made for each project. The results indicate that variations within the batch, σs_1, are by far less than those between batches. Thus, it appears that there is a variance inherent in the operation of the air-compound mechanism, rather than in the operation of the air-compound mechanism, rather than in the mixing process. Also, the data $\bar{x} \pm 2\sigma$ indicate that it is possible to conform to current specifications, 3 to 6 percent. Each of the 50 points in the quality control chart represents the average of four observations, as is applicable with the slump, and the UCL and LCL, based on average values, although numerically equal to $\bar{x} \pm \sigma$, are actually $\bar{x} \pm \frac{2\sigma}{\sqrt{n}}$ where $n = 4$.

The Chase air meter was used sparingly and randomly as a secondary control. Because the observations are limited, they are not reported here but they showed tendencies for good correlation between the two methods; however, the chance of hitting a high or low air-concentration spot with the Chase air meter is always high. Therefore, this particular limitation should be borne in mind whenever the Chase air meter is used as a control tool.

5.4 Cylinder Compressive Strength

The data presented for each project relate to the compressive strength of 200 duplicate cylinders (400 total) which were sampled over a period of two to four weeks and cured for 28 days at 95 percent relative humidity. A very popular test, the 28-day compressive strength, is believed to reflect the quality of concrete; however, insofar as quality control practice is concerned, it is recognized as an ineffective test because the results are available at a time when immediate corrective measures, if required, cannot be taken and rejections, if necessary, are impractical. While the 28-day strength of concrete had not been specified (there is no strength requirement in Oklahoma), the mean values of 4288, 3803, and 4238 psi for Projects I, II, and III, respectively, fall within reasonable values. In general, tests for normality showed good fit of the population. The mean values, UCL and LCL, were calculated from $\bar{x} \pm \frac{2\sigma}{\sqrt{n}}$, where n = 1 as each point on the quality control chart represents the average of two readings. A large part of the total variation seemed to result from the handling, curing, and testing methods. This is evident in Project II, where the values of the testing variance and the material variance are very close. To minimize the testing variance, a new test method has to be devised which will not be influenced by the many factors indicated above.

5.5 Cement Content of Cured Concrete

The purpose of this test is to indicate the amount of cement present in a sample compared to the design value; thus, the ratio is expressed as a percentage. In this study, each sample tested represents eight concrete cylinders which, after being tested for strength, were crushed and the total mass by successive quartering was reduced to the required size of approximately 100 gm and tested.

The mean values in all three projects are above 100 percent, but the standard deviation indicates that values of less and more than 100 percent were obtained, which means that some samples were either too lean or too rich.

5.6 Coarse Aggregate

The coarse aggregate, which consisted of crushed stone, was tested for grain-size distribution, including percent passing U.S. Standard sieve No. 200, durability, Los Angeles loss, and presence of deleterious materials. The latter was effected by visual examination of the samples and was found satisfactory. While the mean of the percent passing No. 200 was, in Projects I and II, less than the specified value of 2 percent maximum, the overall standard deviation for Project II indicates that there were instances where the specification was violated. In Project III, the mean value of 4.22 percent indicates that there was an excess of fine material passing No. 200 sieve.

The durability of the coarse aggregate, as indicated by the data obtained from the California test, gave high and, therefore, satisfactory values. Also, the standard deviations were small. The results of the Los Angeles abrasion test are satisfactory for all three projects, primarily because a rather high value of 40 percent is specified as the maximum limit. It should be borne in mind that the inherent variability depends entirely on the quality of raw material and its location at the quarry.

The gradation analyses indicate that the mean values $\bar{x}$ for each sieve size fell within the specification limits. This may accrue from the fact that the coarse aggregate is well controlled prior to being used. On the other hand, the UCL and the LCL, which represent $\bar{x} \pm 2\sigma_T$ values at 95 percent confidence level, fall at times outside the specification limits.

5.7 Fine Aggregate

River sand, washed and screened, was used as fine aggregate in the three projects. Gradation specification provisions, including UCL and LCL, were satisfactorily met. The amount passing the No. 200 sieve was satisfactory in Projects II and III, while in Project I it was slightly above specifications. This is probably due to the fact that, in Projects II and III, the fine aggregate was preprocessed, i.e., control was exercised during the initial production stage. While the projects did not include provisions for fineness modulus and sand equivalent, the values obtained seemed logical and satisfactory. Assuming that this may be applicable always, it is conceivable that the fineness modulus test may suffice as a single control as long as the same source of fine aggregate is used.

5.8 Cement

One of the important ingredients of concrete is, of course, Portland cement. The tests conducted for cement were compressive strength, air content, and alkali content. While no specification provisions were set for each project in this study, the values obtained for the air and alkali content fall within generally accepted values. The compressive strength data show a unique characteristic in that they are lower than 1200 psi (Type I, 3-day strength). This difference can possibly be explained by the fact that the cement was tested long after (an average lag period of about four months) the samples were taken.

CHAPTER VI

OBSERVATIONS

During this study, a considerable amount of field and laboratory data were obtained. Using the information developed, it is possible to approach the problem of quality control in PCC pavements from a general point of view, although the study, with the exception of the standard tests, was limited to localized conditions.

The main purpose of quality control is quality assurance and, thus, the problem becomes one of quantifying quality. In the concrete-paving industry, one may ask the question "What are the desirable levels and acceptable variation of measured values in individual materials, and in the product in view of the inevitable natural law of variability?" From the implication that statistical methods have to be used to establish realistic requirements of quality, it becomes evident that the capability of the production or better of the producers involved will bear on the specifications and conversely. This may well lead to establishing regional specifications.

The whole problem of quality control (or quality assurance) may be examined by investigating its three areas of application: sampling, testing, and control criteria. Since it is evident that it is impossible to sample the whole population, the question is reduced to defining the adequate number of samples and the most suitable location of sampling. In the present study, a particular set of design was used. Therefore, there is no real basis of comparison insofar as sampling number and location are concerned. If an opinion has to be expressed, however, it may be stated that the sampling locations seemed logical, but the number of samples taken excessive. It should be borne in mind that the number of samples should be economically and physically feasible. Modern methods have made possible a very rapid construction pace, thus requiring more efficient sampling which is representative. This study has demonstrated that too frequent sampling is expensive, in fact very expensive, and may not necessarily lead to the identification of variations in the product. It has been demonstrated earlier in this report that the number of samples required is partially a problem of economics.

Insofar as aggregates are concerned, there is a school of thought which promotes the idea that sampling of aggregates should take place at the batching bin. It seems that this is too late because the purpose of quality control is to prevent the use of undesirable or unacceptable aggregate as early as possible. Therefore, it seems logical that early detection can be effected if the stockpiles are sampled.

Testing and control criteria may be discussed together because they are closely interrelated. It seems that a new philosophy of quality control should permeate the highway industry. Along with the acceptance of the concept of quality assurance, there is a need to exercise control at the control system first rather than in the product. This constitutes one of the major conclusions made as a result of this study. While there was no opportunity to study the proposed philosophy, there is no doubt that producers will have to effect the quality control, and it is expected that they will be responsive to this new attitude once they realize that it is to their benefit.

In re-examining the standard procedures employed in this study, it became apparent that some tests are antiquated and some cannot be used as a criterion to pinpoint the errors, if any. As a specific example, it may be argued that lack of compliance with a specified slump may be attributed not only to an improper water-cement ratio, but also the the shape of the aggregates assuming that the proper amounts of aggregates were used.

Rapid on-site tests lend themselves to more meaningful corrective actions than laboratory tests after some lapse of time. In this study, instead of using the Oklahoma test of measuring the pavement thickness (by extracting a core after the pavement has been cured), a simple test was used, as stated earlier in the report. There were instances where, upon the request of the contractor, the thickness data were made available which enabled him to correct the error immediately. On the other hand, the cement-content test of cured concrete was run in the laboratory long after the pavement was laid, and a low percentage, such as 92 percent, provides no basis for corrective action. Field test procedures have been suggested, and their adoption should be carefully considered. The same argument can be proposed for the 28-day, cured concrete, cylinder strength test. A 24-hour test has been suggested, but it seems that is does not accomplish the goal of control; it rather, as the 28-day test, may serve as a means of penalizing the contractor if the actual product does not comply with the desirable product. Meanwhile, a considerable section of the pavement has been laid. Relevant to this is the exploration of new testing methods, such as introduction and employment of non-destructive tests.

One of the problems involved in the acceptance or rejection of aggregates, both coarse and fine, is the complication which arises in a situation where only one of the sieves is out of specifications. Another problem arises if an average point falls within, but very close to, the specification limit. This means that the variability reflected by the standard deviation, σ_T, is such that some observations (more than the ones predicted by the confidence level) may have to fall outside the specification limits. Likewise, a zigzagging curve within the specification limits is not qualitatively the same as a smooth curve which is coincident with the average specification line. Thus, it appears that specifying the upper and lower limits of the gradation curve is not adequate to produce uniform results. Tighter specifications do not seem to be the plausible answer. Therefore, some thought should be given to the possibility of incorporating into the specifications some realistic maximum deviation from the mean of the upper and lower limits. These limits can well be established using $\bar{x} \pm 2\sigma$ values once the capability of the best producer for the job is determined, again in terms of the $\bar{x} \pm 2\sigma$ values. This is of great significance since the design of satisfactory concrete mixes is partly based on the gradation of the aggregate (6).

The fineness modulus (FM) of aggregate can be easily computed once the gradation is available. Thus, it is a very inexpensive "test." Also, since the fineness modulus represents in some index form a composite effect, it is highly probable that it lends itself into a correlation between either the sum total of all the sieves used or any one of them. A regression analysis may serve to establish a regression coefficient between FM and the amount passing a certain sieve size. The mathematical expression will result in the form:

$$FM = A + R_c B$$

where: FM = fineness modulus
A = an intercept
R_c = regression coefficient
B = percent passing a certain sieve size

Furthermore, it may be possible to establish a similar expression including all the sieves used. In that instance, the mathematical expression will be:

$$FM = A + R_{c_1} \circ B_1 + R_{c_2} \circ B_2 + \text{--} R_{c_n} \circ B_n$$

where: FM = fineness modulus
A = an intercept
$R_{c_1}, R_{c_2}, R_{c_n}$ = regression coefficients corresponding to amount passing individual sizes
B_1, B_2, B_n = percent passing sieve sizes

It is envisioned that some sieves will show good correlation and others better or poorer. The regression coefficients may be positive or negative.

Once such correlations are proven to exist, it may become unnecessary to use seven sieve sizes to obtain the gradation of the aggregate. Two or three sieve sizes may suffice because the equations given above can act as reference to establish the gradation picture of the aggregate. While these statements are speculative at this time, they may lead to a shorter and, therefore, less expensive procedure for gradation evaluation.

Presently, specifications are based on average (mean) values, and rejection-acceptance methods follow this philosophy without any consideration to variance. This possibly leads to gross errors between actual quality and presumptive quality. Also, it may pave the way for uneconomical designs if compliance of simple observations and measurements with safest limits are strictly enforced.

A word needs to be said about the cement tests. While cement is a very important ingredient in concrete, its manufacture is apparently closely controlled and, thus, the product is very uniform. Therefore, it is recommended that cement tests be abolished from the overall program. The quality of cement is very well reflected in the tests which are run at the cement-manufacturing plant by the manufacturer. A visual examination seems to be sufficient to detect poor storage procedures and carbonation, if any.

REFERENCES

1. Neville, A. N., Properties of Concrete. John Wiley and Sons, New York. 1963.

2. Ostle, B., Statistics in Research. Iowa State College Press, Ames, Iowa.

3. R. Moave Science Faculty. Foundation of Statistical Analysis. Hebrew University of Jerusalem. Fourth ed. 1960.

4. Enrick, N. L., Quality Control. The Industrial Press, New York. Fourth ed. 1962.

5. Crown, E. L., Davis, F. A., and Maxfield, M.W., Statistics Manual. Dover Publication, Inc., New York.

6. Enrick, N. L., Hughes, C. S., Statistical Quality Control in Highway Engineering and Construction. Virginia Council of Highway Investigation and Research, Virginia. Second ed. 1965.

7. Miller - Warden. Effect of Different Methods of Stock Piling Aggregates. Highway Research Board of the Division of Engineering and Industrial Research National Academy of Sciences. National Research Council. 1964.

8. Nur, E. A., Designing Specification - A Challenge Journal of Construction Division. ASCE. Vol. 91, pp. 29-44. May, 1965.

9. Freudenthal, A. M., Reflection on Standard Specifications for Structural Design. ASCE Transaction. Vol. 113, pp. 269-293.

10. Ross, H. C., Uniformity of Concrete on the Average Job. ACI Journal. 1936.

11. Blanks, R. F., Concrete Quality Controll. Proceedings, Building Research Congress, Division 2. London, 1951.

12. Quality of Concrete in the Field. Committee on the Quality of Concrete in the Field. Institution Research Committee. London, England, 1953.

13. Maxon, G., Quality Concrete for Highway Construction with Central Mixing Plant. H. R. Bull, December, 1956. pp. 1-10.

14. Howard, E. L., Control and Inspection of Ready Mixed Concrete. Rock Production. Vol. 59, No. 6, pp. 229-232. June, 1956.

15. Maxon, G., Suggested Quality Control Method for Highway Concrete, Road and Streets. Vol. 99, No. 7, pp. 72-78. July, 1956.

16. Rusch, H., On the Statistical Quality Control of Concrete. Materia Lprufung (VFI Verlag-Gabh, Bandgardstr, 3 Dusseldorf 10, Germany). Vol. 6, No. 11, pp. 387-394. November, 1964.

17. Blaht, H., Statistical Quality Control in Concrete Construction. Beton-Herstellung and Vernedung (Dusseldorf) Vol. 11, no. 12, pp. 804-805. December, 1961.

18. Tremmel, E., Wogrin, A., Mathematical - Statistical Evaluation of Quality Testing of Mass Concrete. Der Bauingenieur (Berlin) Vol. 30, No. 1, pp. 28-32. January, 1955.

19. ACI Committee 214, Evaluation of Compression Test Results of Field Concrete. ACI Journal. Vol. 27, No. 1, pp. 241-259. November, 1955.

20. Nur, E. A., Tuthill, L. H., Criteria for Modern Specification and Control. ACI Journal. Vol. 55, pp. 759-768. January, 1959.

21. Nur, E. A., How Good is Good Enough? ACI Journal. Vol. 59, No. 1, pp. 31-47. January, 1962.

22. Improved Quality Control in Highway Construction, Baker, R. F., Office of Research and Development, U.S. Department of Commerce, B.R.P., Washington, D. C., January, 1963.

23. Lammi, T., Application of Statistical Quality Control of Concrete. Laboratories of Concrete Technology, State Institute for Technical Research. Helsinki, pp. 45, 1962.

24. Korin, A., In the Field of Building. Building Research Station. Israel Institute of Technology, Bulletin No. 117, September, 1964.

25. Volin, M. E., Park B., Problems in Sampling Gravel Aggregate. 49th Annual Convention of the National Sand and Gravel Association. Hotel Americana, Miami Beach, Florida. January 28, 1965.

26. Hanna, S. J., McLaughlin, J. F., Lott, A. P., Application of Statistical Quality Control Procedure to Production of Highway Pavement Concrete. Purdue University, Lafayette, Indiana, 1966.

27. Quality Control and Acceptance Specifications. Highway Conference on Research and Development of Quality Control and Acceptance Specification. Washington, D. C., Vol. 1, April, 1965.

28. Shea, J. E., Statistical Quality Control for Pavements. National Limestone Institute. Washington, D. C.

29. Tolerances and Payment for Out of Tolerance Work. Construction and Material Conference. Bureau of Public Roads. Atlanta, Georgia. March, 1965.

30. Quality Control of Concrete. ACI Journal. Vol. 59, pp. 975-979. July, 1962.

31. Nur, E. A., Quality Control for Large Highway Projects. ASCE Proceedings. Vol. 84, HW 2, pp. 1926-1. 1926-10. May, 1958.

32. Proposed Revision of Recommended Practice for Evaluation of Compression Test Results of Field Concrete. Report by ACI Committee 214, ACI Proceedings. Vol. 61, No. 9, pp. 1057-1070. September, 1964.

33. Alabama Joint Highway Engineering Conference. Auburn University. April, 1964.

34. Clague, E. J., The Use of Computers in Concrete Control and Specifications. The Surveyor and Municipal Engineer. London. Vol. 125, No. 3788. 1965.

35. McMahon, T. F., The Statistical Approach to Quality Control. Quality Control Task Group, Office of Research and Development, U.S. Department of Commerce, BRR. February, 1964.

36. Blanks, R. F., Chairman of Advisory Committee. Ten-year Report on the Long-Time Study of Cement Performance in Concrete. ACI Journal Vol. 49, No. 49-42, pp. 601-614. March, 1953.

37. Nur, E. A., Control of Concrete Mix. ACI Journal Proceedings, Vol. 55, No. 9, pp. 947-961. March, 1959.

38. Woods, Hubert, Observations on the Resistance of Concrete to Freezing and Thawing. ACI Journal, Vol. 26, No. 51-17, pp. 345-349. December, 1954.

39. Design and Control of Concrete Mix. Tenth ed. Portland Cement Association. 1952.

40. Standard Specification for Highway Construction. Oklahoma State Highway Commission, 1959.

41. Singh, B. G., Effect of the Specific Surface of Aggregate on the Consistency of Concrete. Journal of the American Concrete Institute., Vol. 28, No. 10, pp. 989-997, April, 1957.

42. Walker, S., Bloon, D. L., Gaynor, R. D., Relationship of Concrete Strength to Maximum Size of Aggregate. HRB Proceedings. Vol. 38, pp. 367-385. 1959.

43. Hveem, F. H., Tramper, B., Some Factors Influencing Shrinkage of Concrete Pavements. Journal of American Concrete Institute. Vol. 28, No. 8, pp. 781-789. February, 1957.

44. State of California, Department of Public Works, Division of Highways. Materials Manual, Testing and Control Procedures. Vol. I, No. 7320, Sacramento, California, 1963.

APPENDIX A

Computer Program

```
C      VARIANCE ANALYSIS LAGUROS,CONCRETE QUALITY CONTROL
C      L MUST BE PUNCED AT THE BEGINNING OF EACH SET
C      OF DATA AND MUST DIFFER FROM ZERO IF THE
C      SET IS TO BE EXECUTED(AT THE END OF THE
C      LAST SET L MUST BE READ AS ZERO.
C      A1=0 IDENTIFIES THE LAST SAMPLE OF THE SET
       DOUBLE PRECISION W, Q, T, XT, DUM1, DUM2, DUM3, E
    70 READ(1,800)L
    10 WRITE(3,900)
       WRITE(3,300)L
       WRITE(3,910)
       N=0
       A=0.
       B=0
       C=0.
       D=0.
       YT1=0.
       YT2=0.
       YT3=0.
       YT4=0.
       AT=0
       XT=0
     1 N=N&1
       IF (N-L)3,3,2
     3 READ(1,100)A1,A2,B1,B2
       B=B&(A1-A2)*(A1-A2)&(B1-B2)*(B1-B2)
       AT=A1+A2+AT
       AA=(A1&A2)/2.
       C=C&(A1&A2-B1-B2)*(A1&A2-B1-B2)
       A=A&A1&A2&B1&B2
       BB=(B1&B2)/2.
       CC=(BB&AA)/2.
       D=D&(A1&A2&B1&B2)*(A1&A2&B1&B2)
       YT1=YT1&A1
       YT2=YT2&A2
       YT3=YT3&B1
       YT4=YT4&B2
       XT=XT&A1*A1&A2*A2&B1*B1&B2*B2
       WRITE(3,950)AA,BB,CC
       GO TO 1
     2 CONTINUE
       P=N
       W=YT1*YT1&YT2*YT2&YT3*YT3&YT4*YT4
       Q=((4.*P)*XT-(A*A))/(4.*P)
       T=(4.*W-A*A)/(4.*P)
       E=Q-T
       F=(T*(4.*P-4.))/(3.*E)
       DUM3=A*A
       DUM1=(4.*P)*XT
       DUM2=(A*A)/(4.*P)
       WRITE(3,999)P,A,W
       WRITE(3,1000)XT,W,Q,T
       WRITE(3,1001)DUM1,DUM2,DUM3,E
       WRITE(3,1002)F
```

```
      V1=D/4.-(A*A)/(P*4.)
      SM1=V1/(P-1.)
      SM2=C/(4.*P)
      SGTS=B/(4.*P)
      SGSS=(SM2-SGTS)/2.
      SGAS=(SM1-SM2)/4.
      IF(SGSS)4,4,5
    4 SGSS=0.
      SS=0.
      GO TO 6
    5 CONTINUE
      SS=SQRT(SGSS)
    6 CONTINUE
      ST=SQRT(SGTS)
      IF(SGAS)7,7,8
    7 SGAS=0.
      SA=0.
      GO TO 9
    8 SA=SQRT(SGAS)
    9 CONTINUE
      SGTT=SQRT(SGTS+SGSS+SGAS)
      AM=A/(4.*P)
      ATM=AT/(2.*P)
      WRITE(3,999)SM1,SM2,SGTS
  999 FORMAT(3E20.7)
      WRITE(3,400)
      WRITE(3,500)SGTS,SGSS,SGAS
      WRITE(3,600)
      WRITE(3,700)ST,SS,SA,SGTT
      WRITE(3,710)
      WRITE(3,500)AM,ATM
  100 FORMAT(4F10.2)
  950 FORMAT(F11.5,10X,F11.5,10X,F11.5)
  400 FORMAT(/15X,3HSGT,16X,4HSGSS,16X,4HSGAS)
  500 FORMAT(3F19.5)
 1002 FORMAT(3X,2HF=,F10.3)
  600 FORMAT(/16X,2HST,17X,2HSS,18X,2HSA,16X,4HSGTT)
  700 FORMAT(4F19.5)
  710 FORMAT(/16X,2HAM,16X,3HATM,16X,3HBTM)
  800 FORMAT(I3)
  300 FORMAT(12H SET NUMBER ,I3)
  900 FORMAT(46H VARIANCE ANALYSIS OF CONCRETE QUALITY CONTROL)
  910 FORMAT(48H        AA                  BB                 CC)
 1000 FORMAT(1H ,4(1PD20.14,5X))
 1001 FORMAT(1H ,4(1PD20.14,5X))
      GO TO 70
      END
```

APPENDIX B

Statistical Parameters for Graphs for Project I

No.	Thickness Range %	F	%	Cum %
1	- 8.0	5	6.9	6.9
2	8.1 - 8.5	43	59.7	66.6
3	8.6 - 9.0	19	26.4	93.0
4	9.1 - 9.5	4	5.6	98.6
5	9.6 - 10.0	1	1.4	100.0
		72	100	

n	72
specs	
$\overline{x}$	8.5
σ_T	0.3
σ_t^2	-
σ_s^2	-
σ_a^2	-
v	3.5%

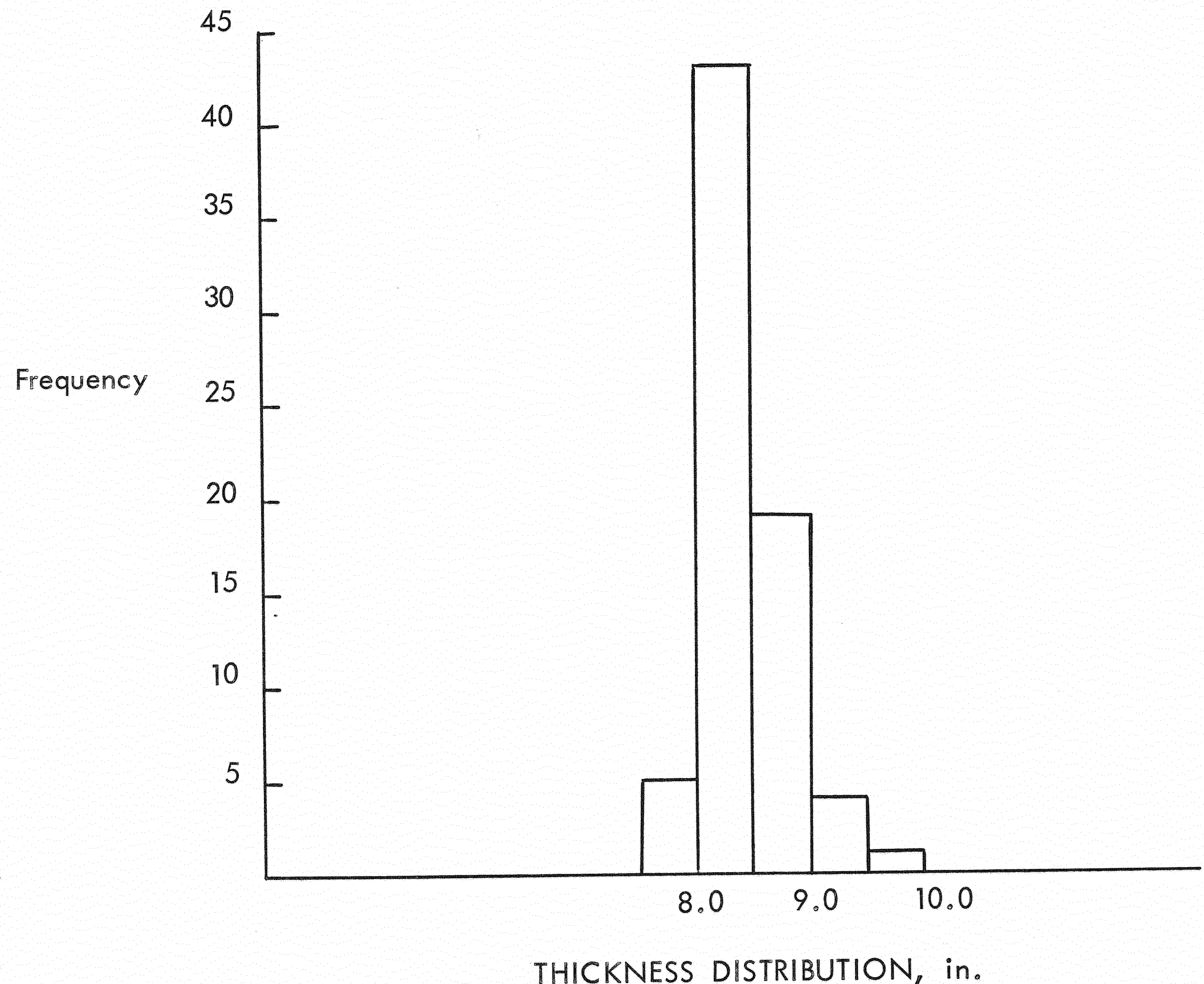


Figure I-6. Thickness - statistical properties

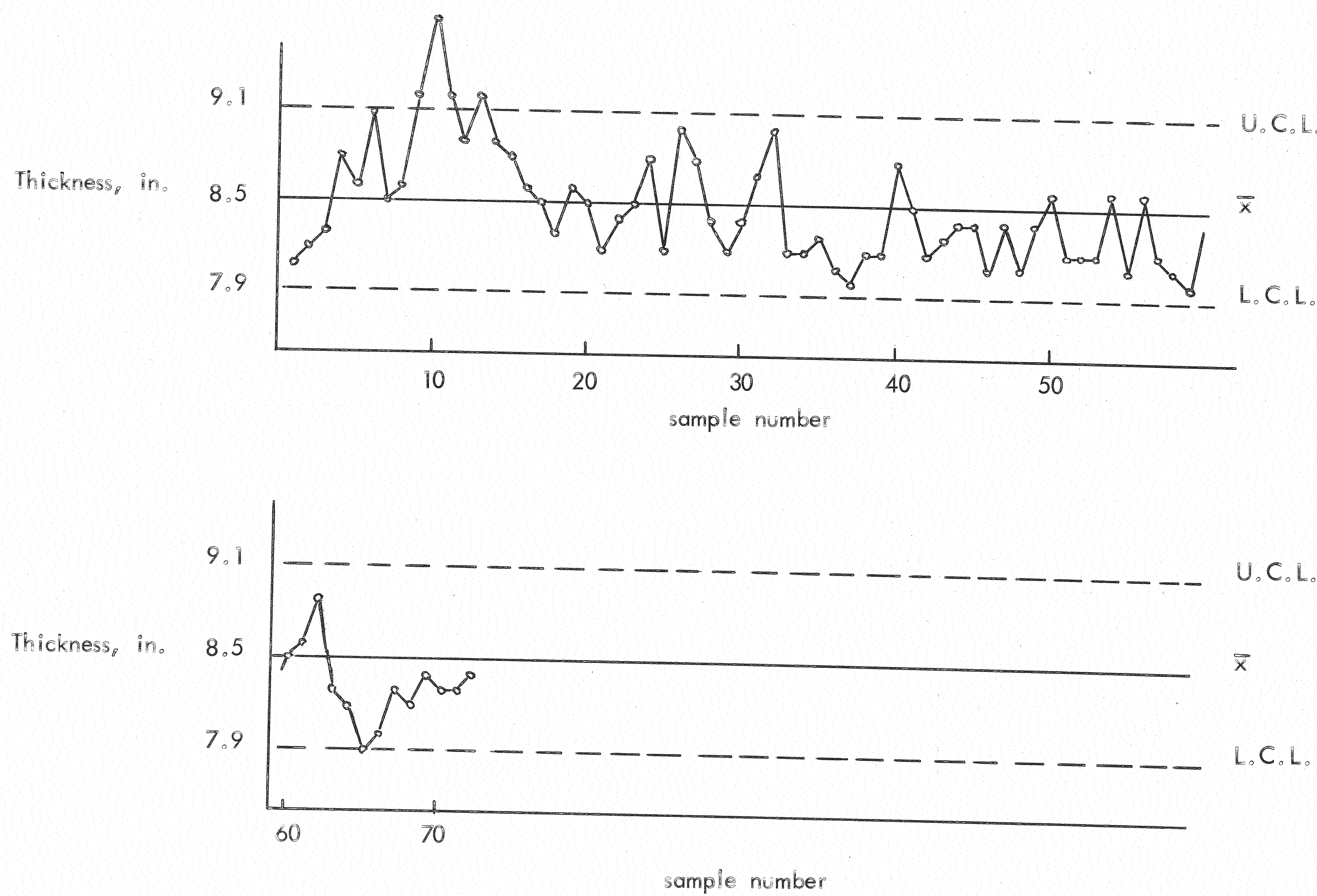


Figure I-7. Thickness - quality control chart

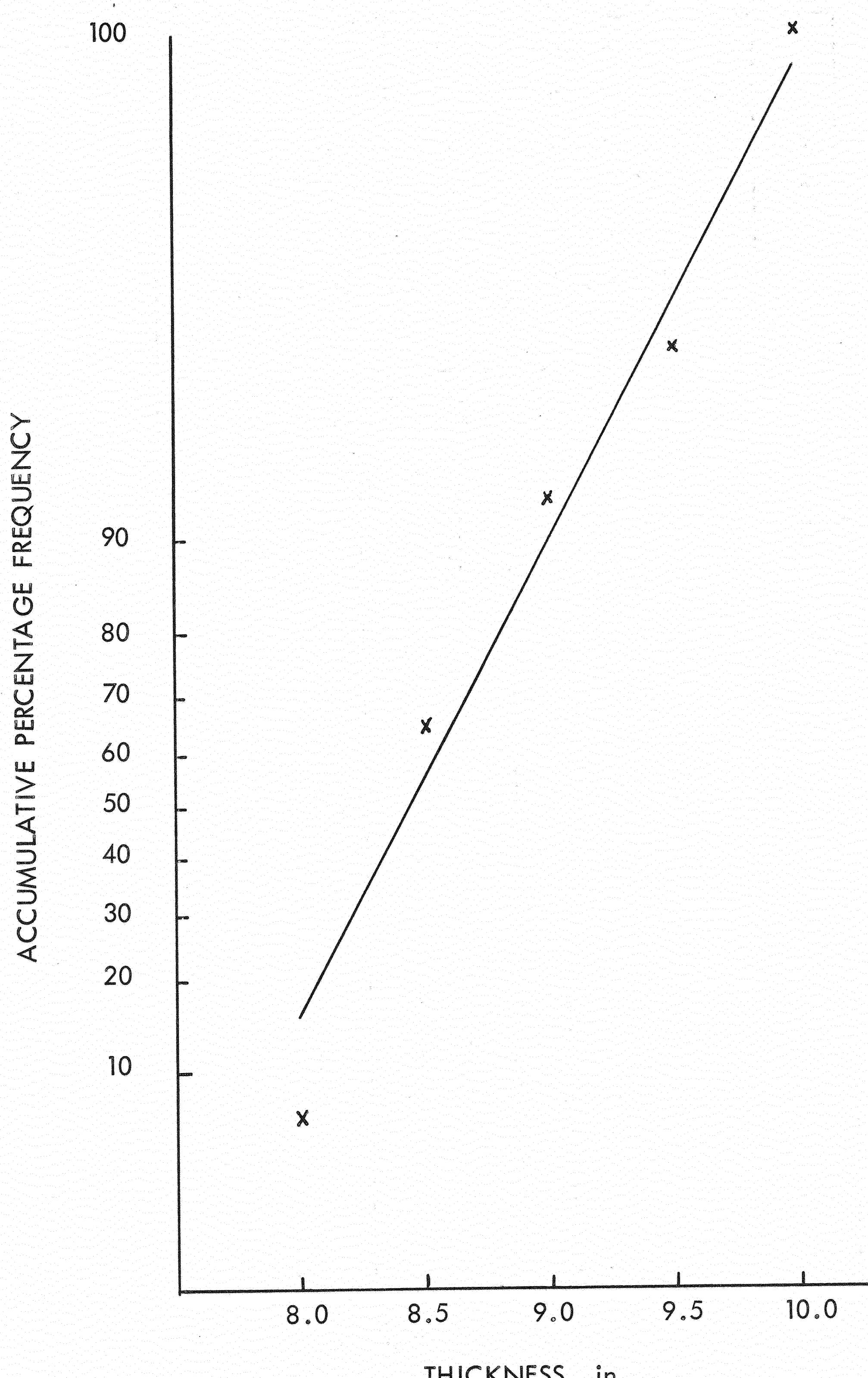


Figure I-8. Thickness - goodness of fit curve

No.	Slump Range (in)	f	%	Cum.%
1	- 1.0	1	0.6	0.6
2	1.1 - 1.5	17	9.2	9.8
3	1.6 - 2.0	43	23.2	33.1
4	2.1 - 2.5	49	26.7	59.8
5	2.6 - 3.0	48	26.1	85.9
6	3.1 - 3.5	14	7.6	93.5
7	3.6 - 4.0	12	6.5	100.0
		184	100.0	

n	184
spec.	0.5-3.5 in.
$\bar{x}$	2.40
σ_T	0.68
σ_t^2	0.16
σ_s^2	0.04
σ_a^2	0.26
v	28.3%

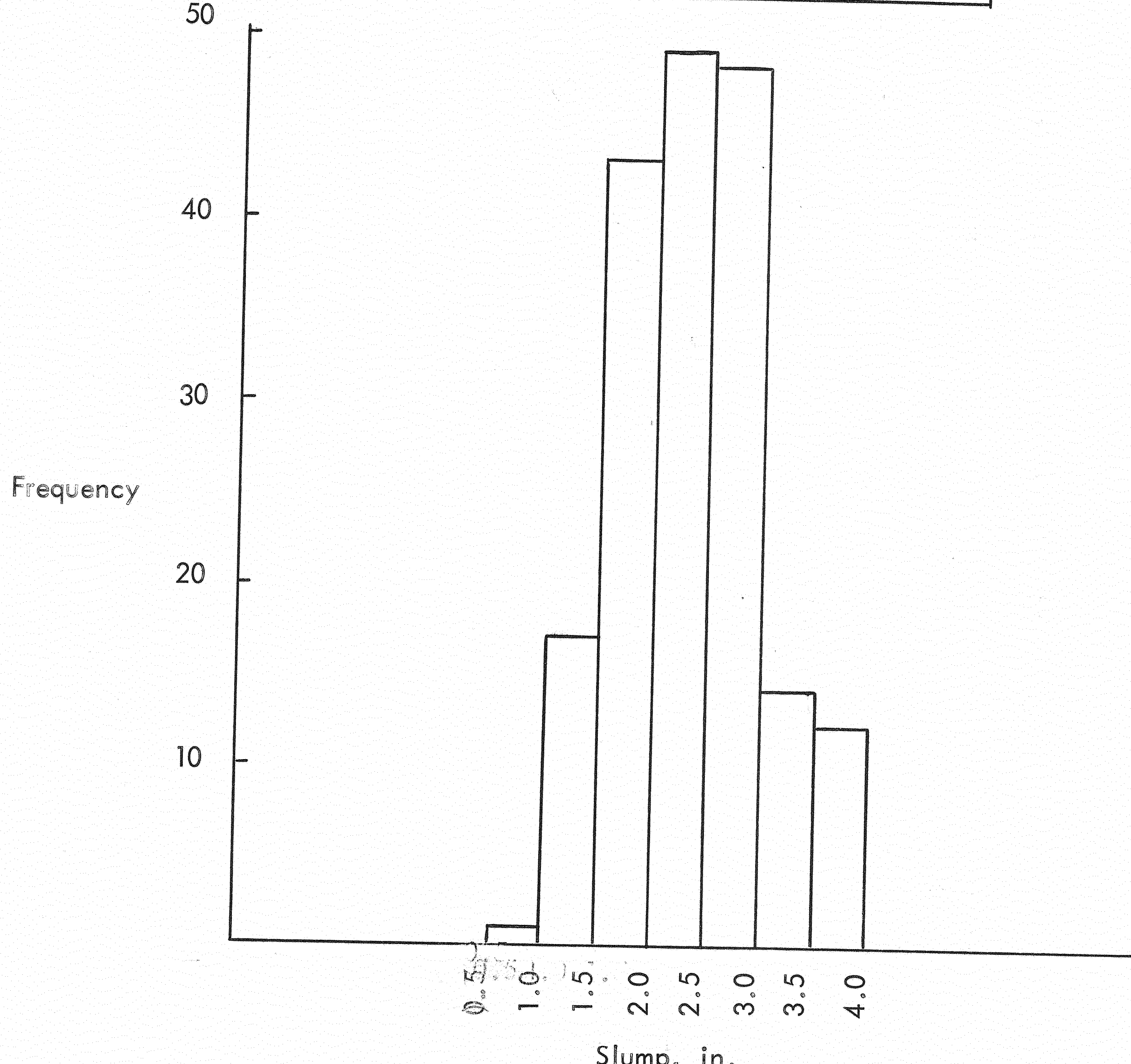
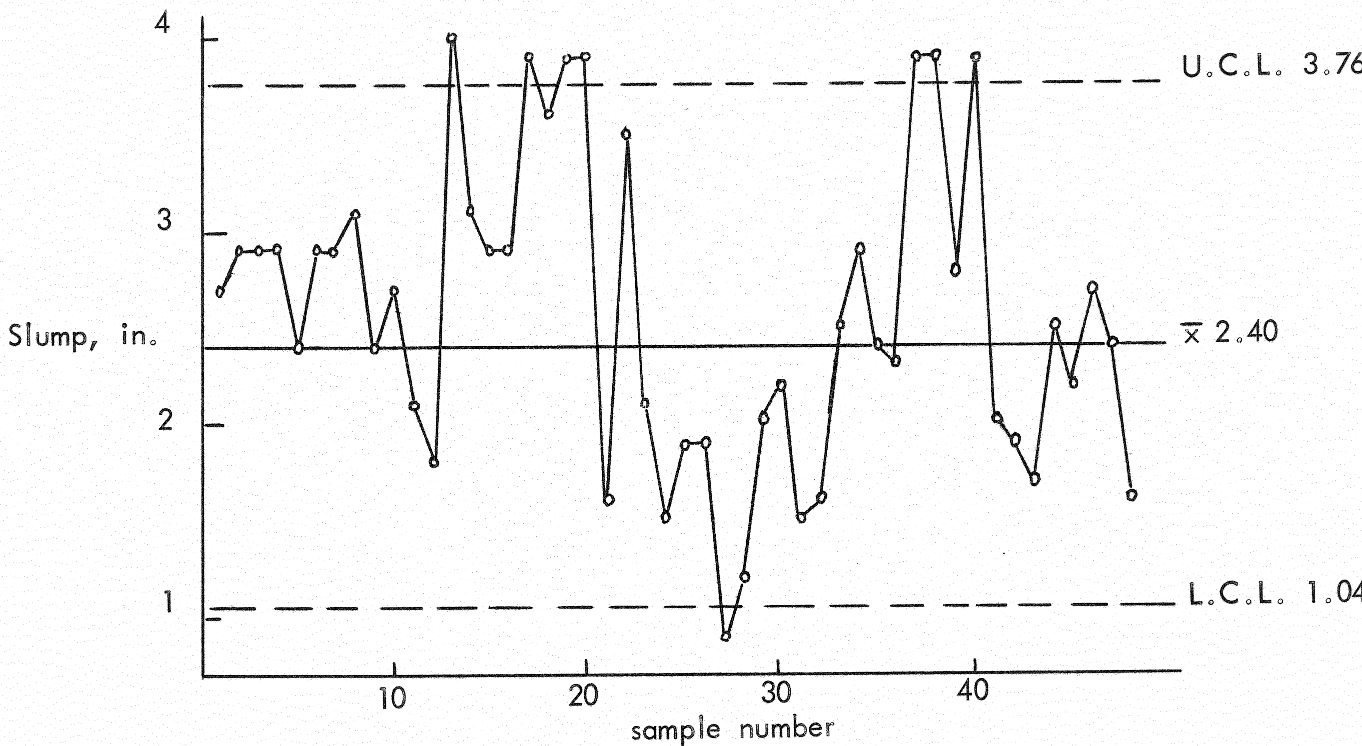


Figure I-9. Slump - statistical properties



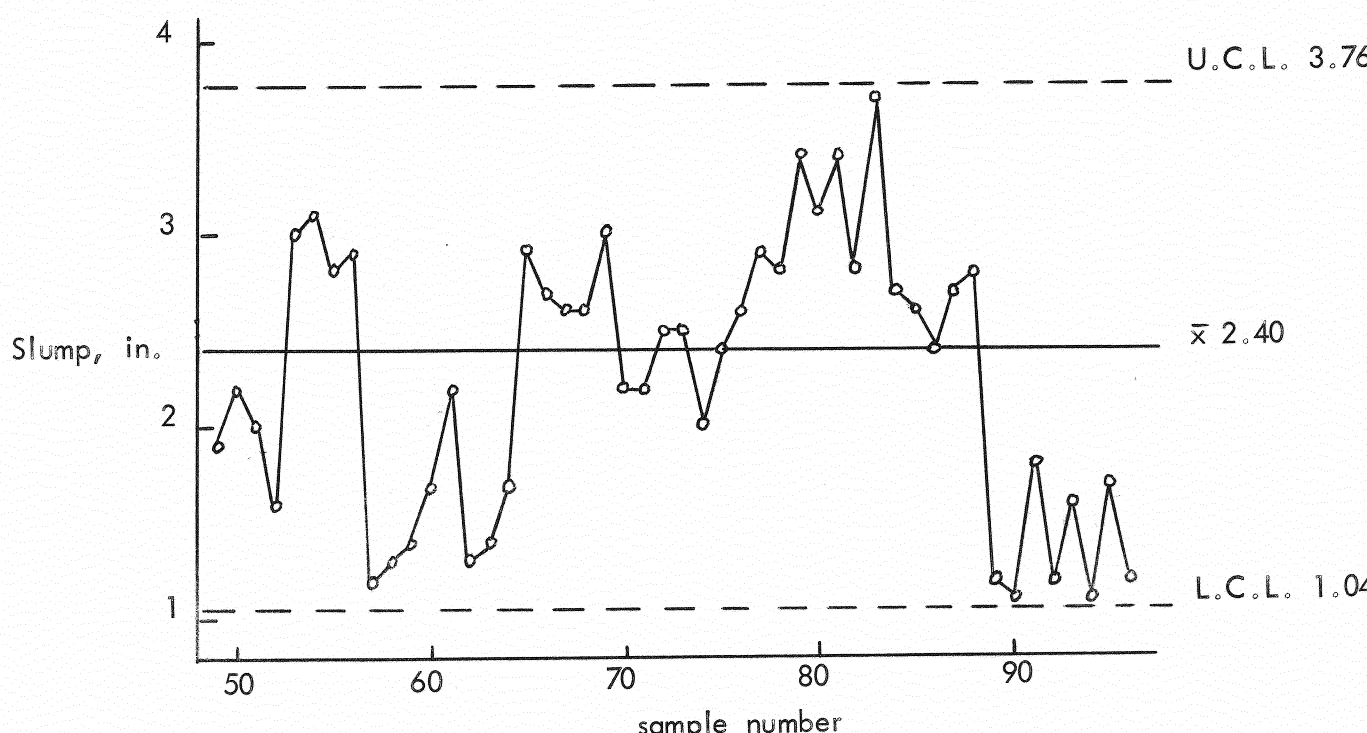
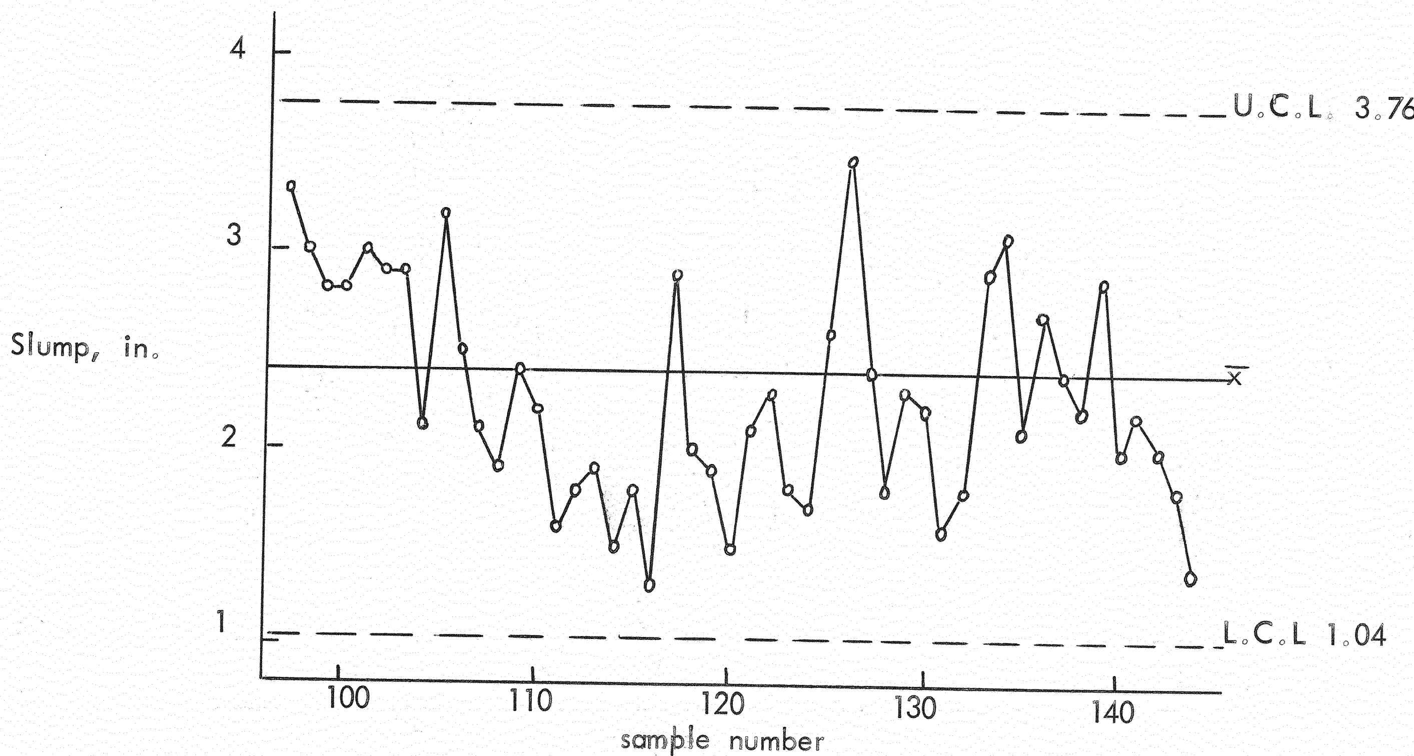


Figure I-10. Slump - quality control chart



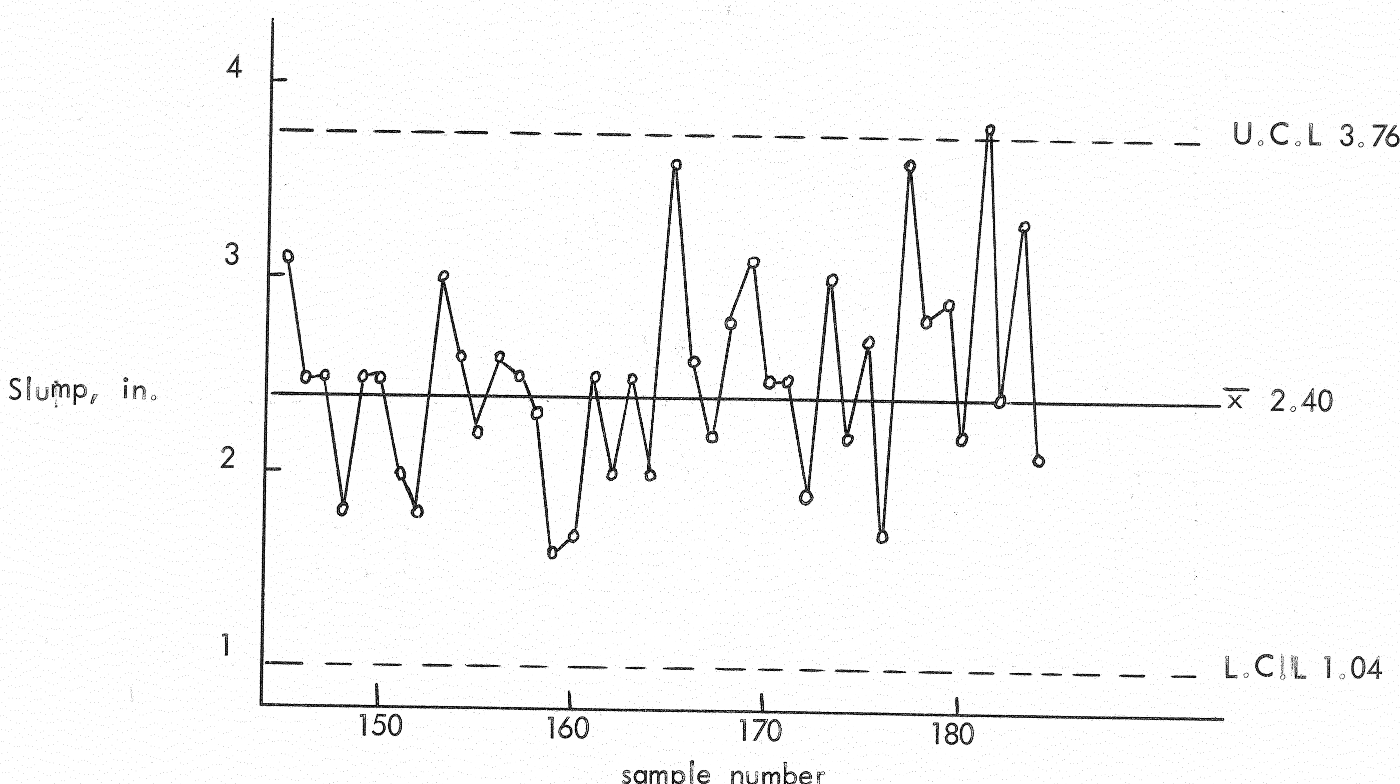


Figure I-10 (cont.) Slump - quality control chart

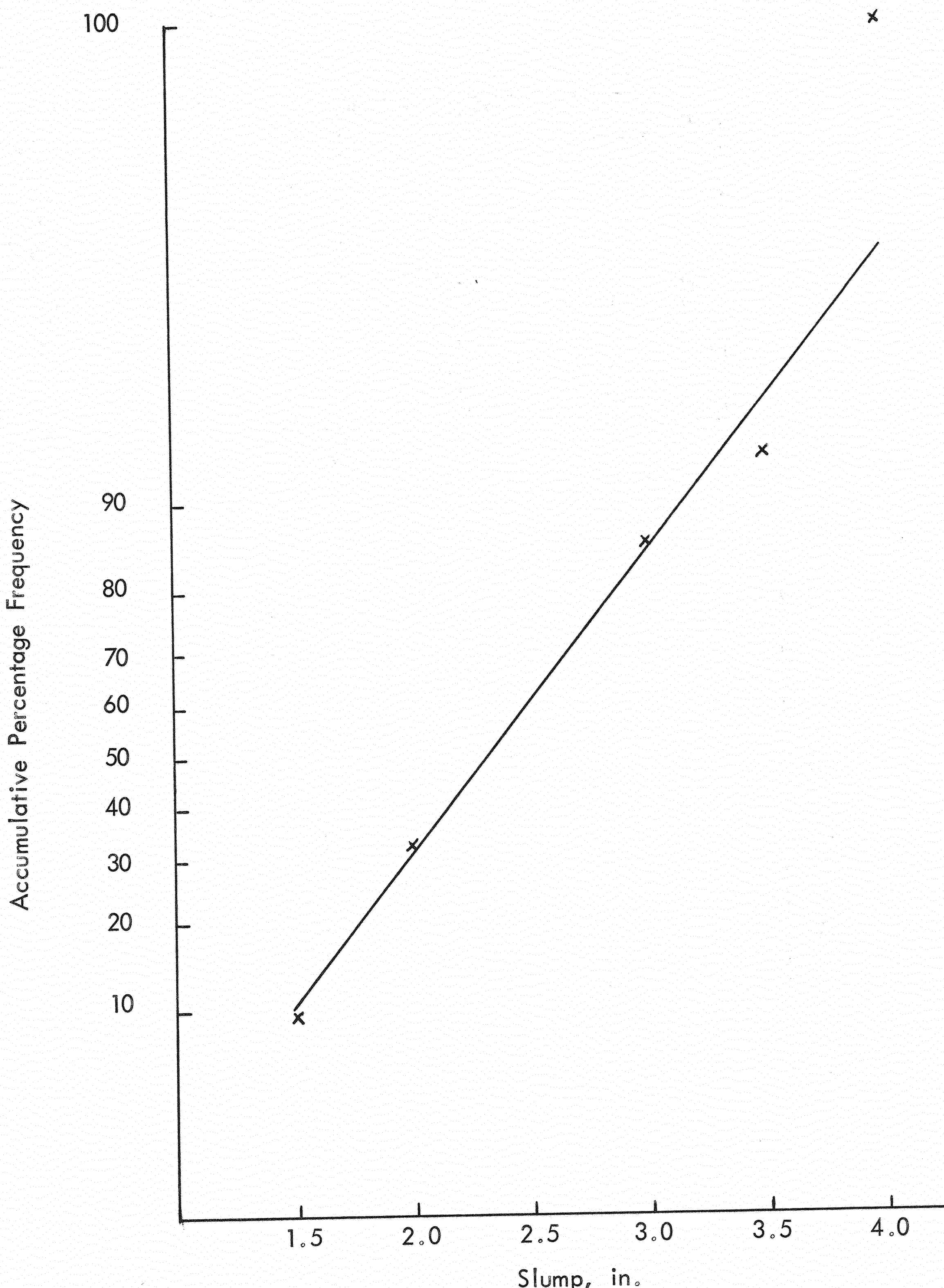


Figure I-II. Slump - goodness of fit curve

No.	Concrete Air Cont. % Range	f	%	Cum. %
1	1.5 - 1.9	3	1.6	1.6
2	2.0 - 2.4	5	2.6	4.2
3	2.5 - 2.9	7	3.7	7.9
4	3.0 - 3.4	12	6.4	14.3
5	3.5 - 3.9	51	27.1	41.4
6	4.0 - 4.4	59	31.4	72.8
7	4.5 - 4.9	32	17.0	89.8
8	5.0 - 5.4	16	8.6	98.4
9	5.5 - 5.9	3	1.6	100.0
		188	100	

n	188
specs.	3-6%
$\bar{x}$	4.6
σ_T	0.82
σ_t^2	0.08
σ_s^2	0.12
σ_a^2	0.47
v	17.8%

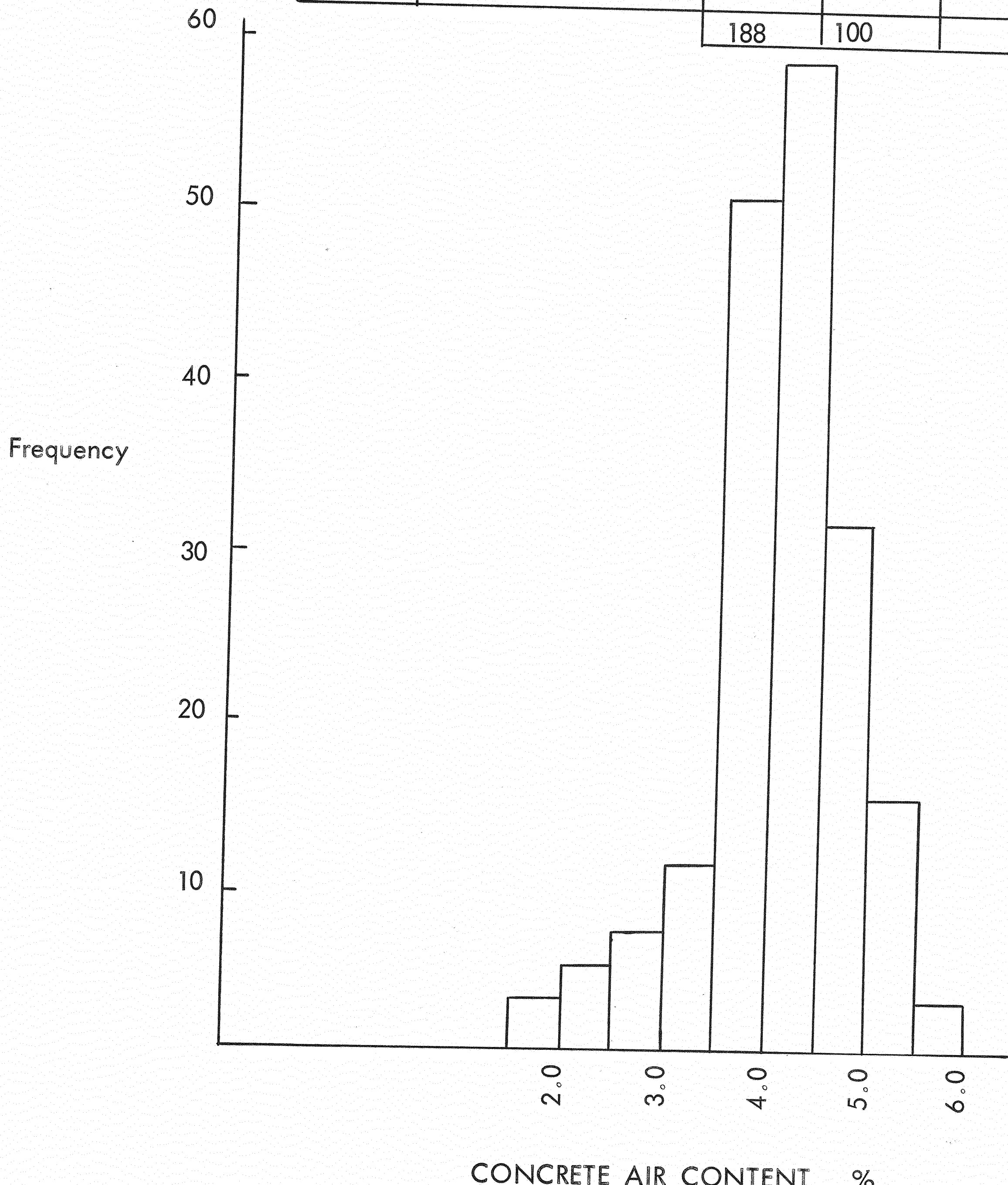


Figure I-12. Concrete air content - statistical properties

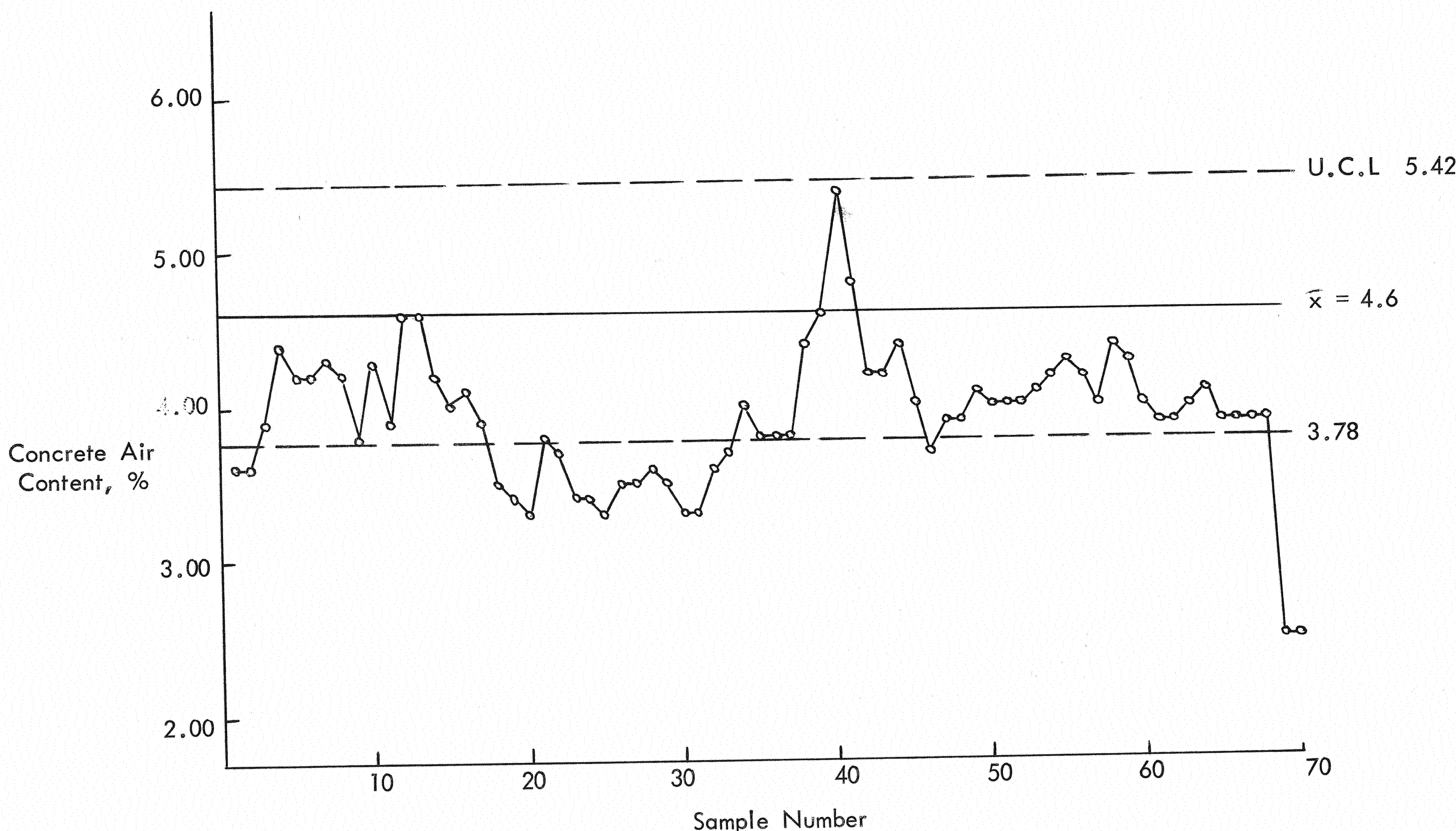


Figure I-13. Concrete air content - quality control chart

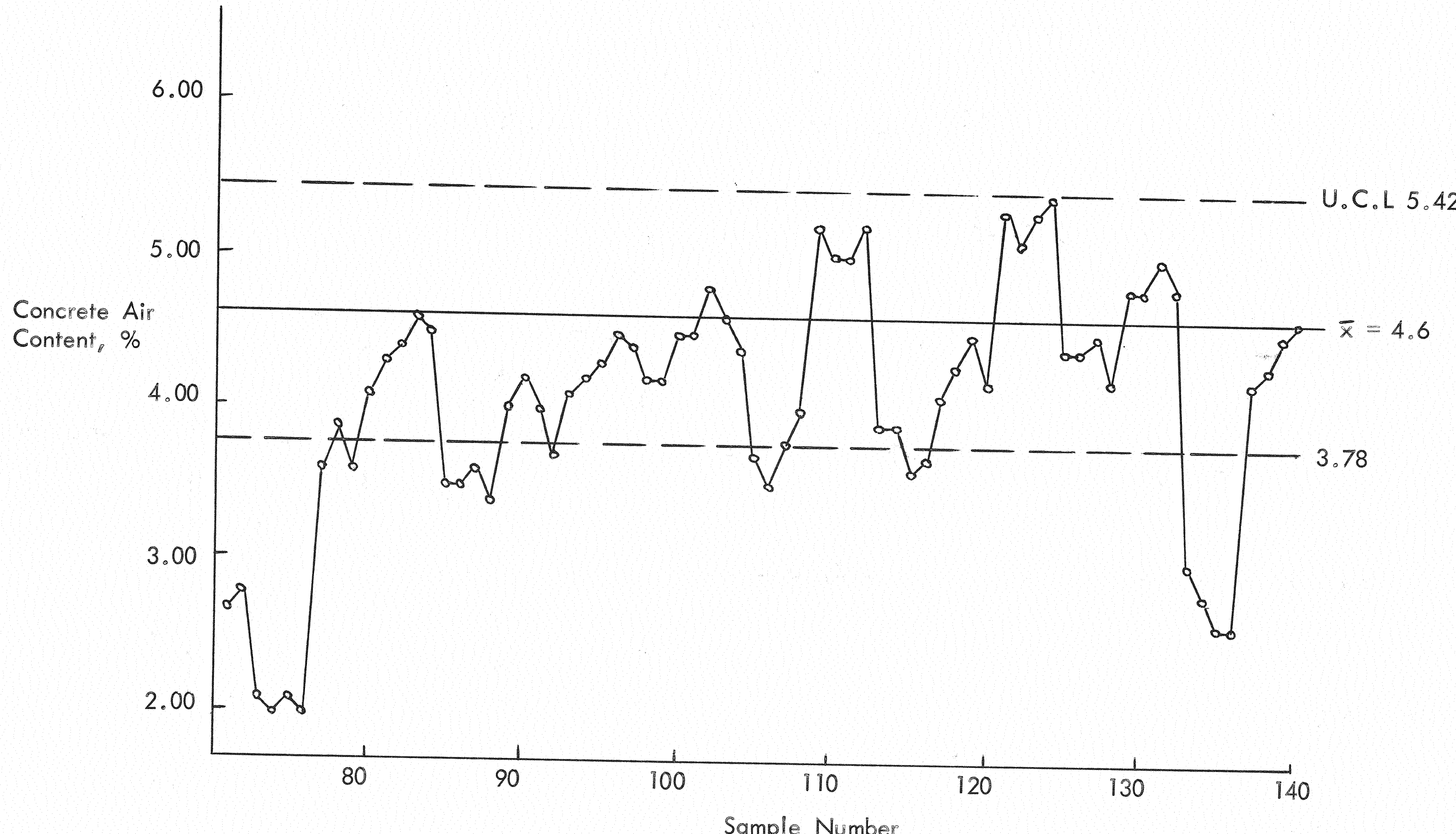


Figure I-13(cont.) Concrete air content - quality control chart

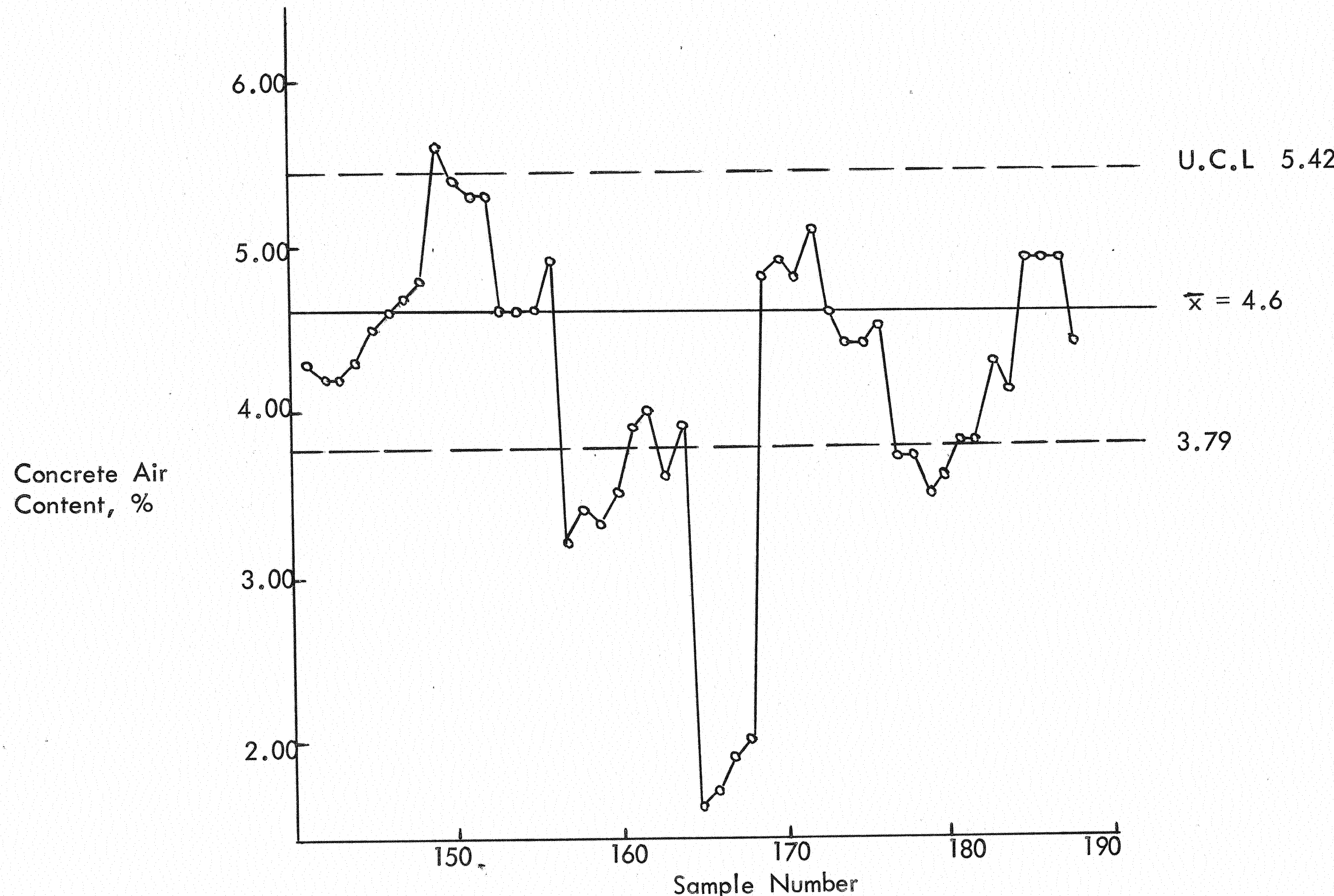


Figure I-13(cont.). Concrete air content - quality control chart

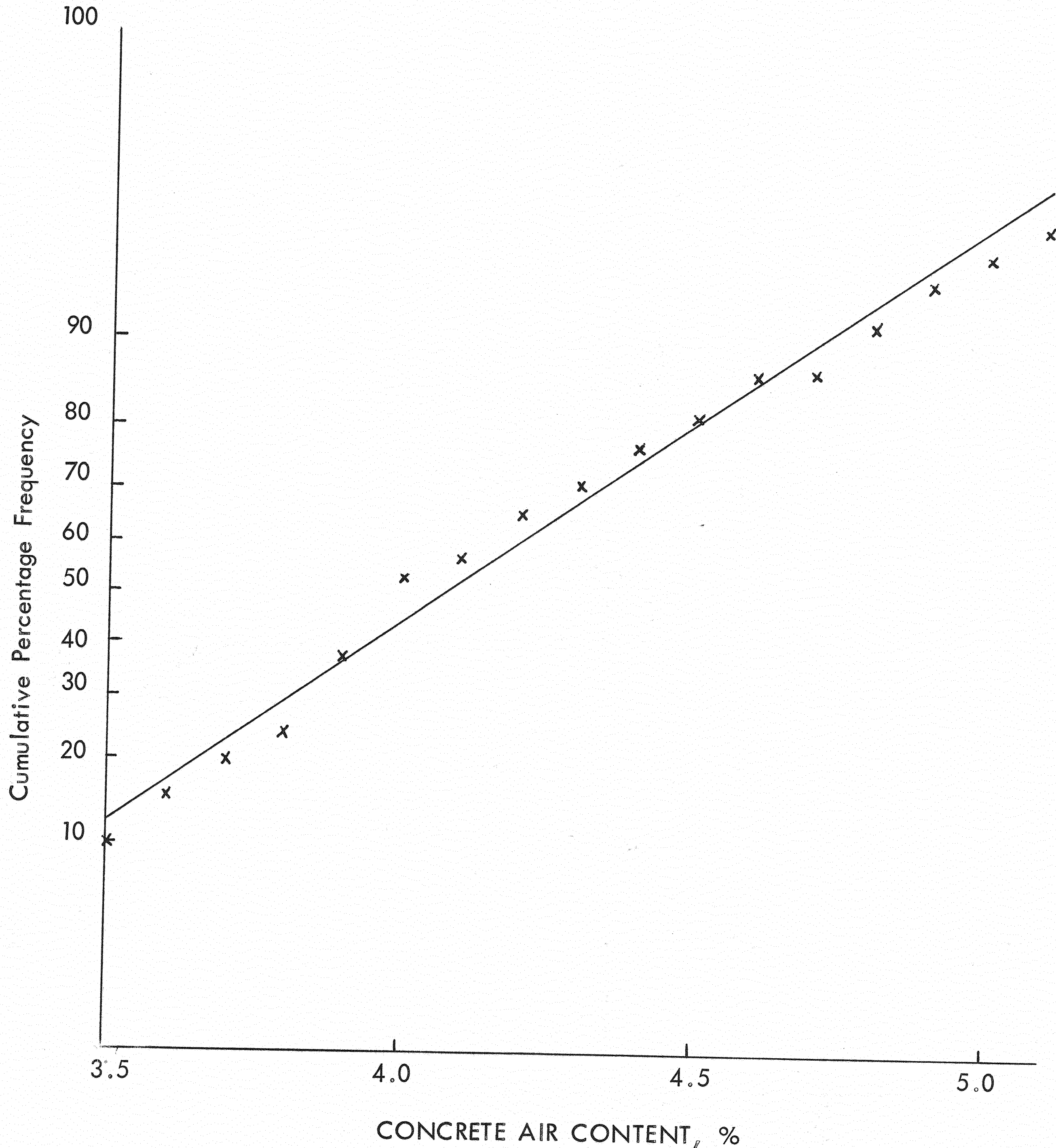


Figure I-14. Concrete air content - goodness of fit curve

No.	Concrete Compr. Strength Range, psi	f	%	Cum%
1	2501 - 3000	6	3	3.0
2	3001 - 3500	27	13.5	16.5
3	3501 - 4000	30	15	31.5
4	4001 - 4500	55	27.5	59.0
5	4501 - 5000	56	28	87.0
6	5001 - 5500	22	11	98.0
7	5501 - 6000	4	2	100.0

n	200
Specs	--
$\bar{x}$	4288
σ_T	673
σ_t^2	424,640
σ_s^2	27,818
σ_a^2	0
v	15.7%

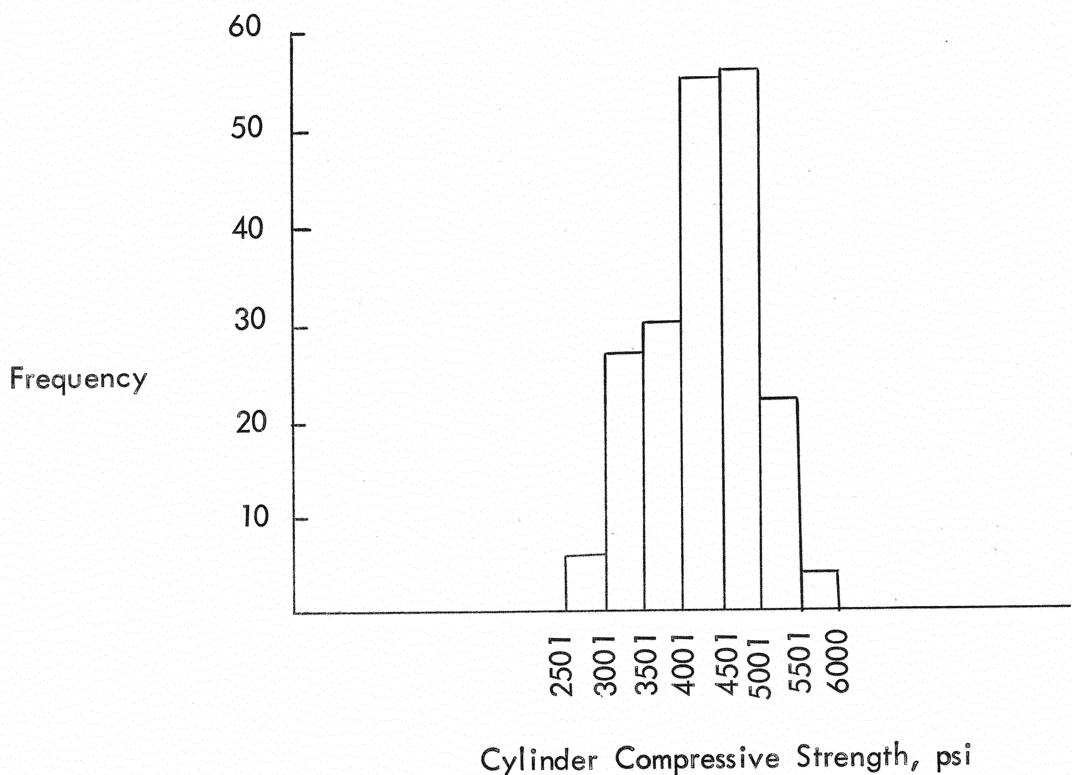


Figure I-15. Cylinder compressive strength - statistical properties

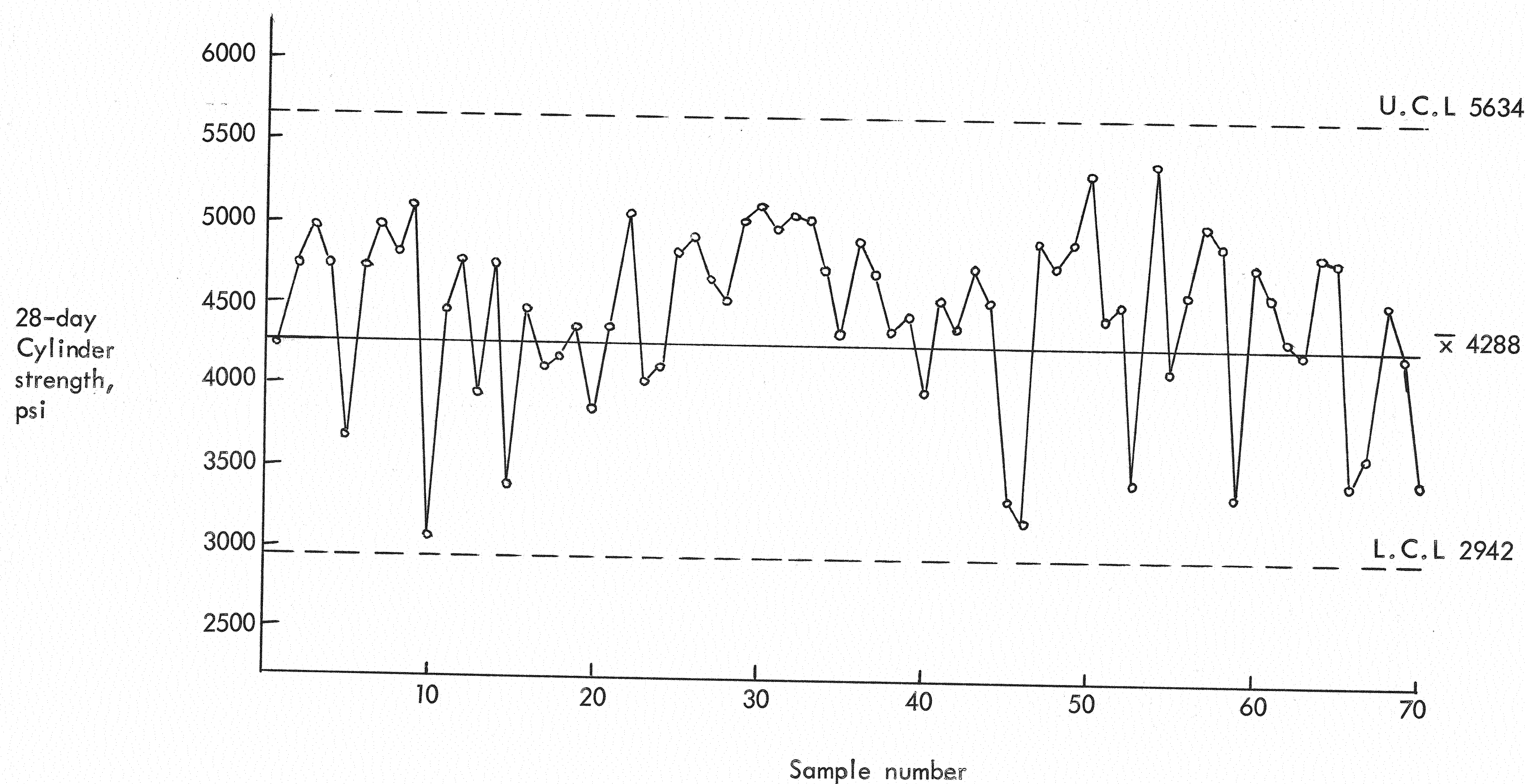


Figure I-16. Cylinder compressive strength - quality control chart

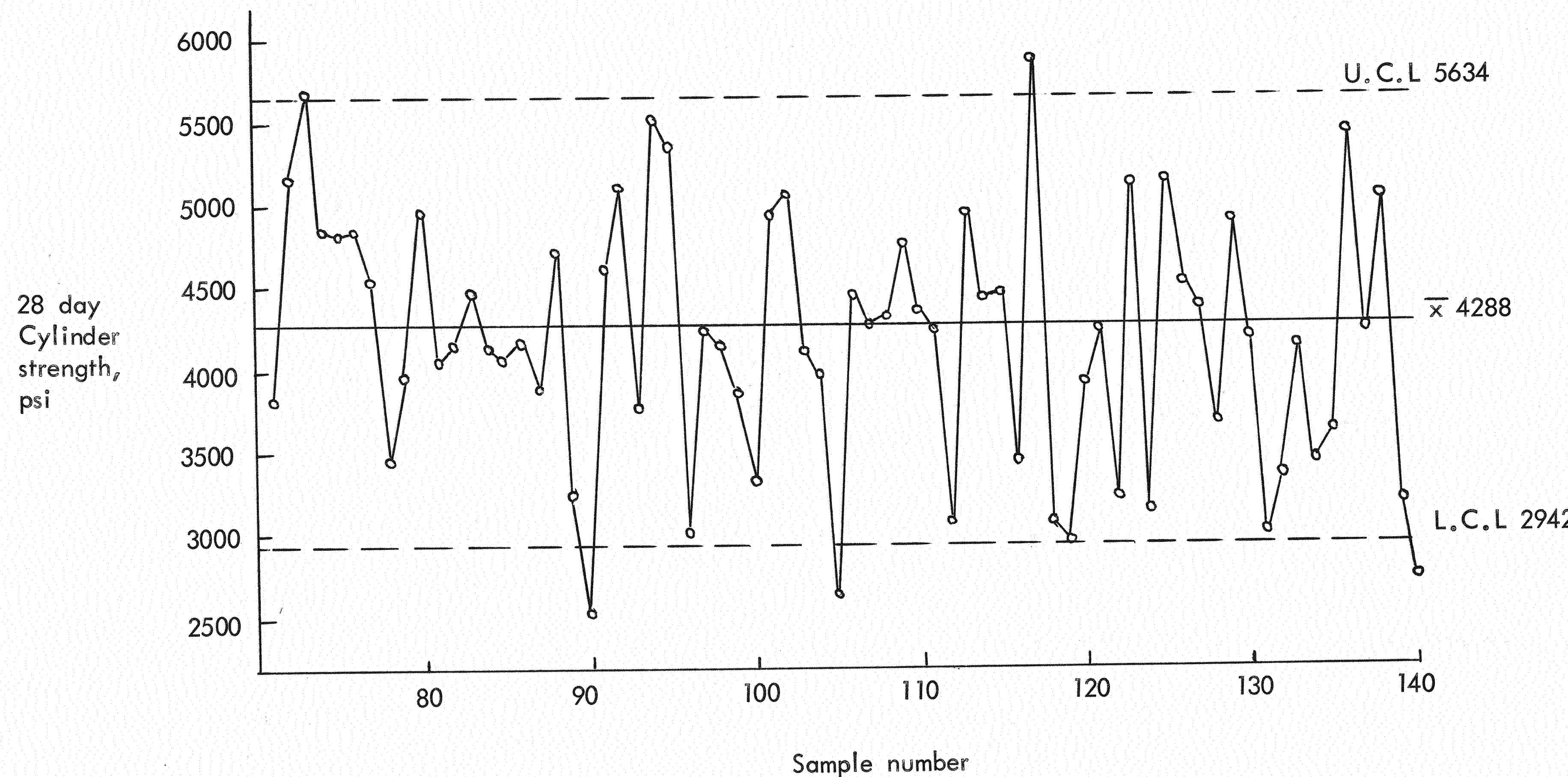


Figure I-16 (cont.). Cylinder compressive strength - quality control chart

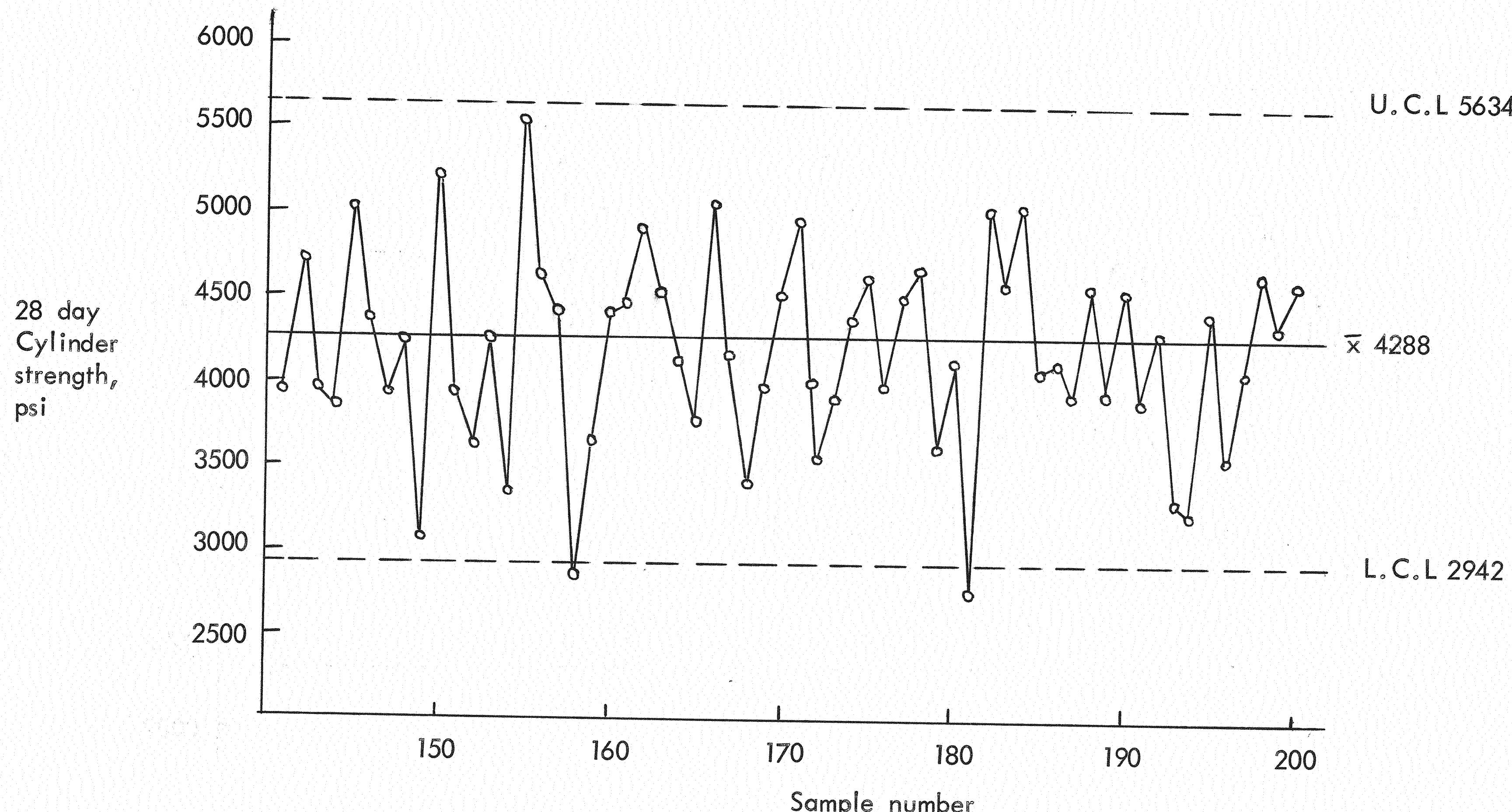


Figure I-16(cont.). Cylinder compressive strength - quality control chart

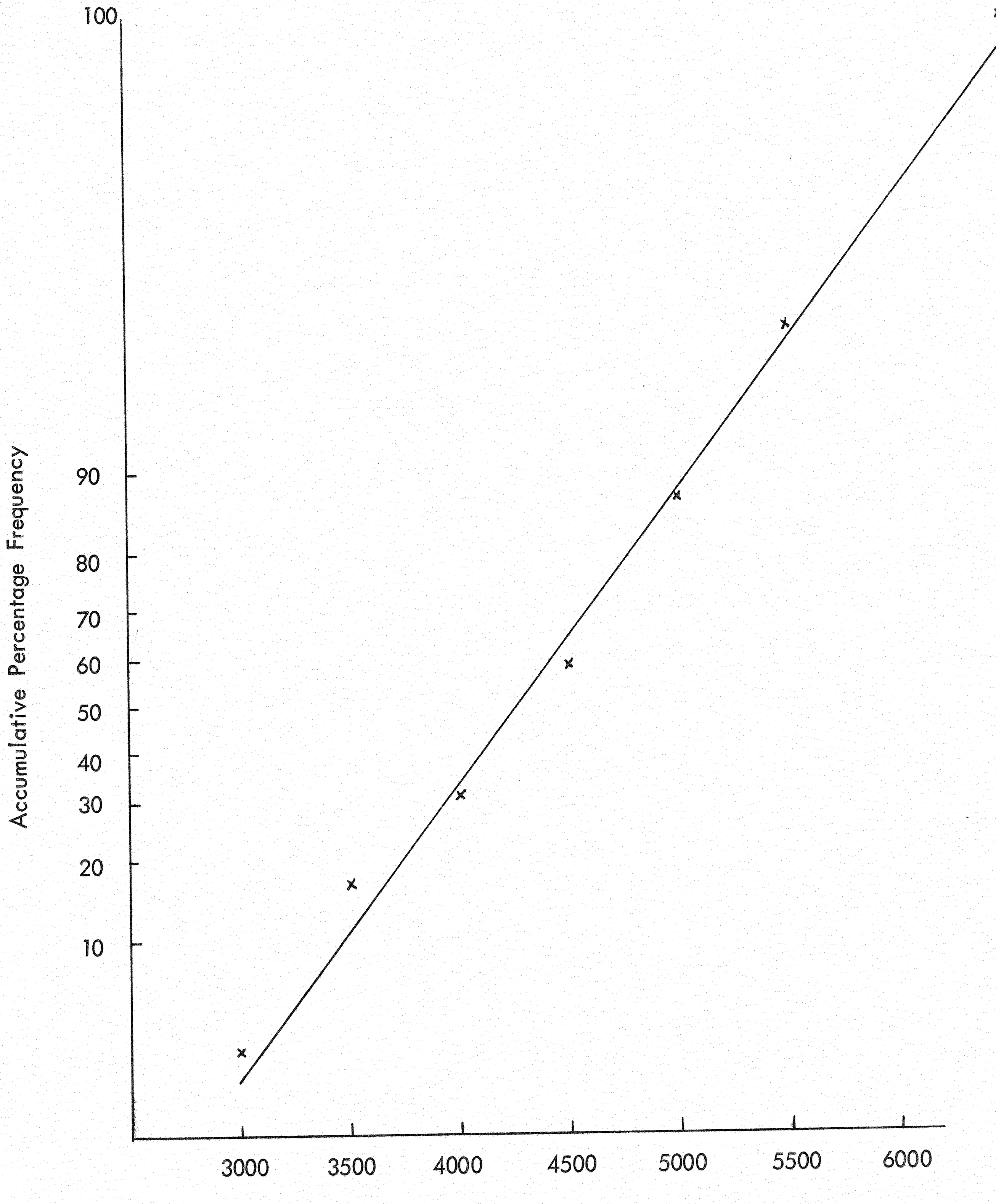
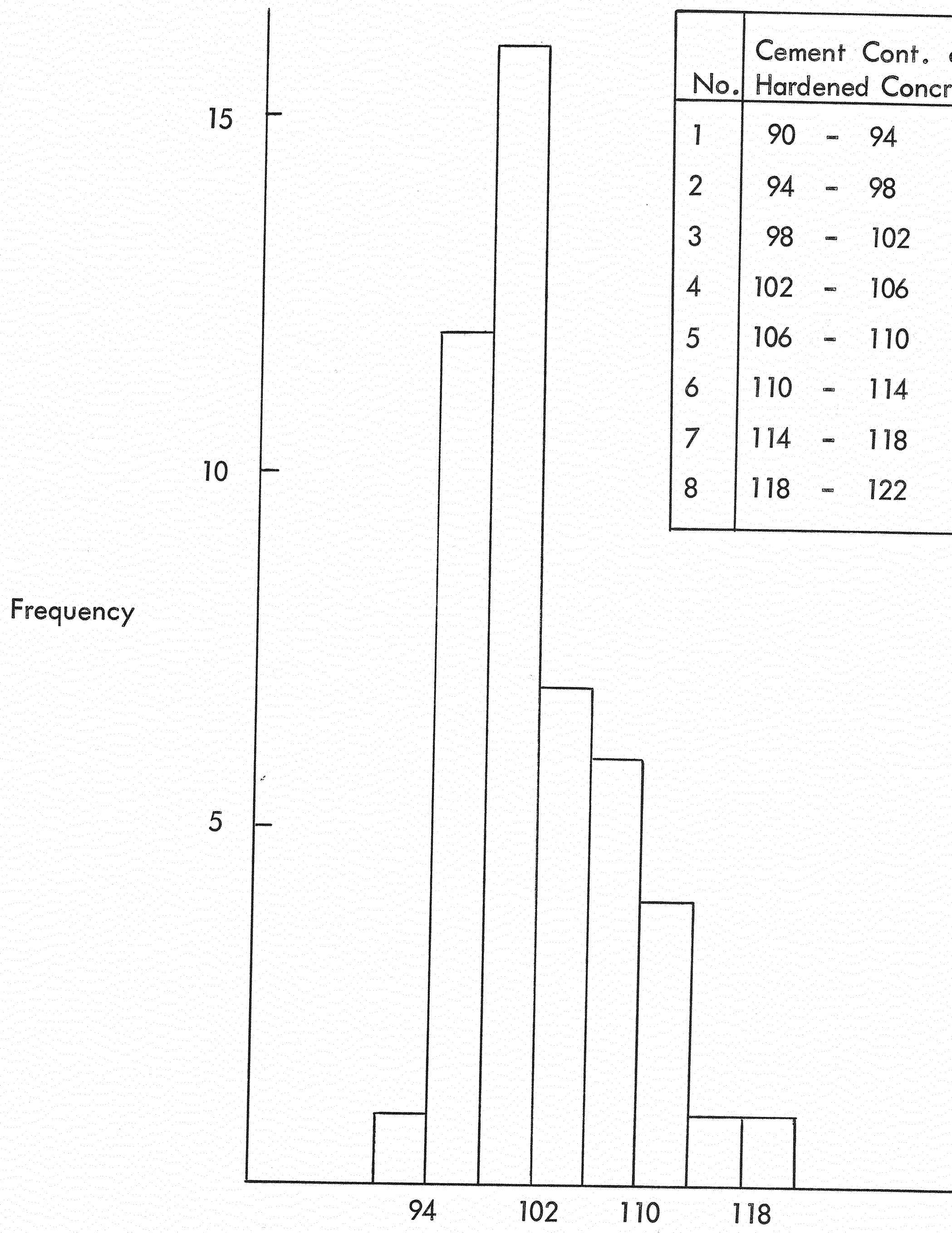


Figure I-17. Cylinder compressive strength - goodness of fit curve



No.	Cement Cont. of Hardened Concrete	f	%	Cum %
1	90 - 94	1	2.1	2.1
2	94 - 98	12	25.0	27.1
3	98 - 102	16	33.3	60.4
4	102 - 106	7	14.6	75.0
5	106 - 110	6	12.5	87.5
6	110 - 114	4	8.3	95.8
7	114 - 118	1	2.1	97.9
8	118 - 122	1	2.1	100.0
		48	100	

n	48
specs	--
$\bar{x}$	101.2
σ_T	6.4
σ_t^2	27.1
σ_s^2	0.0
σ_a^2	14.4
V	6.3%

Figure I-18. Cement content of hardened concrete - statistical properties

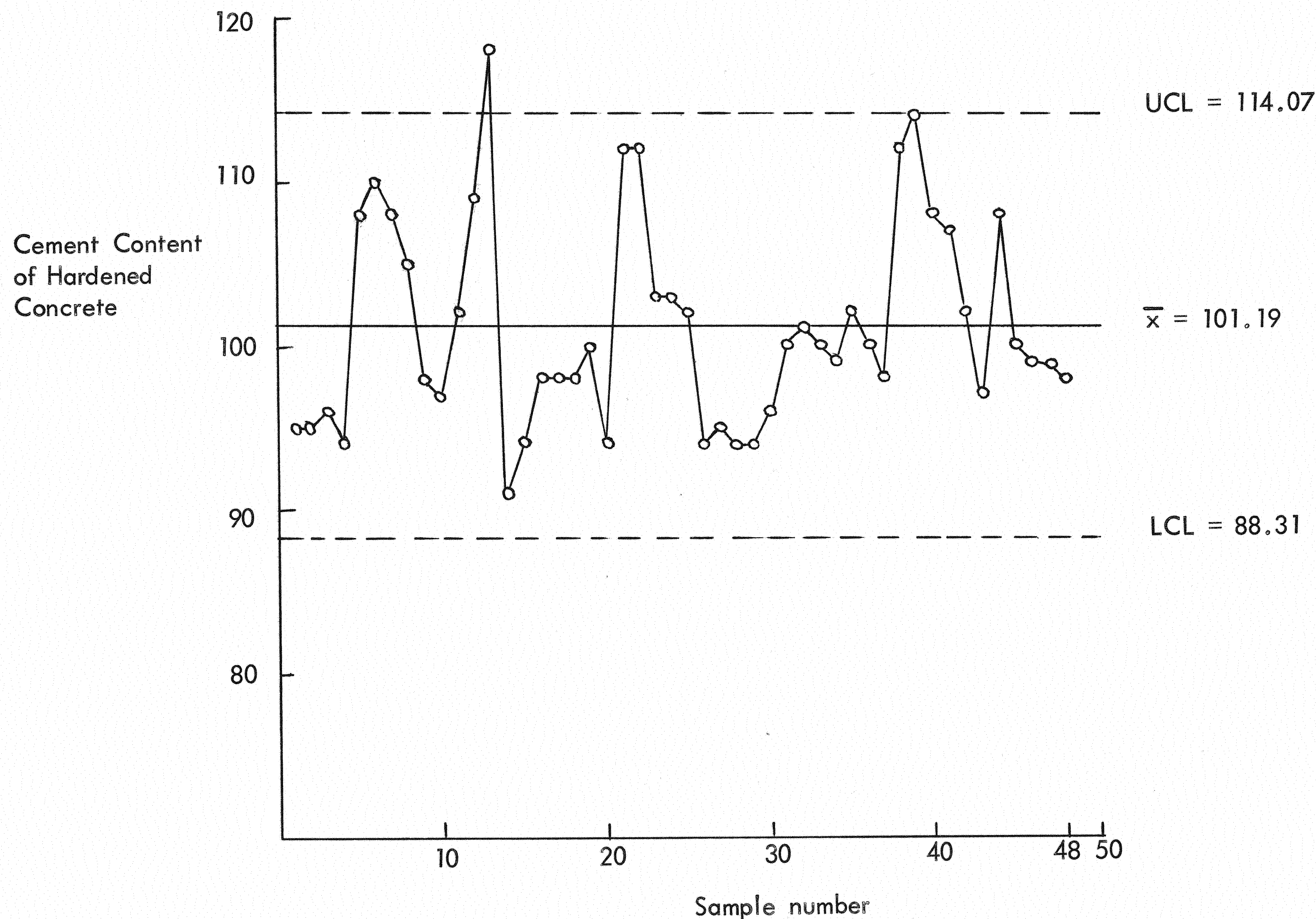


Figure I-19. Cement content of hardened concrete quality control chart

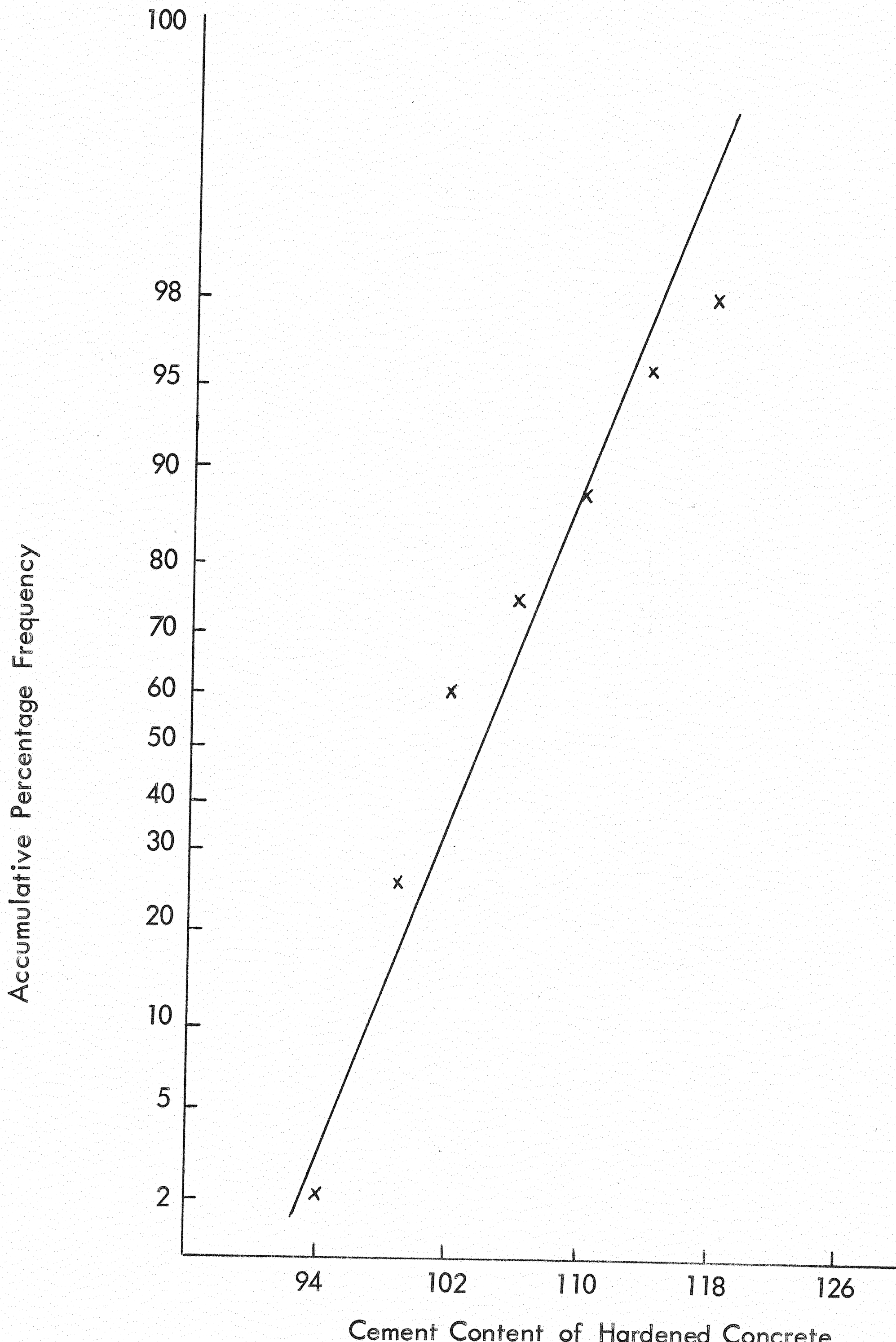
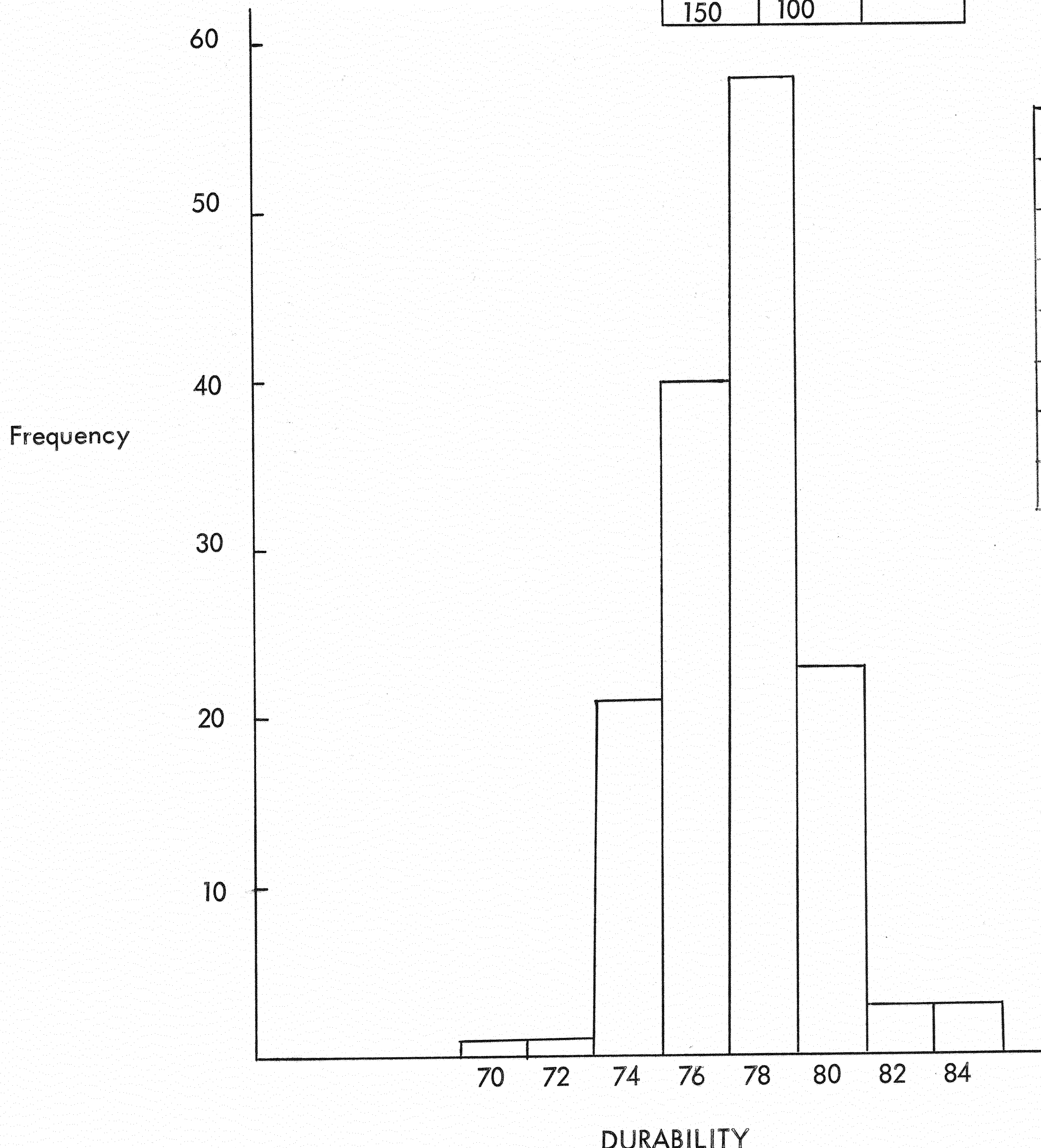


Figure 1-20. Cement content of hardened concrete - goodness of fit curve

No.	Durability Range, %	f	%	Cum%
1	- 70	1	0.7	0.7
2	71 - 72	1	0.7	1.4
3	73 - 74	21	14.0	15.4
4	75 - 76	40	26.7	42.1
5	77 - 78	58	38.6	80.7
6	79 - 80	23	15.3	96.0
7	81 - 82	3	2.0	98.0
8	83 -	3	2.0	100.0
		150	100	



n	150
specs	--
$\bar{x}$	77.3
σ_T	3.0
σ_t^2	5.8
σ_s^2	3.1
σ_a^2	0.0
V	3.9%

Figure I-21. Durability - statistical properties

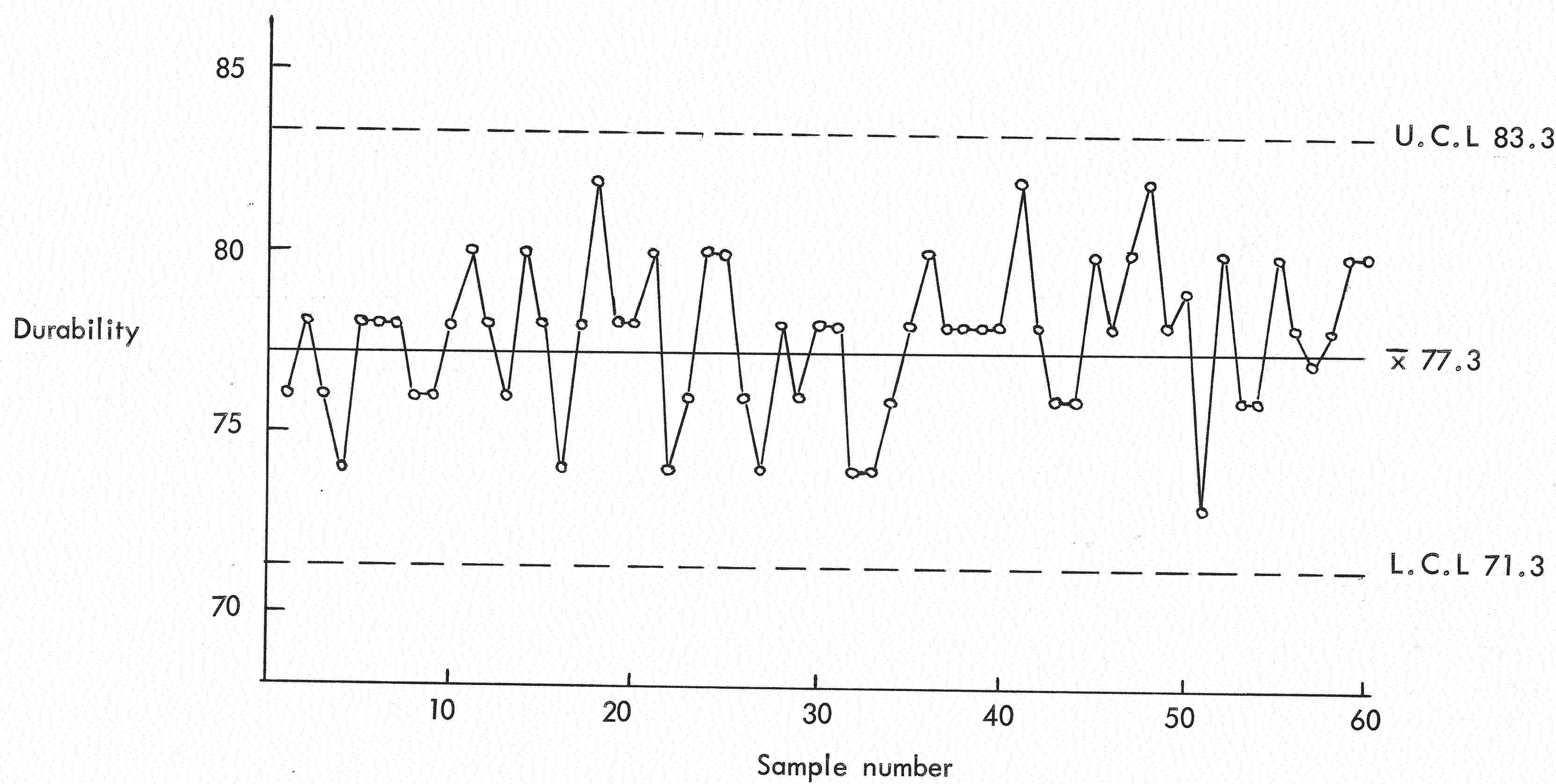


Figure I-22. Durability - quality control chart

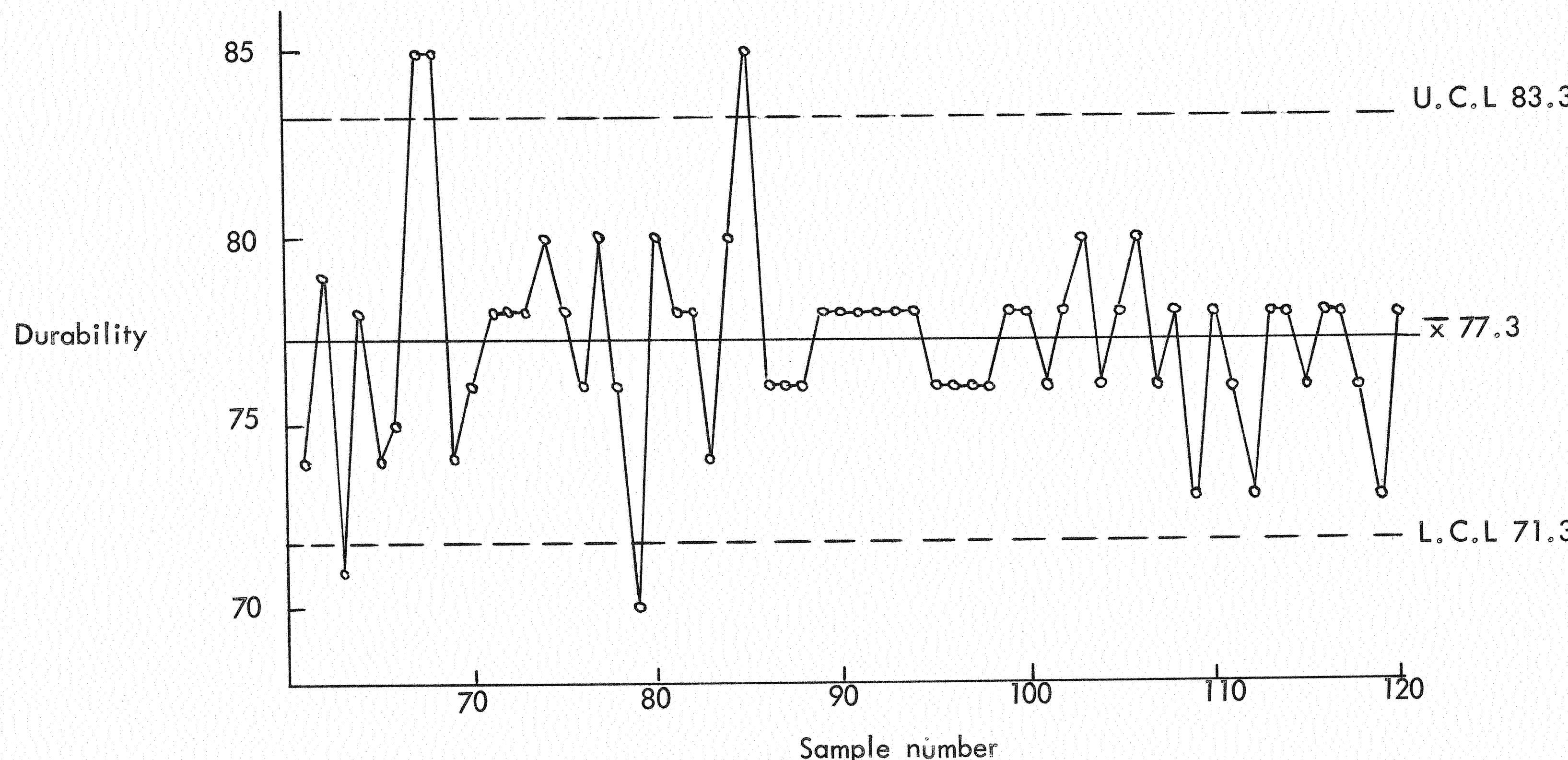


Figure I-22 (cont.). Durability - quality control chart

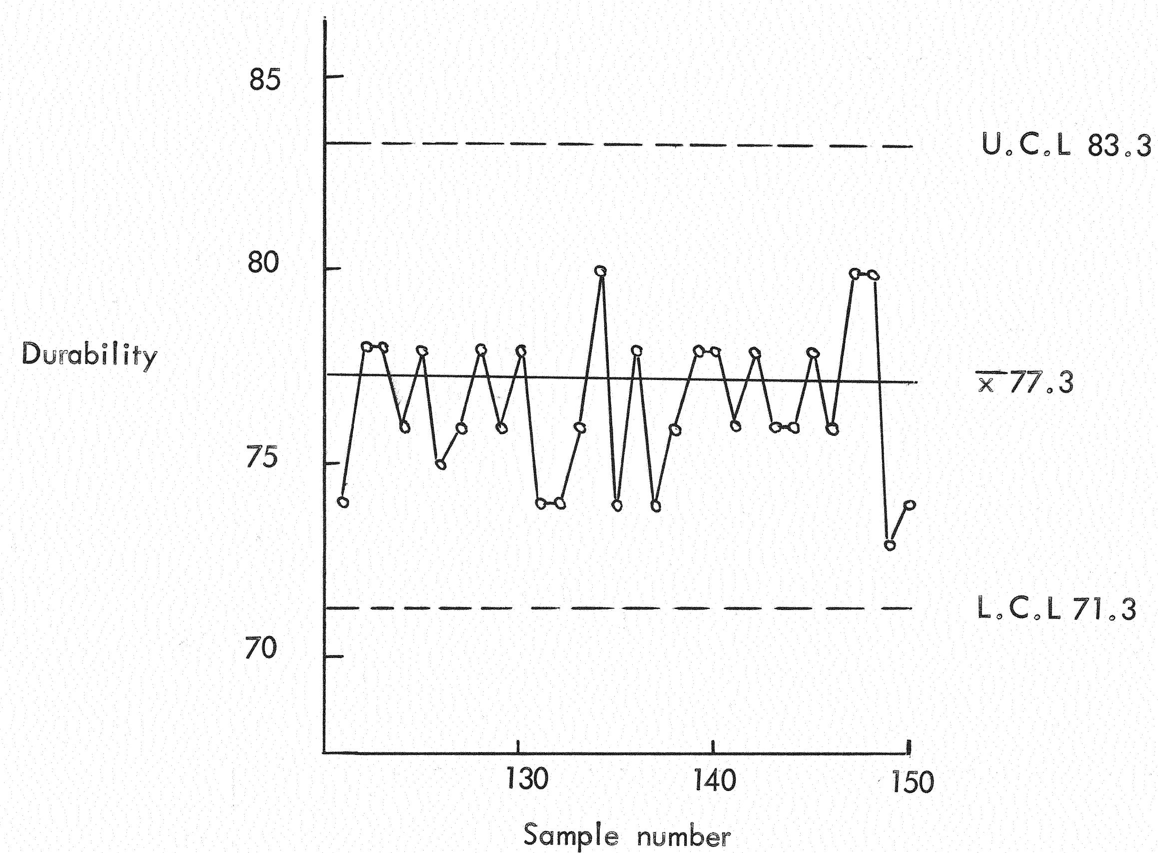


Figure I-22(cont.) Durability - quality control chart

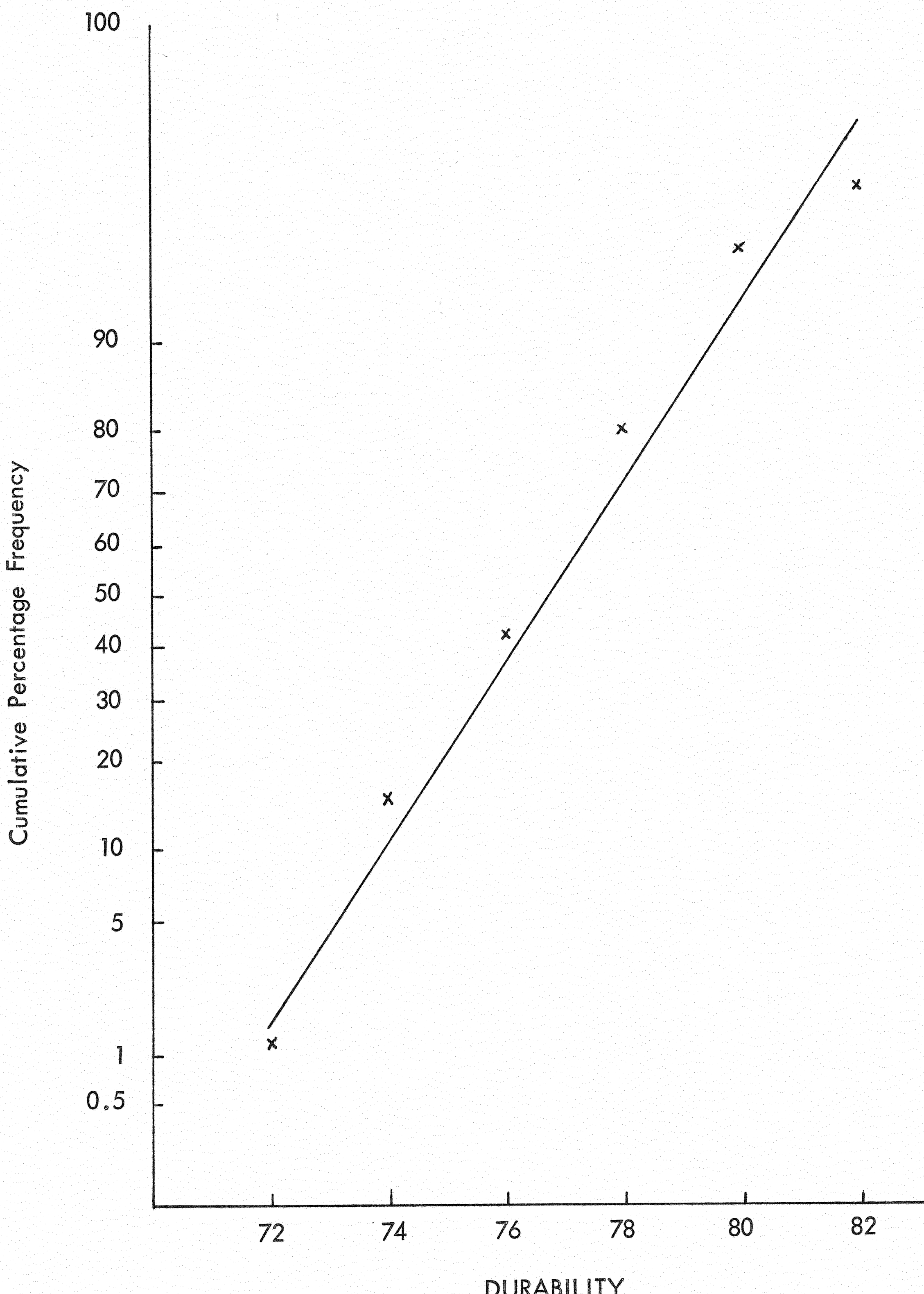
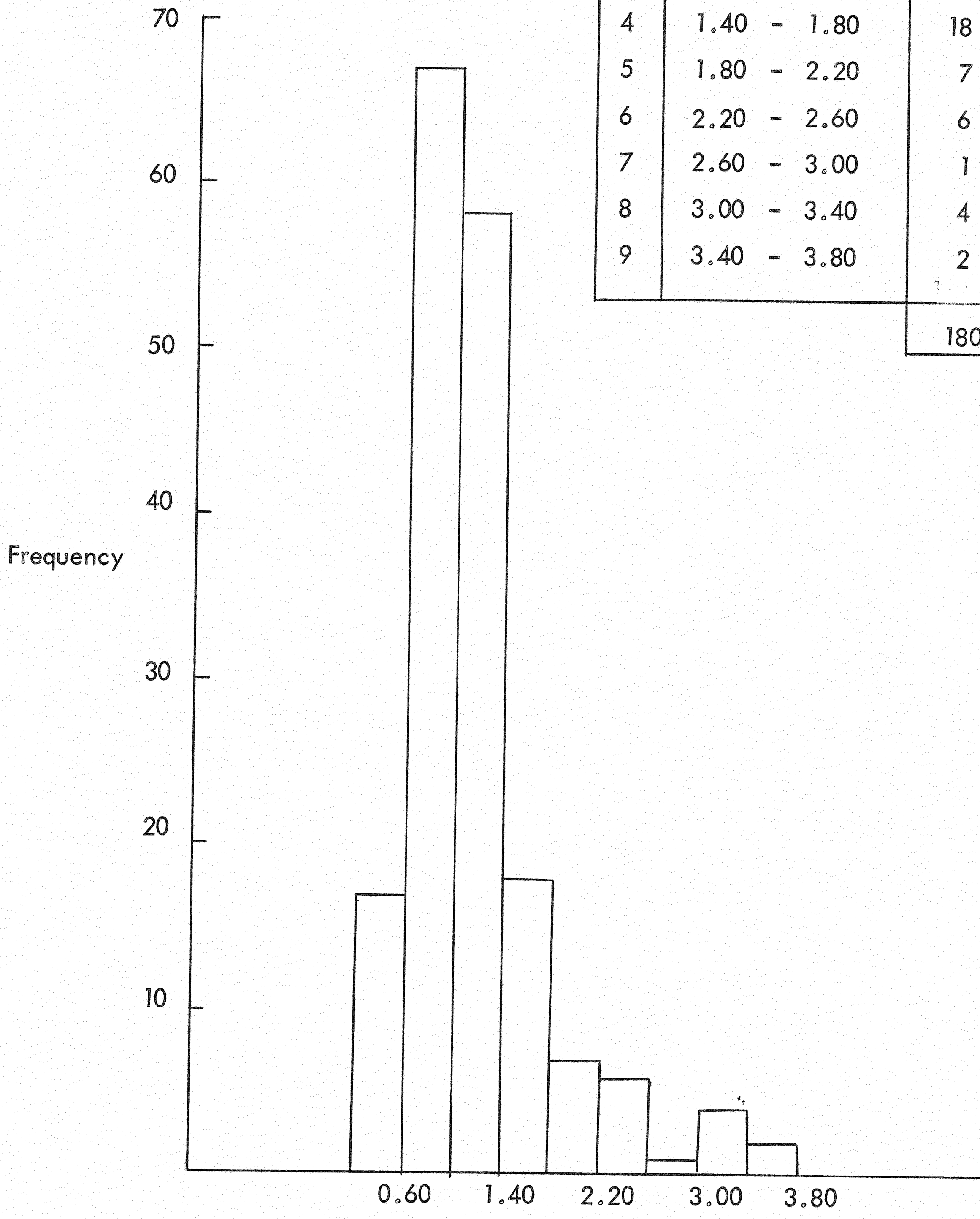


Figure I-23. Durability - goodness of fit curve

No.	C.A. Passing No. 200 Range	f	%	Cum %
1	0.20 - 0.60	17	9.5	9.5
2	0.60 - 1.00	67	37.2	46.7
3	1.00 - 1.40	58	32.2	78.9
4	1.40 - 1.80	18	10.0	88.9
5	1.80 - 2.20	7	3.9	92.8
6	2.20 - 2.60	6	3.3	96.1
7	2.60 - 3.00	1	0.6	96.7
8	3.00 - 3.40	4	2.2	98.9
9	3.40 - 3.80	2	1.1	100.0
		180	100	

n	200
specs	2% max
$\bar{x}$	1.2
σ_T	0.80
σ_t^2	0.5
σ_s^2	0.1
σ_a^2	0.1
V	66.7%



Coarse Aggregate Passing No. 200

Figure I-24. % Passing no. 200 C.A. - statistical properties

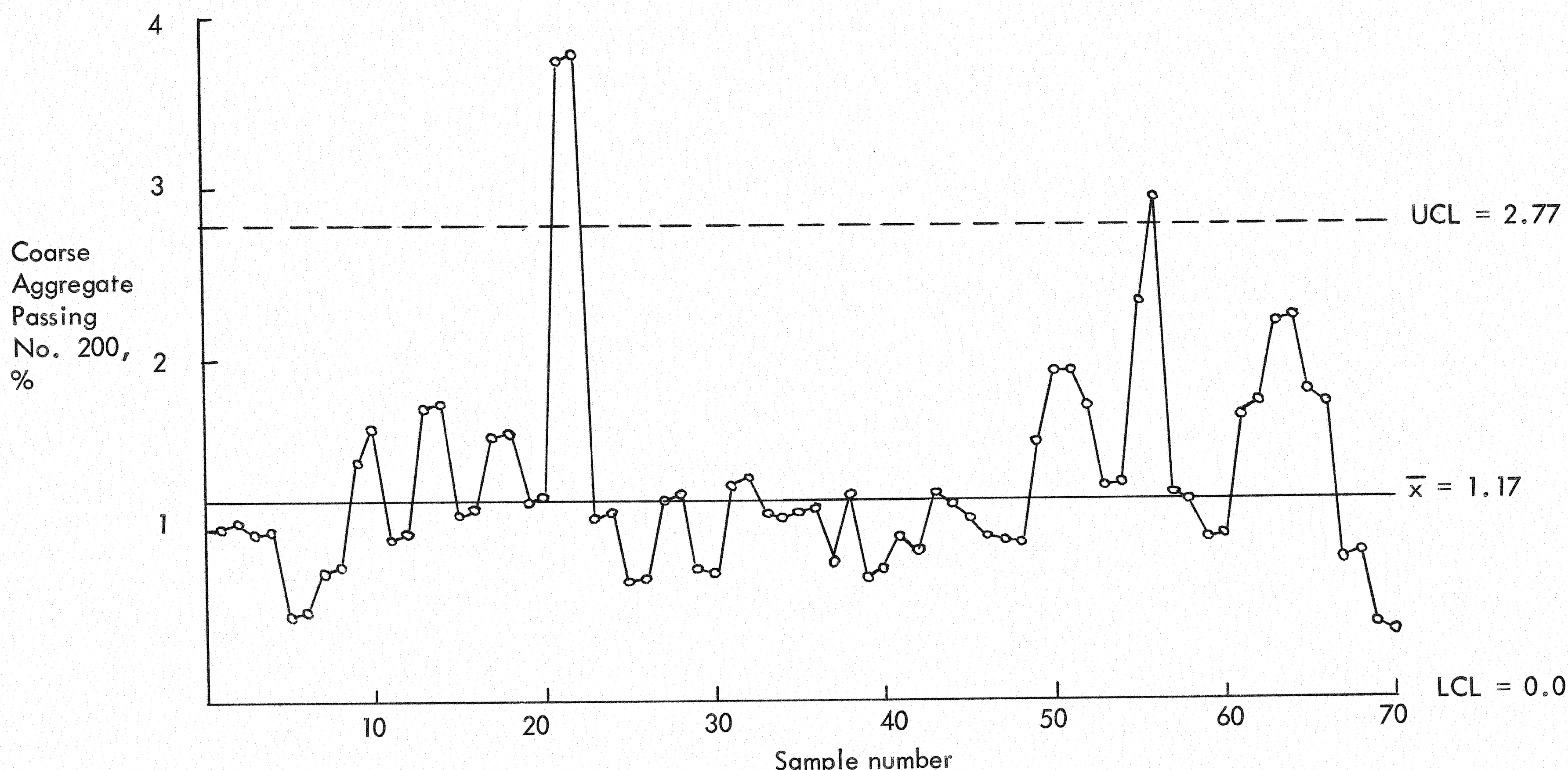


Figure I-25. % Passing No. 200 C.A. - quality control chart

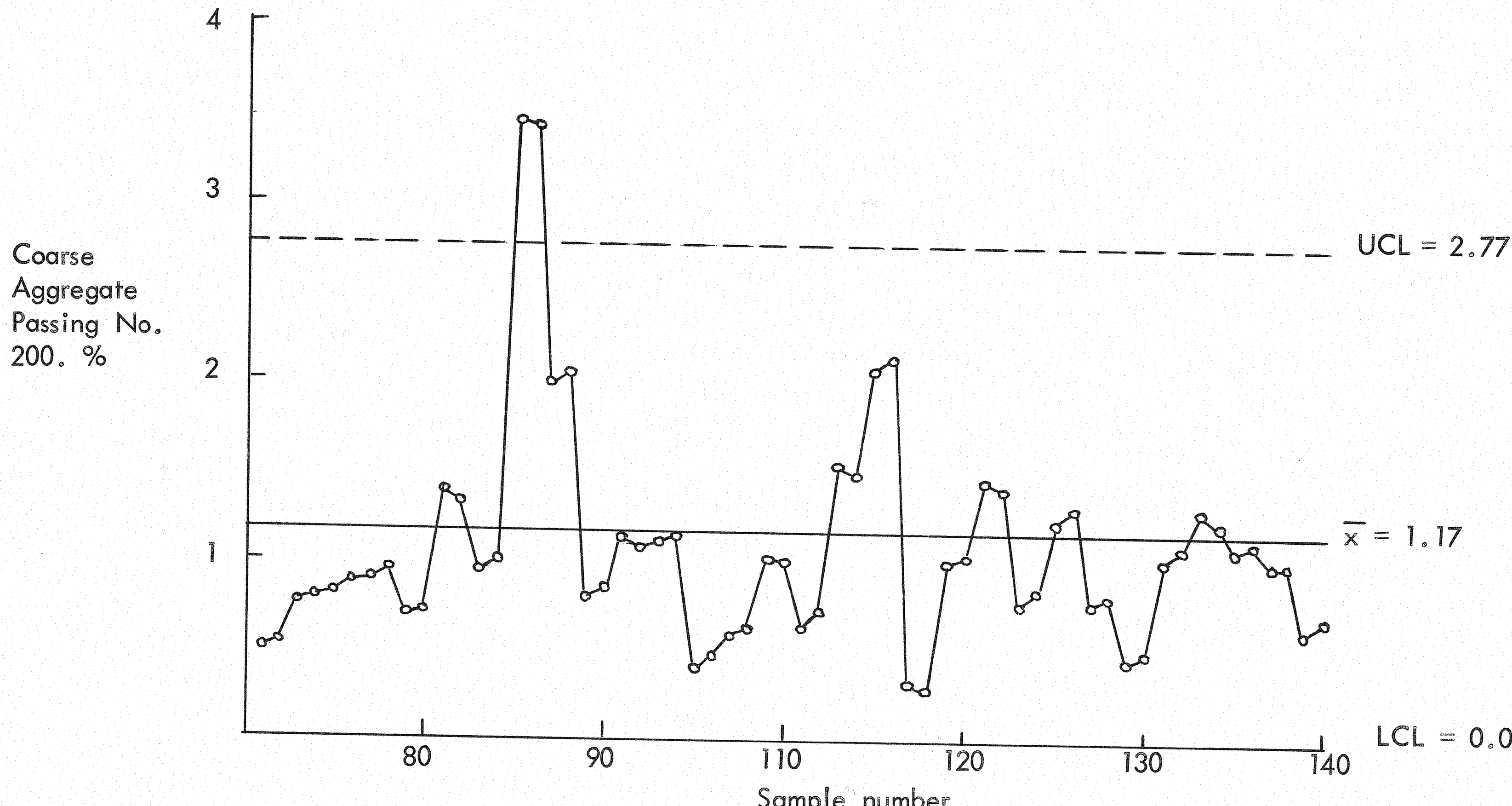


Figure I-25 (cont.). % Passing No. 200 C.A. - quality control chart

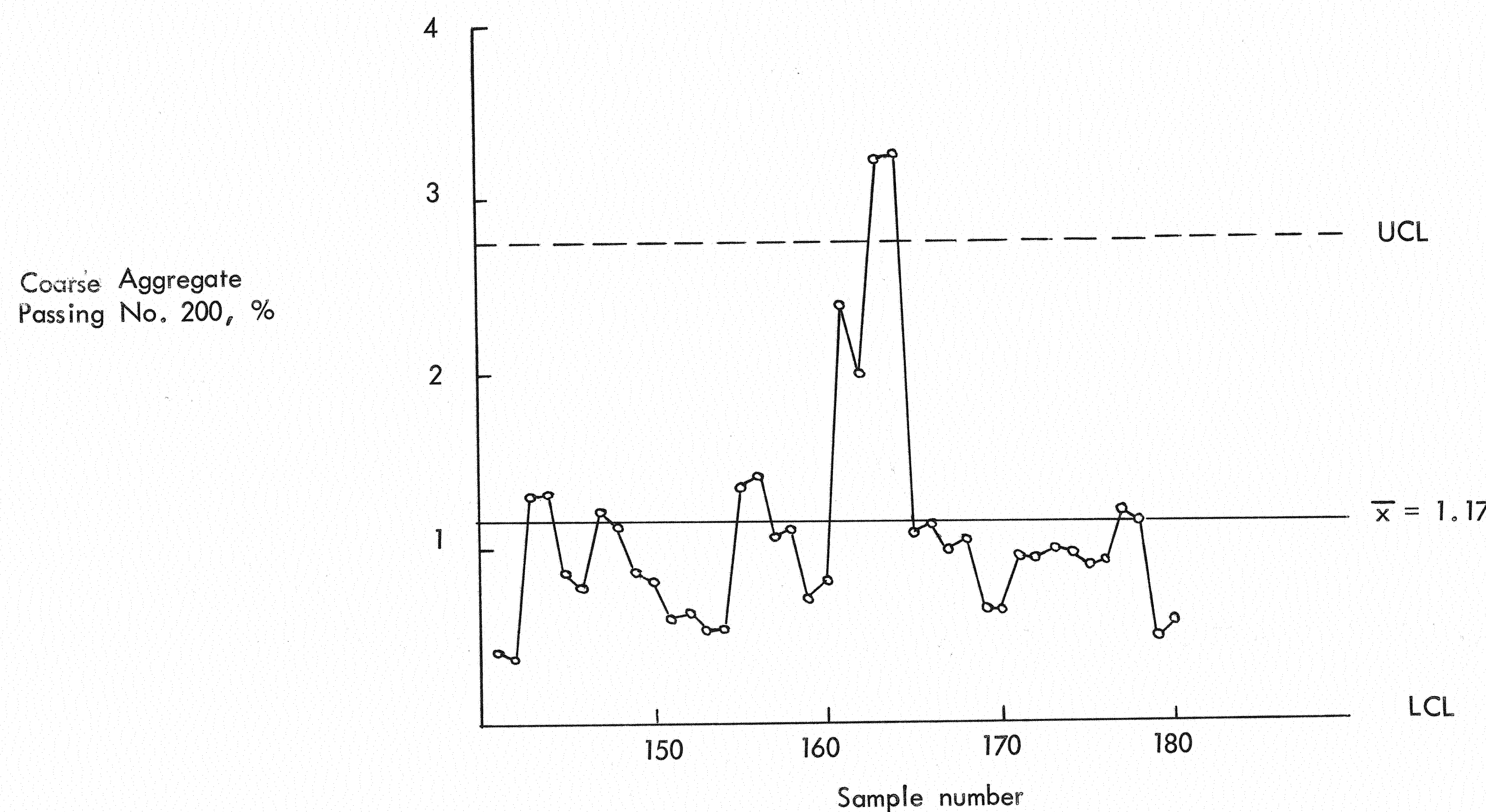


Figure I-25(cont.). % Passing No. 200 C.A. - quality control chart

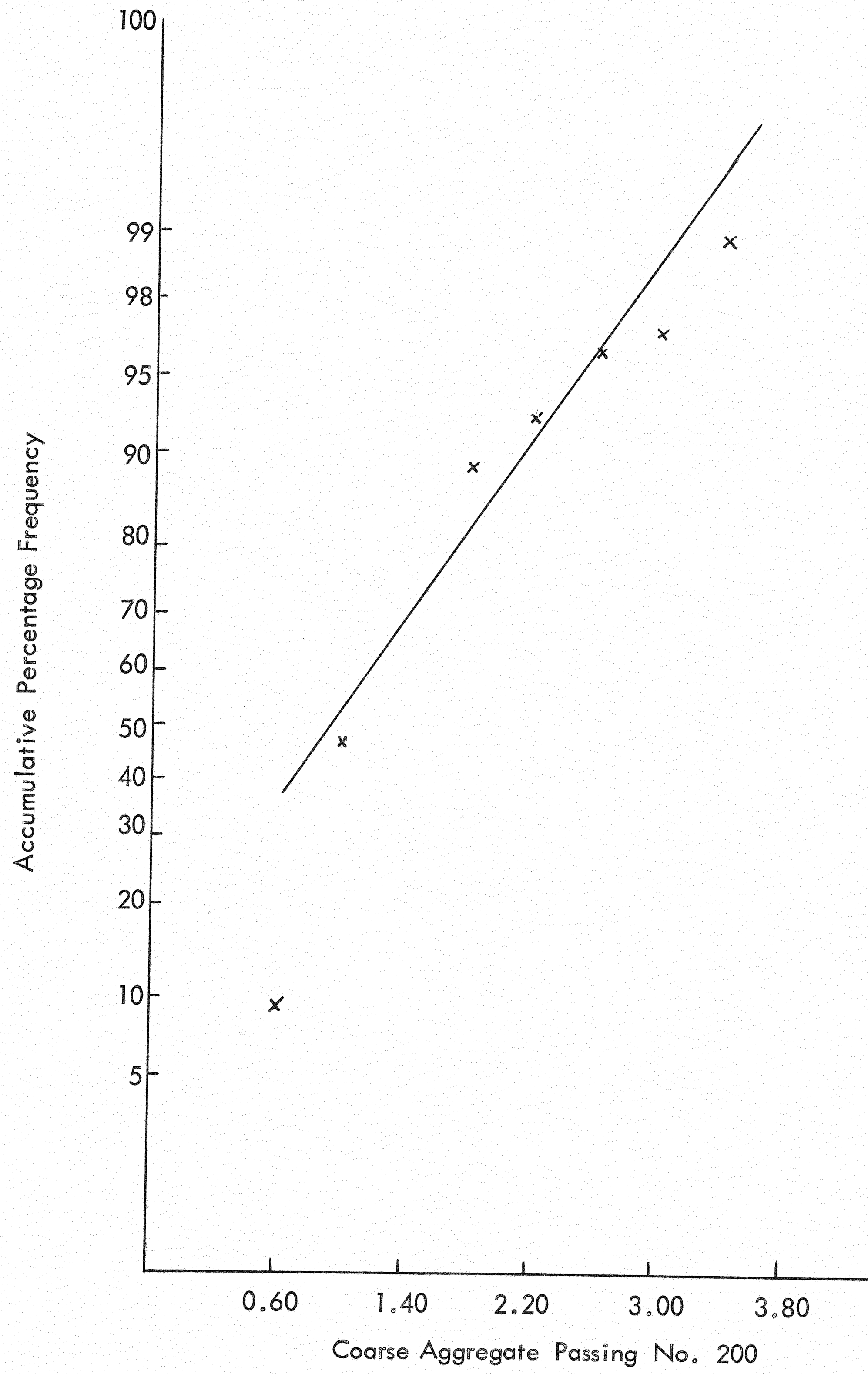


Figure I-26 % passing No. 200 C.A. - goodness of fit curve

No.	Los Angeles Range, %	f	%	Cum %
1	- 20.0	2	1.2	1.2
2	20.1 - 21.0	3	1.8	3.0
3	21.1 - 22.0	7	4.3	7.3
4	22.1 - 23.0	25	15.3	22.6
5	23.1 - 24.0	48	29.5	52.1
6	24.1 - 25.0	55	33.8	85.9
7	25.1 - 26.0	16	9.8	95.7
8	26.1 -	7	4.3	100.0
		163	100	

n	163
specs	
$\bar{x}$	23.9
σ_T	3.1
σ_t^2	7.5
σ_s^2	0.0
σ_a^2	2.0
V	13.0%

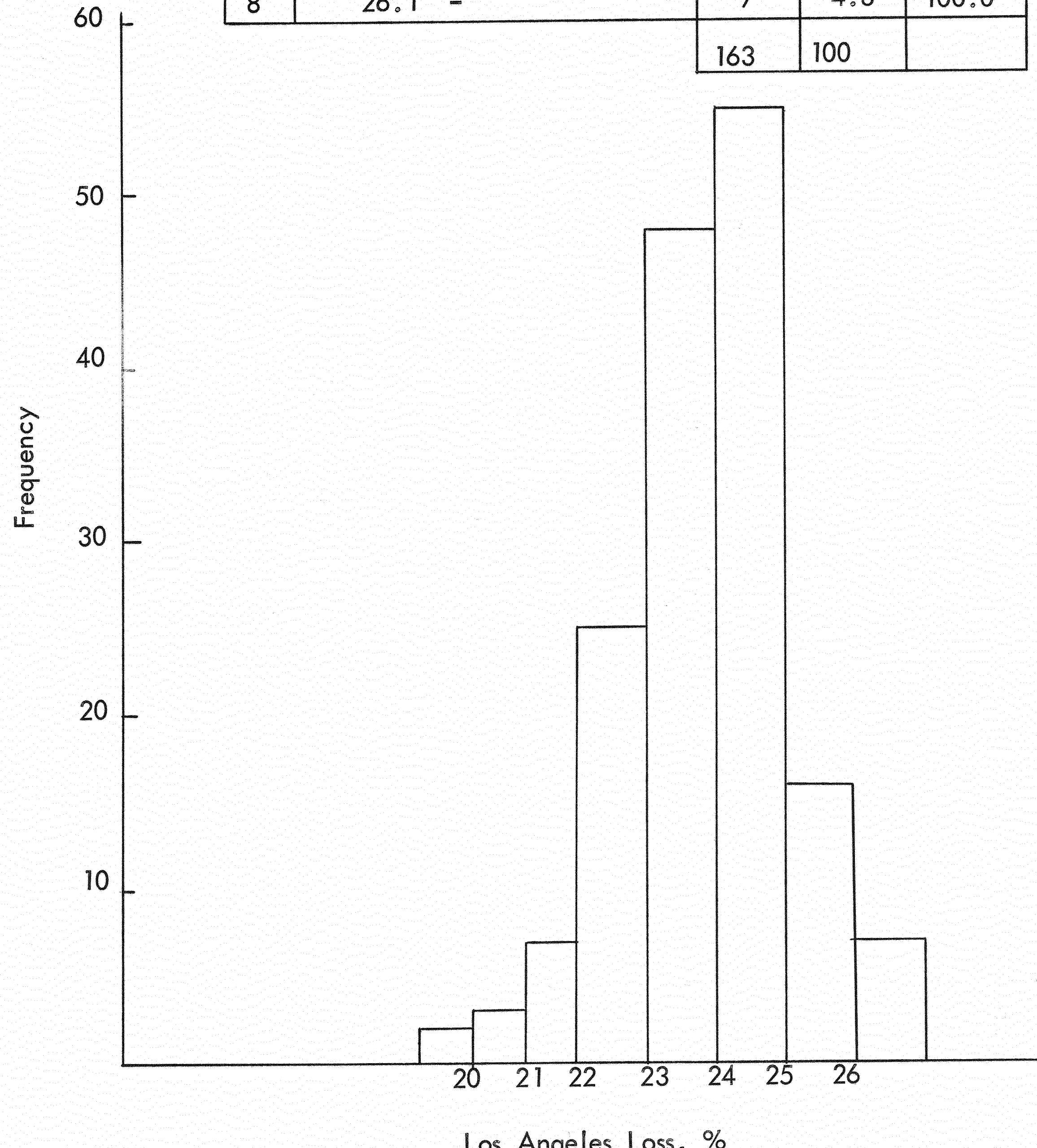


Figure I-27. Los Angeles Loss - statistical properties

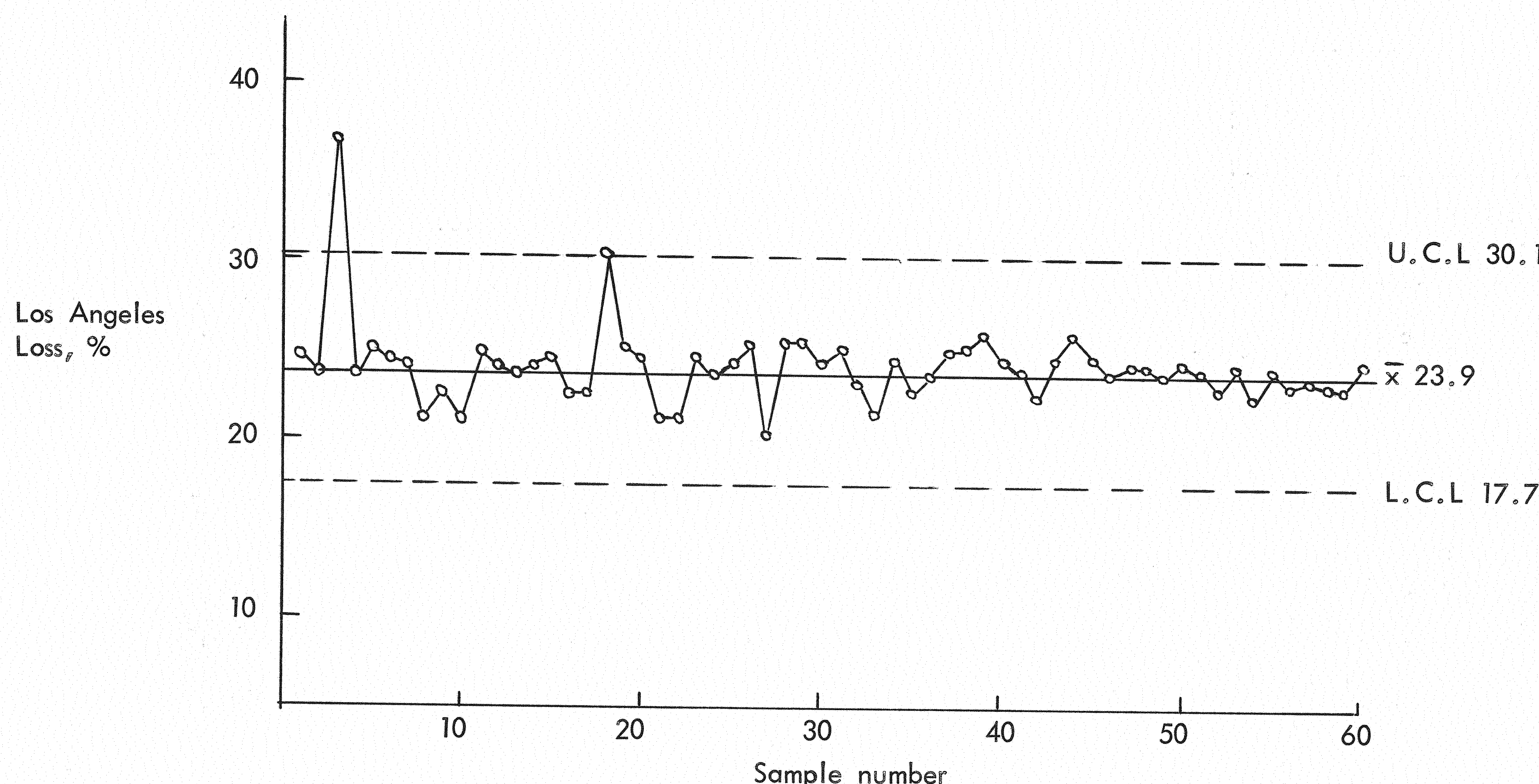


Figure I-28. Los Angeles Loss - quality control chart

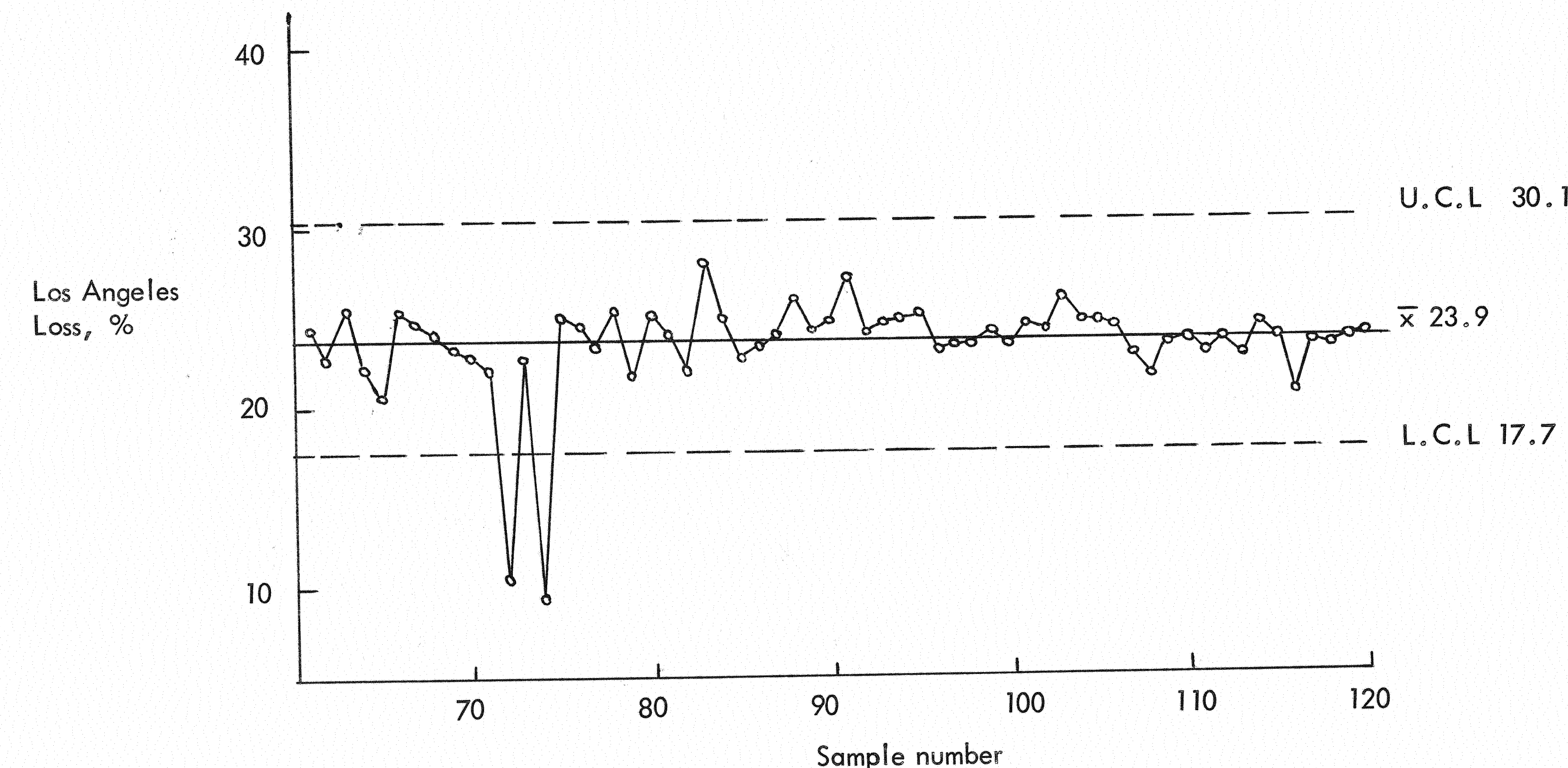


Figure I-28 (cont.). Los Angeles Loss - quality control chart

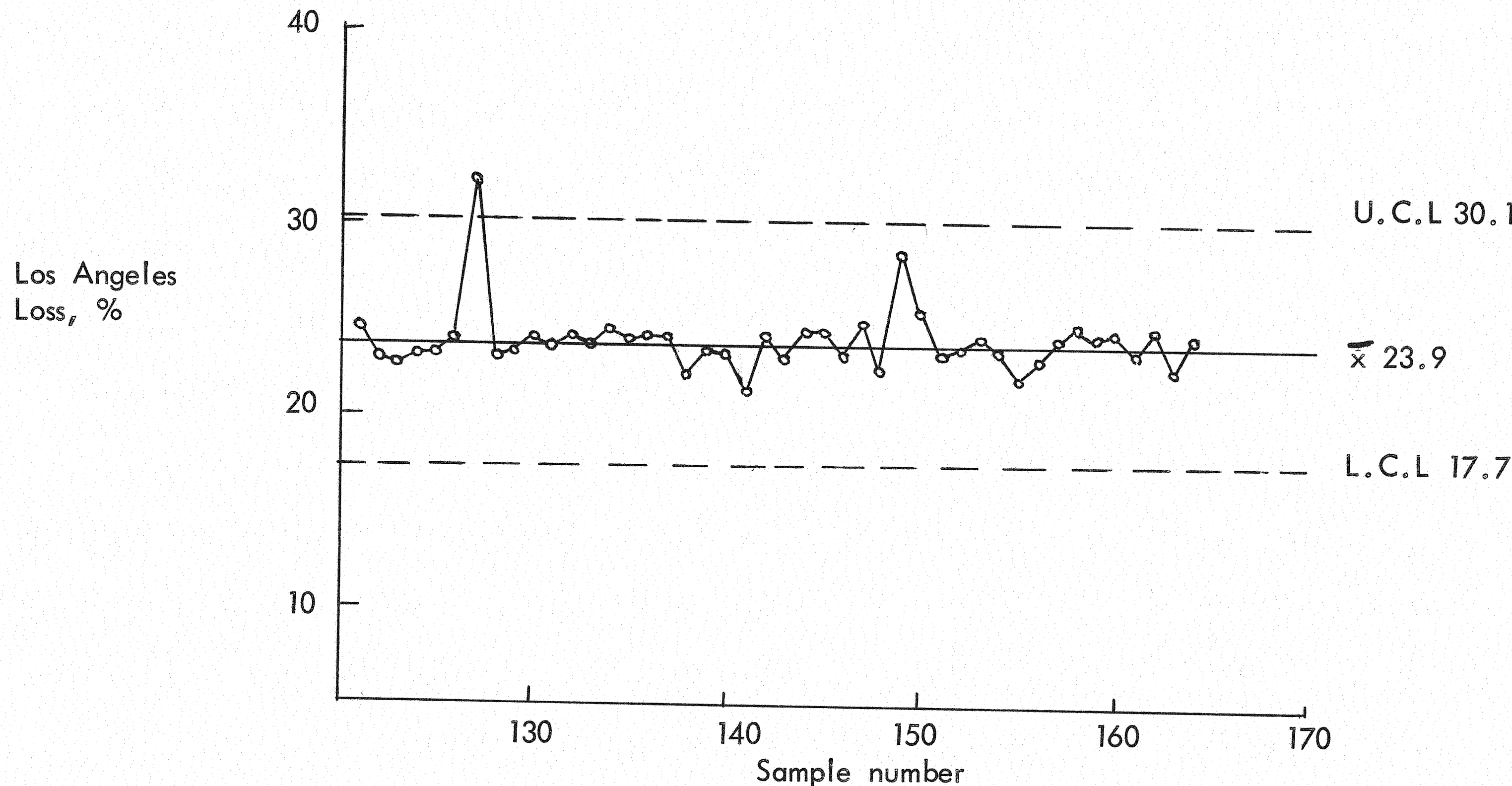


Figure I-28(cont.). Los Angeles Loss - quality control chart

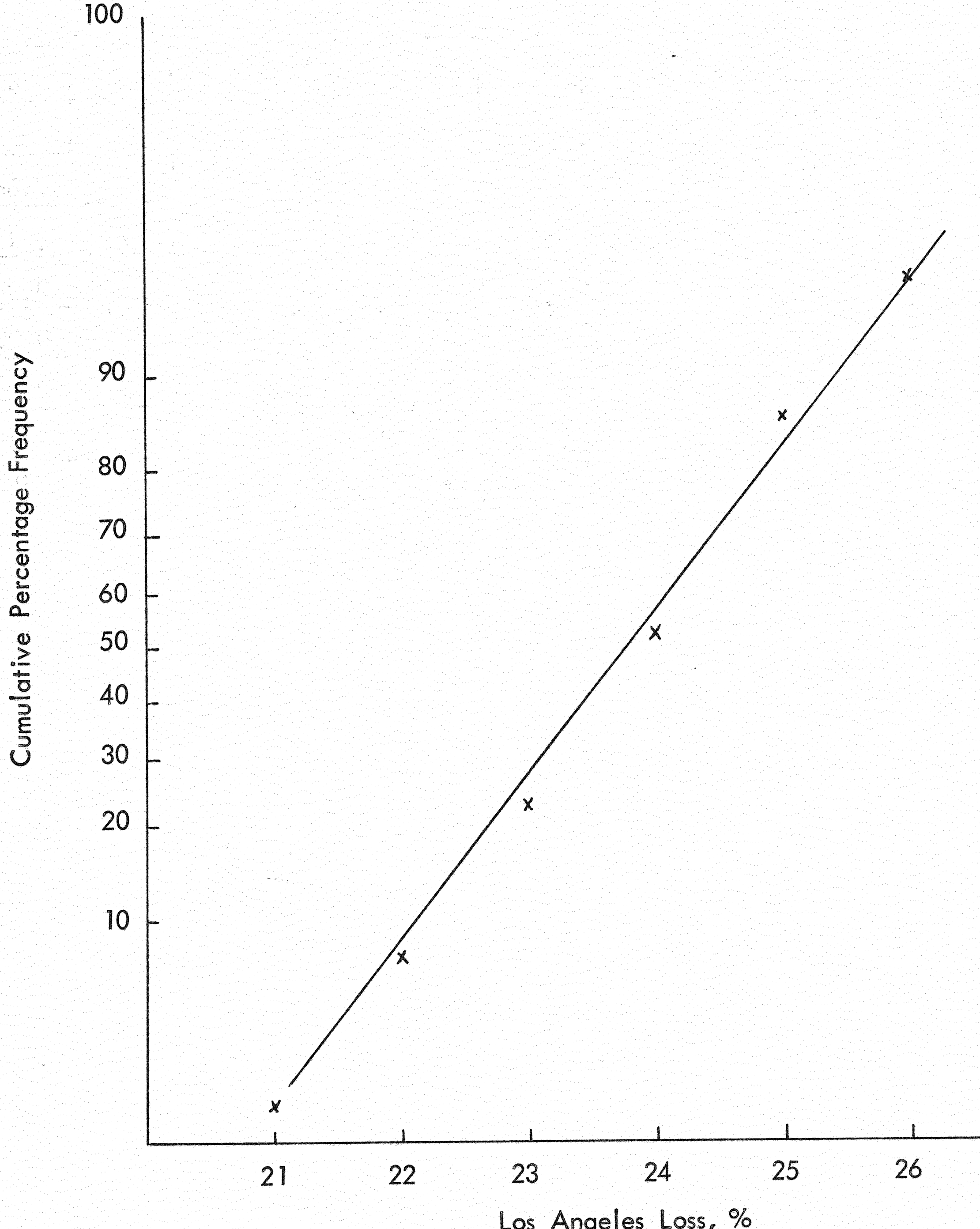


Figure I-29. Los Angeles Loss - goodness of fit curve

No.	Fineness Modulus Range	f	%	Cum%
1	2.51 - 2.60	2	1.0	1.0
2	2.61 - 2.70	15	7.7	8.7
3	2.71 - 2.80	38	19.6	28.3
4	2.81 - 2.90	60	31.0	59.3
5	2.91 - 3.00	69	35.6	94.9
6	3.01 - 3.10	9	4.6	99.5
7	3.10 -	1	0.5	100.0
		194	100	

n	194
specs	--
$\bar{x}$	2.86
σ_T	0.11
σ_t^2	0.003
σ_s^2	0.001
σ_a^2	0.007
V	3.8%

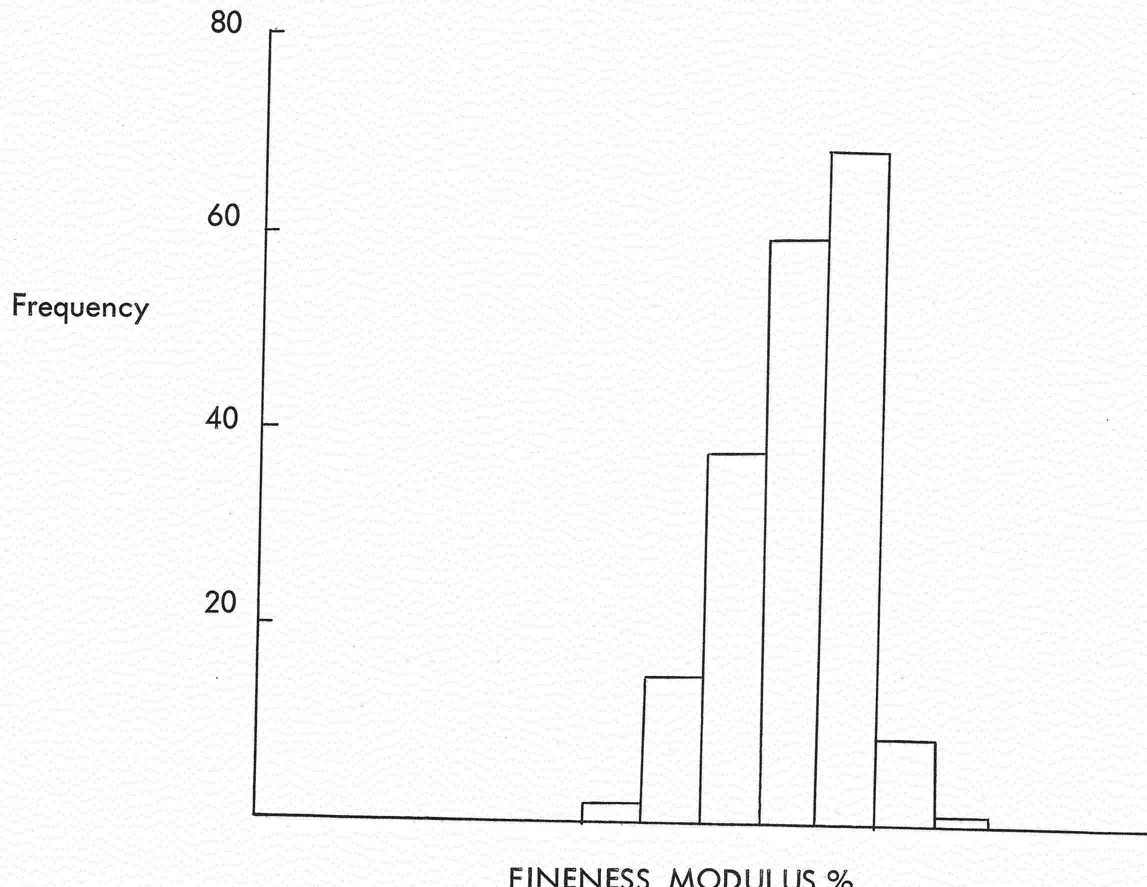


Figure I-30. Fineness Modulus - statistical properties

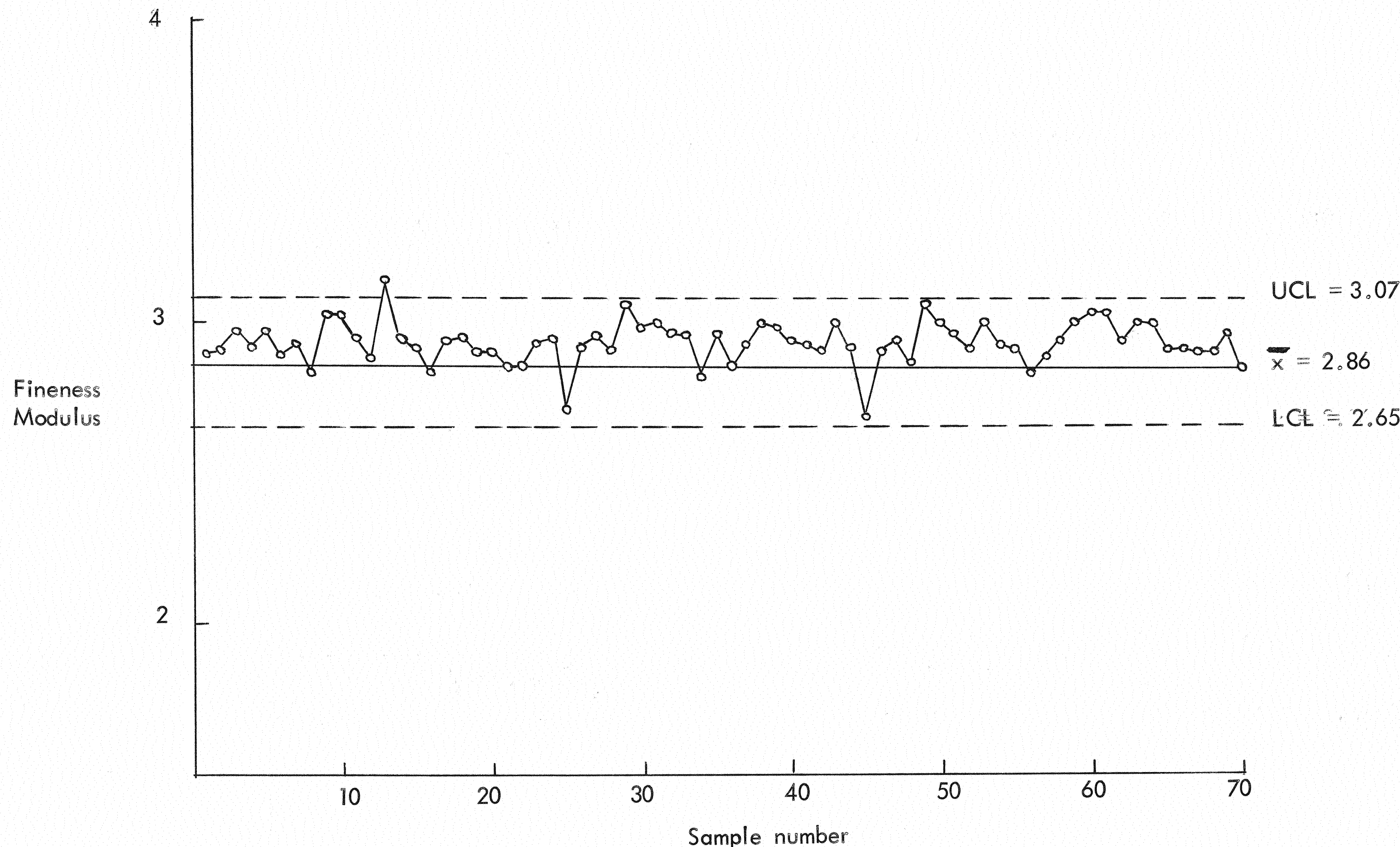


Figure I-31. Fineness Mudulus - quality control chart

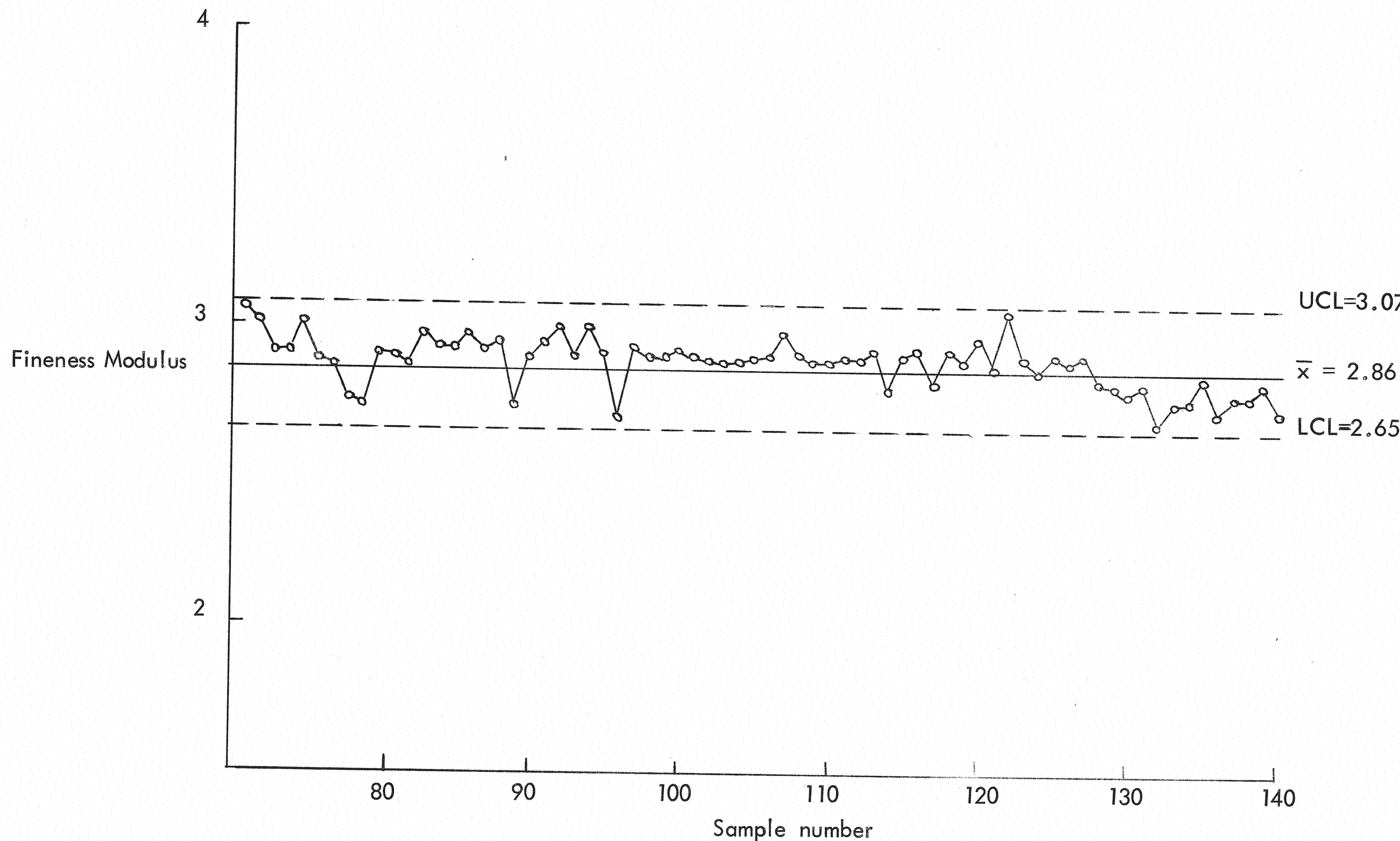


Figure I-31(cont.). Fineness Modulus - quality control chart

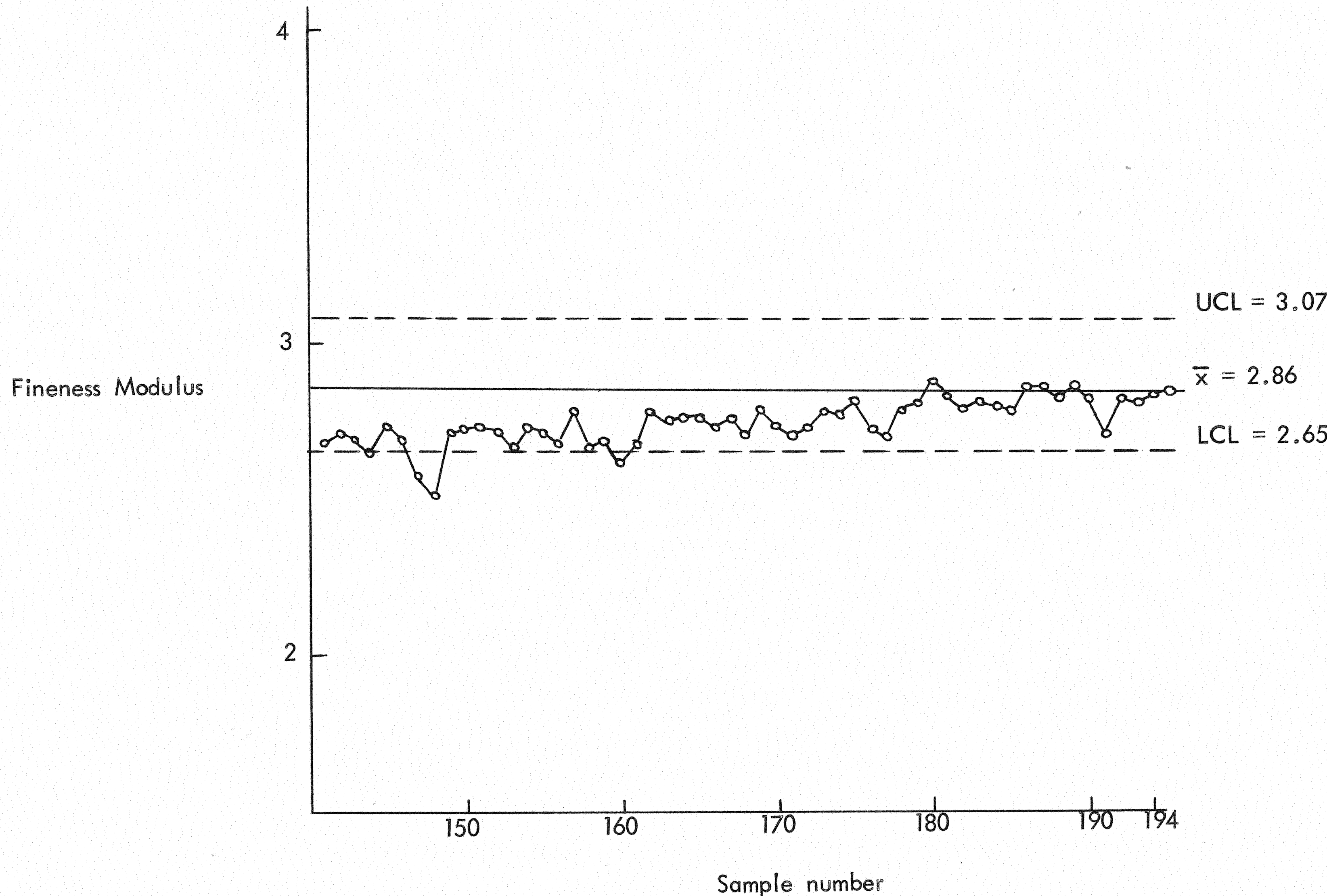


Figure I-31(cont.). Fineness modulus - quality control chart

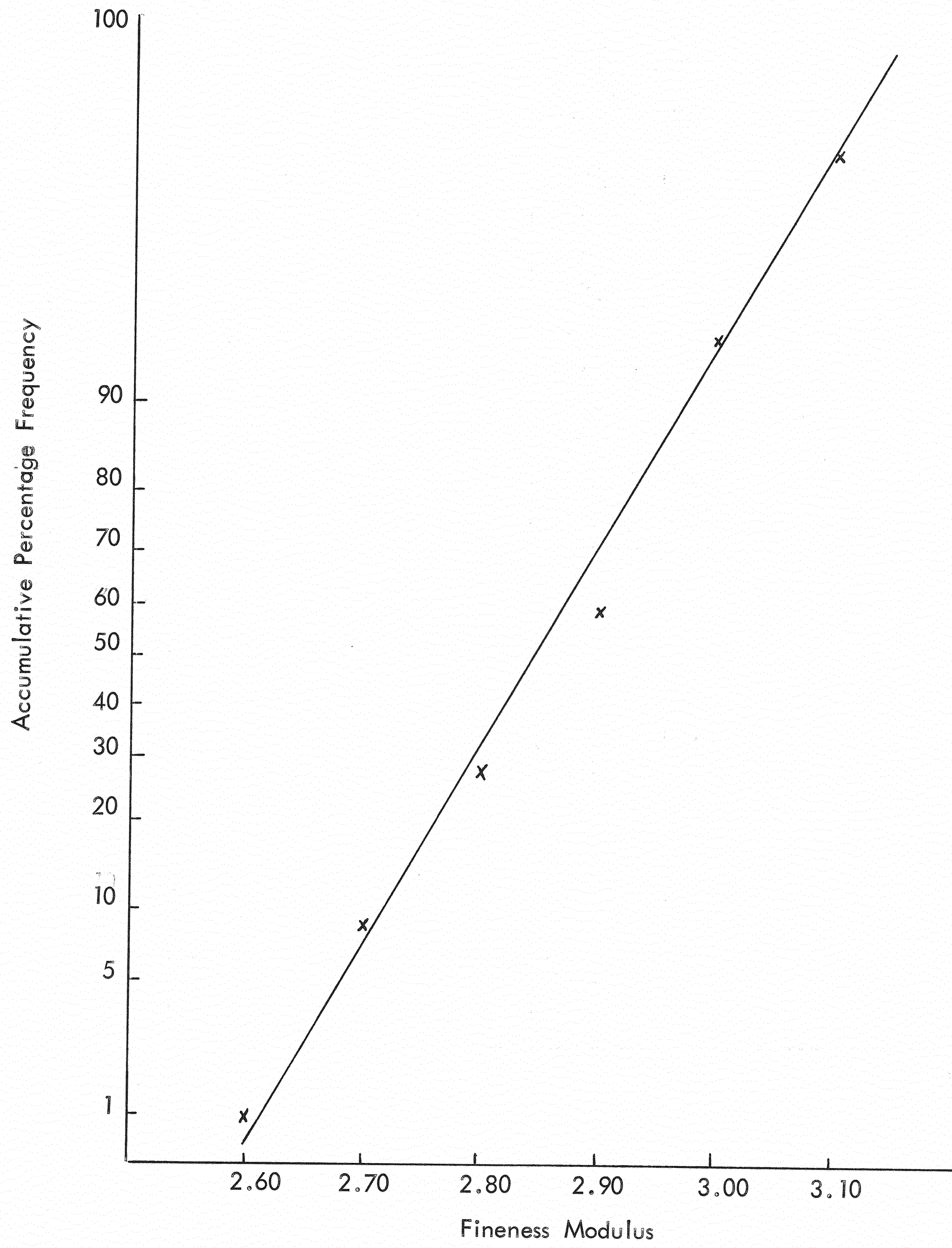


Figure I-32. Fineness Modulus - goodness of fit curve

No.	F.A. Passing No. 200 Range%	f	%	Cum%
1	- 2.30	11	5.7	5.7
2	2.31 - 3.00	21	10.8	16.5
3	3.01 - 3.70	28	14.4	30.9
4	3.71 - 4.40	44	22.7	53.6
5	4.41 - 5.10	40	20.7	74.3
6	5.11 - 5.80	29	14.9	89.2
7	5.81 - 6.50	12	6.2	95.4
8	6.51 - 7.20	5	2.6	98.0
9	7.21 - 7.90	3	1.5	99.5
10	7.91 -	1	0.5	100.0
		194	100.0	

n	194
specs	3%max.
$\bar{x}$	4.3
σ_T	1.2
σ_t^2	0.52
σ_s^2	0.0
σ_a^2	1.0
V	27.9%

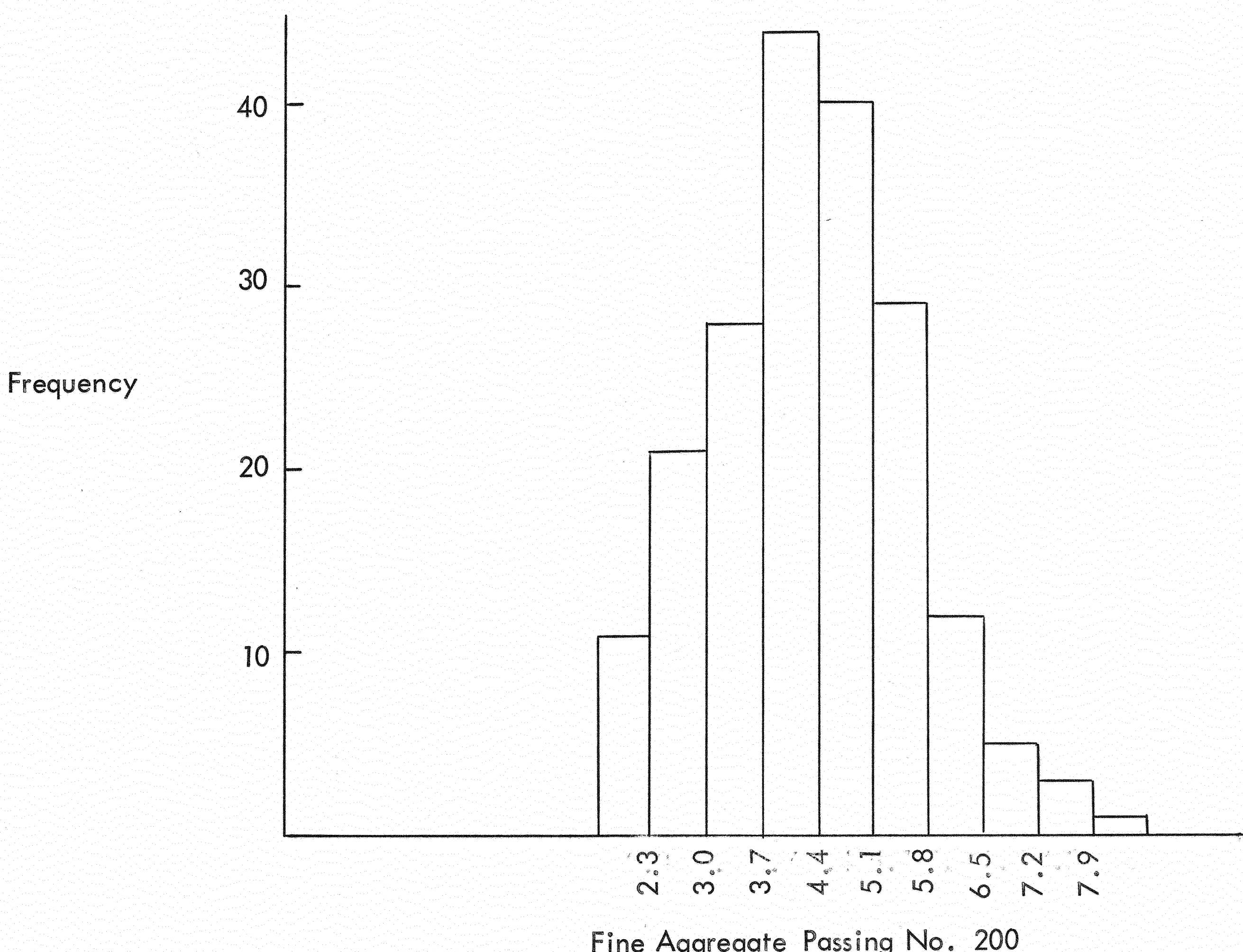


Figure I-33. % Passing No. 200 F.A. - statistical properties

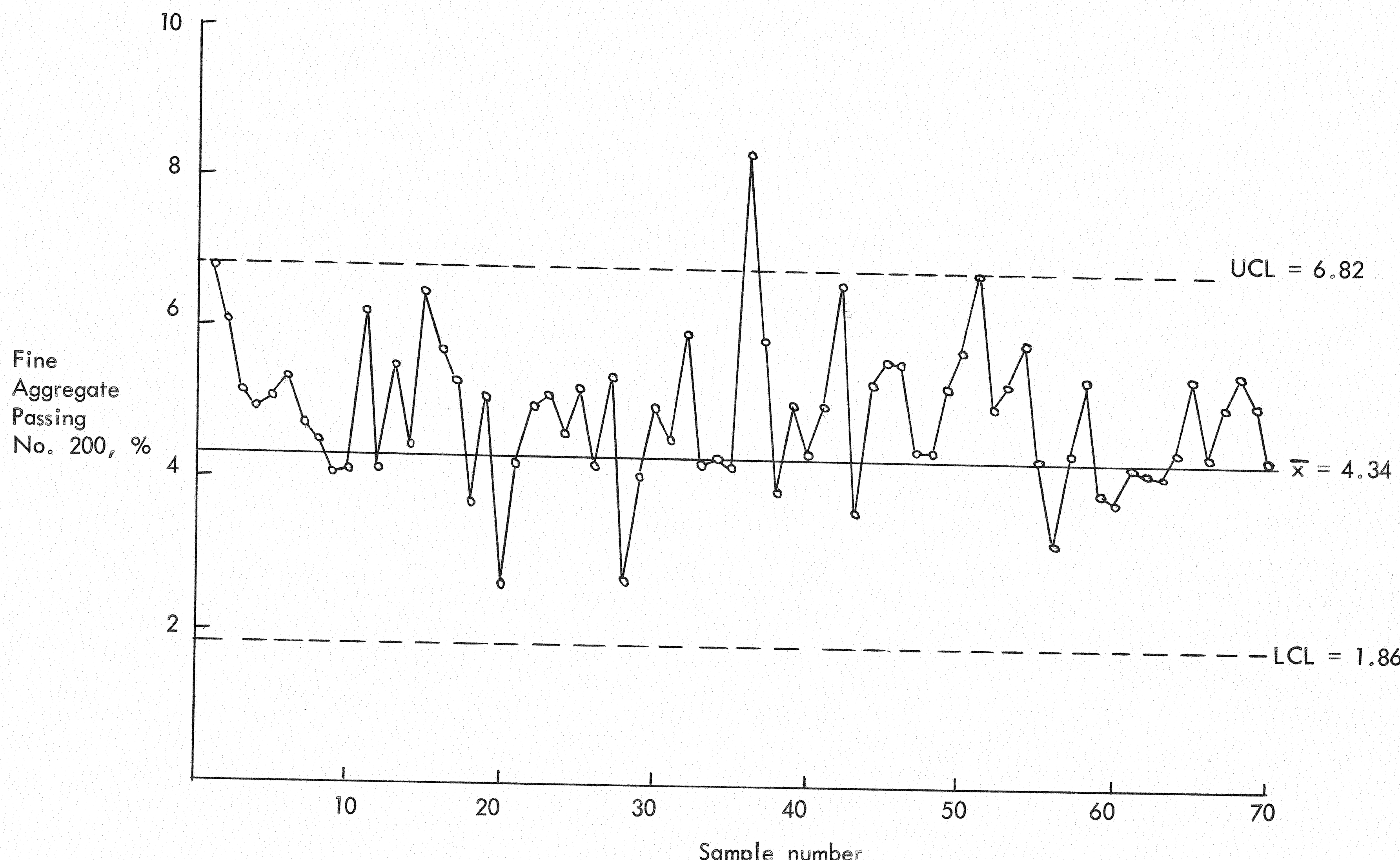


Figure I-34. % Passing No. F.A. - quality control chart

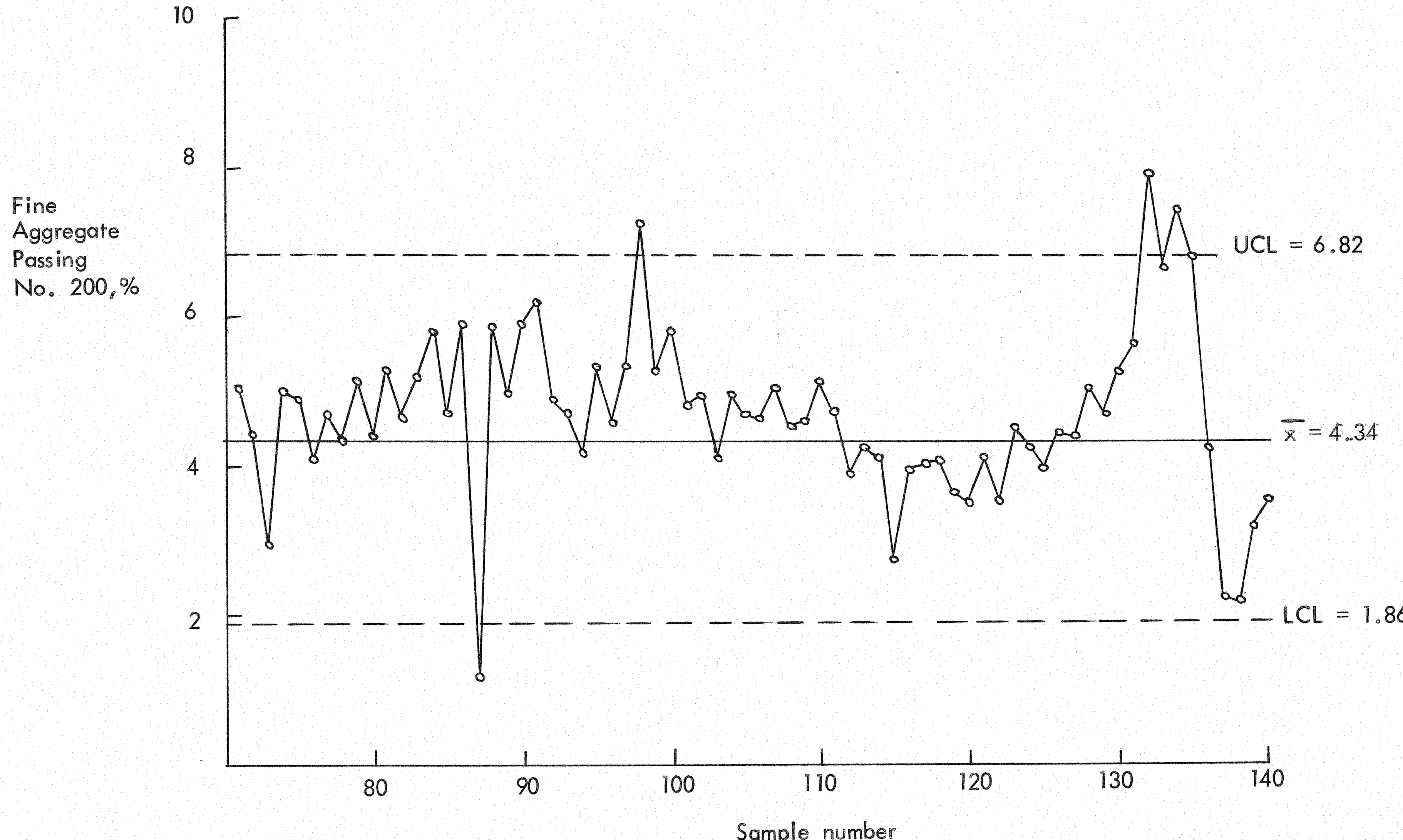


Figure I-34(cont.). %Passing No. 200 F.A. - quality control chart

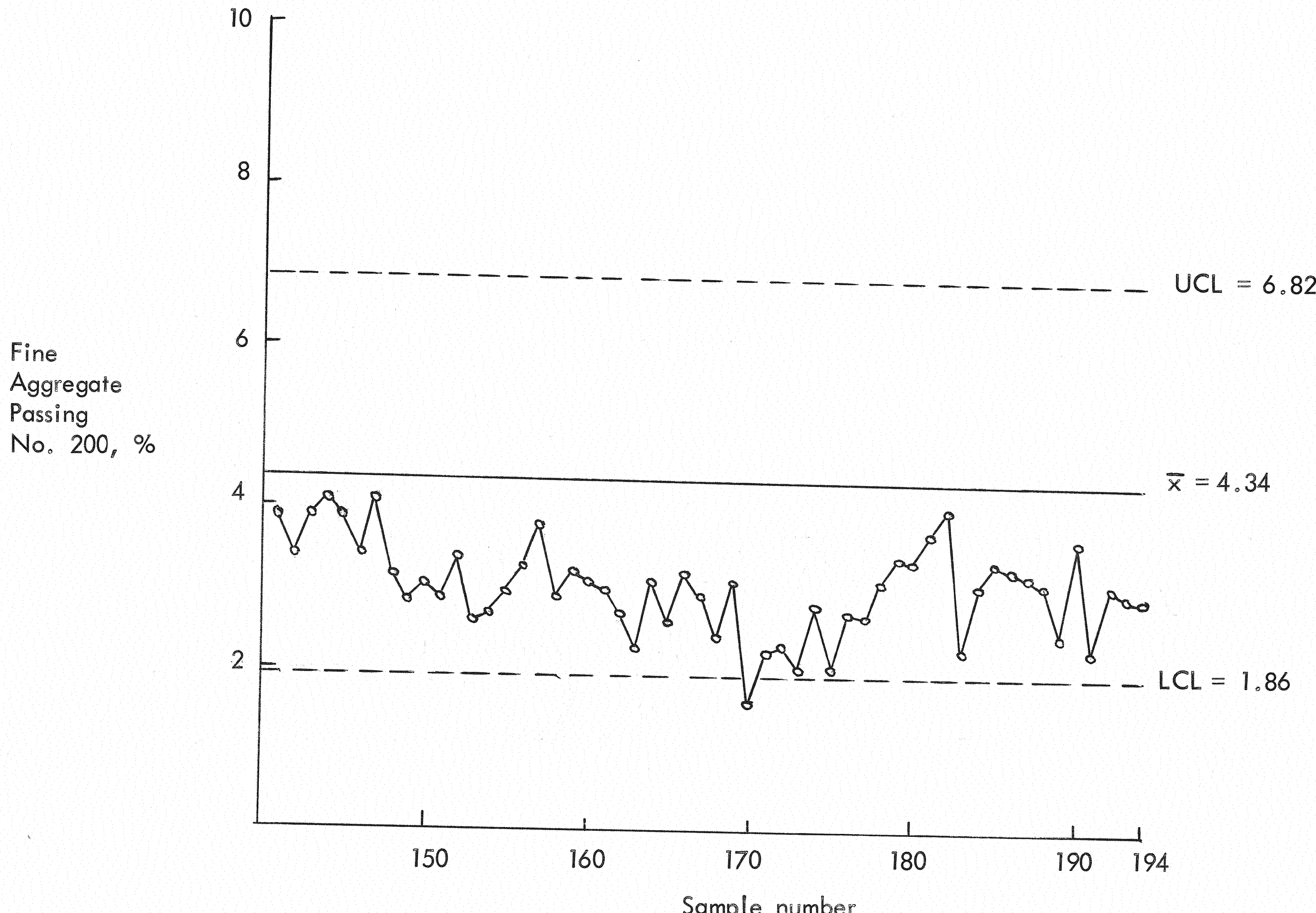


Figure I-34(cont.). % Passing No. 200 F.A. = quality control chart

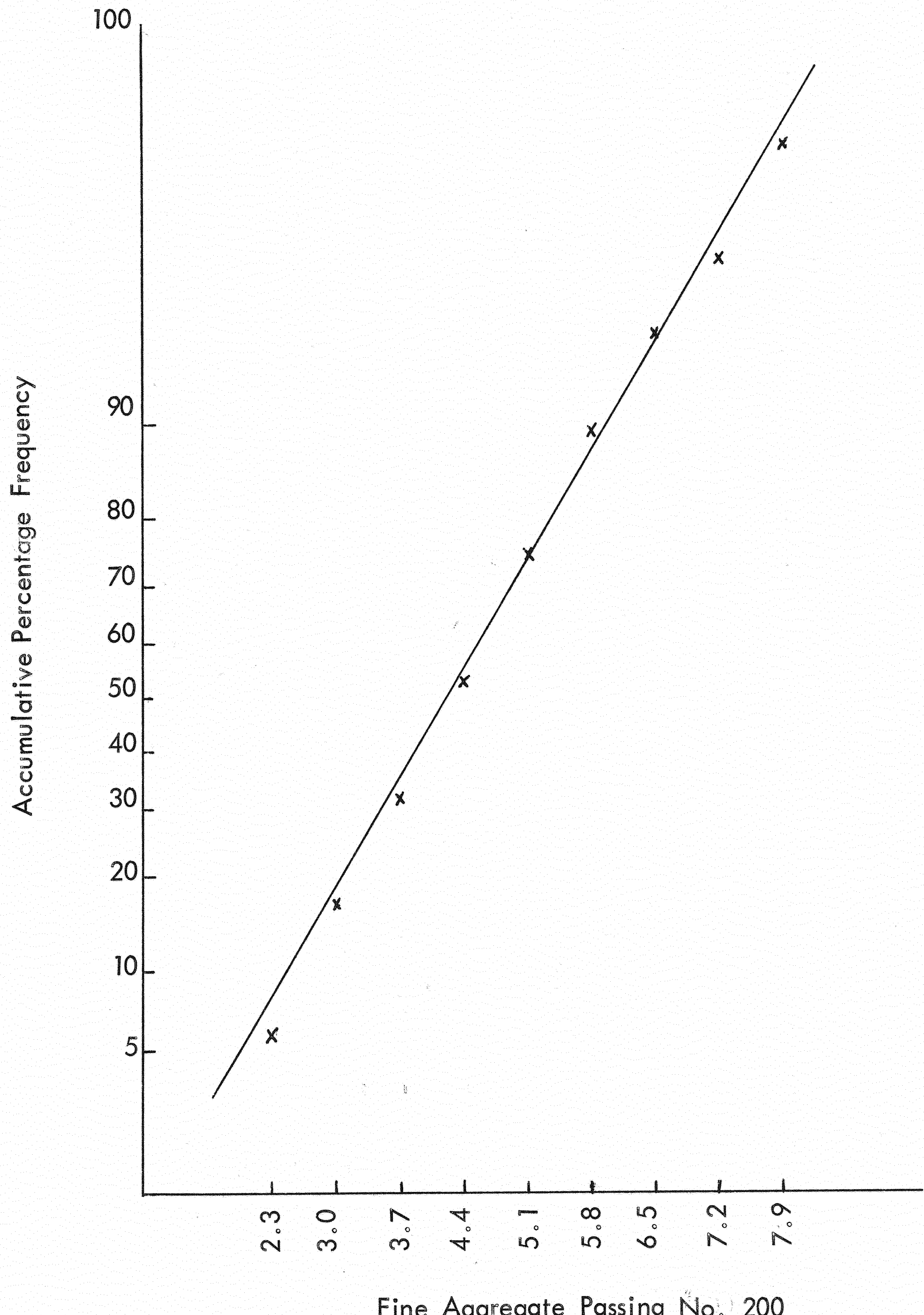


Figure I-35. % Passing No. 200 F.A. - goodness of fit curve

No.	Sand Equivalent Range, %	f	%	Cum%
1	- 83.9	6	3	3
2	84.0 - 84.9	8	4	7
3	85.0 - 85.9	16	8.1	15.1
4	86.0 - 86.9	34	17.2	32.3
5	87.0 - 87.9	32	16.2	48.5
6	88.0 - 88.9	47	23.8	72.3
7	89.0 - 89.9	30	15.2	87.5
8	90.0 - 90.9	13	6.5	94.0
9	91.0 - 91.9	7	3.5	97.5
10	92.0 -	5	2.5	100
		198	100	

n	198
specs	--
$\bar{x}$	87.8
$\hat{\sigma}_T$	2.4
σ_t^2	2.6
σ_s^2	0.3
σ_a^2	2.8
V	2.7%

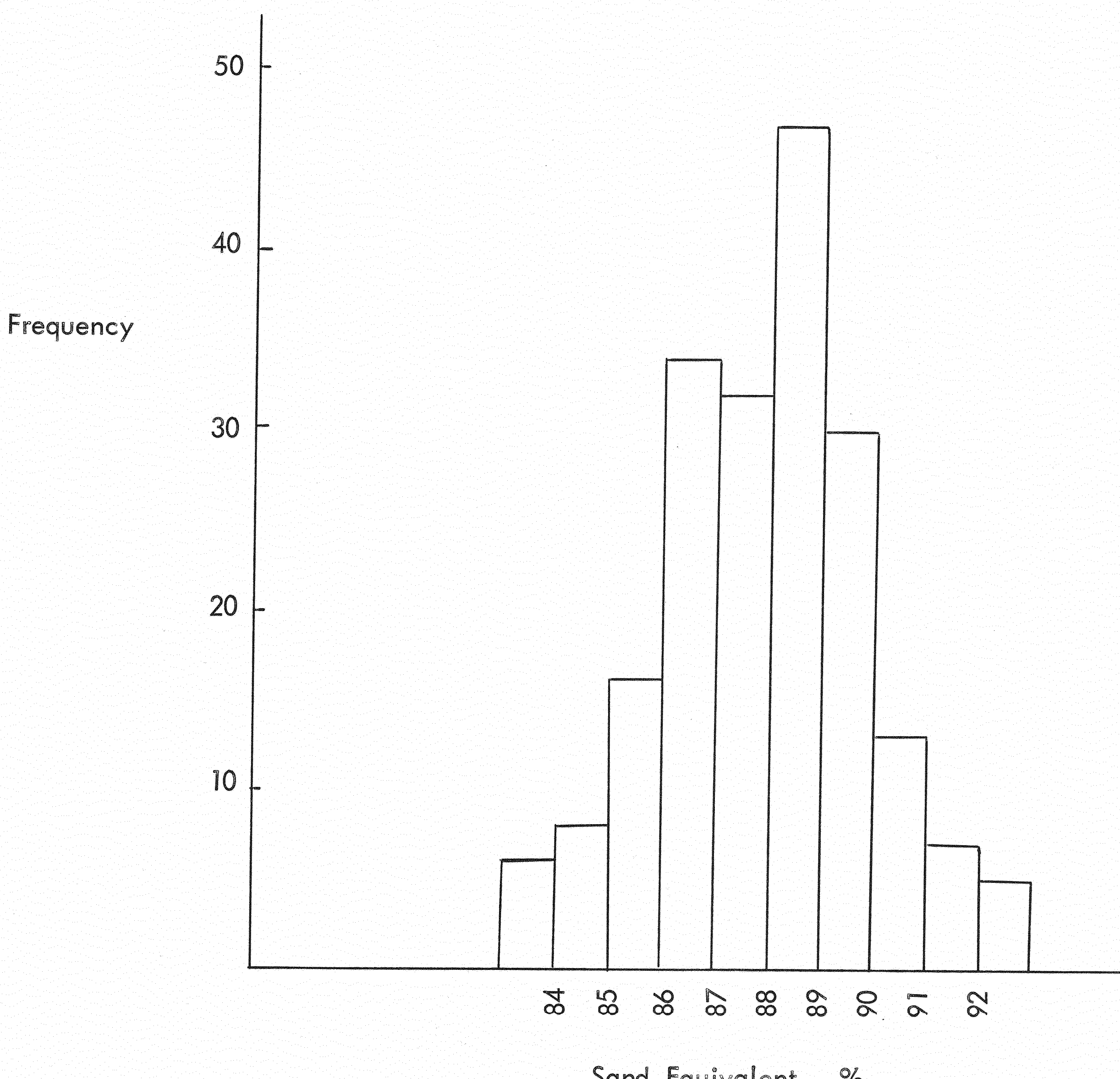


Figure I-36. Sand equivalent - statistical properties

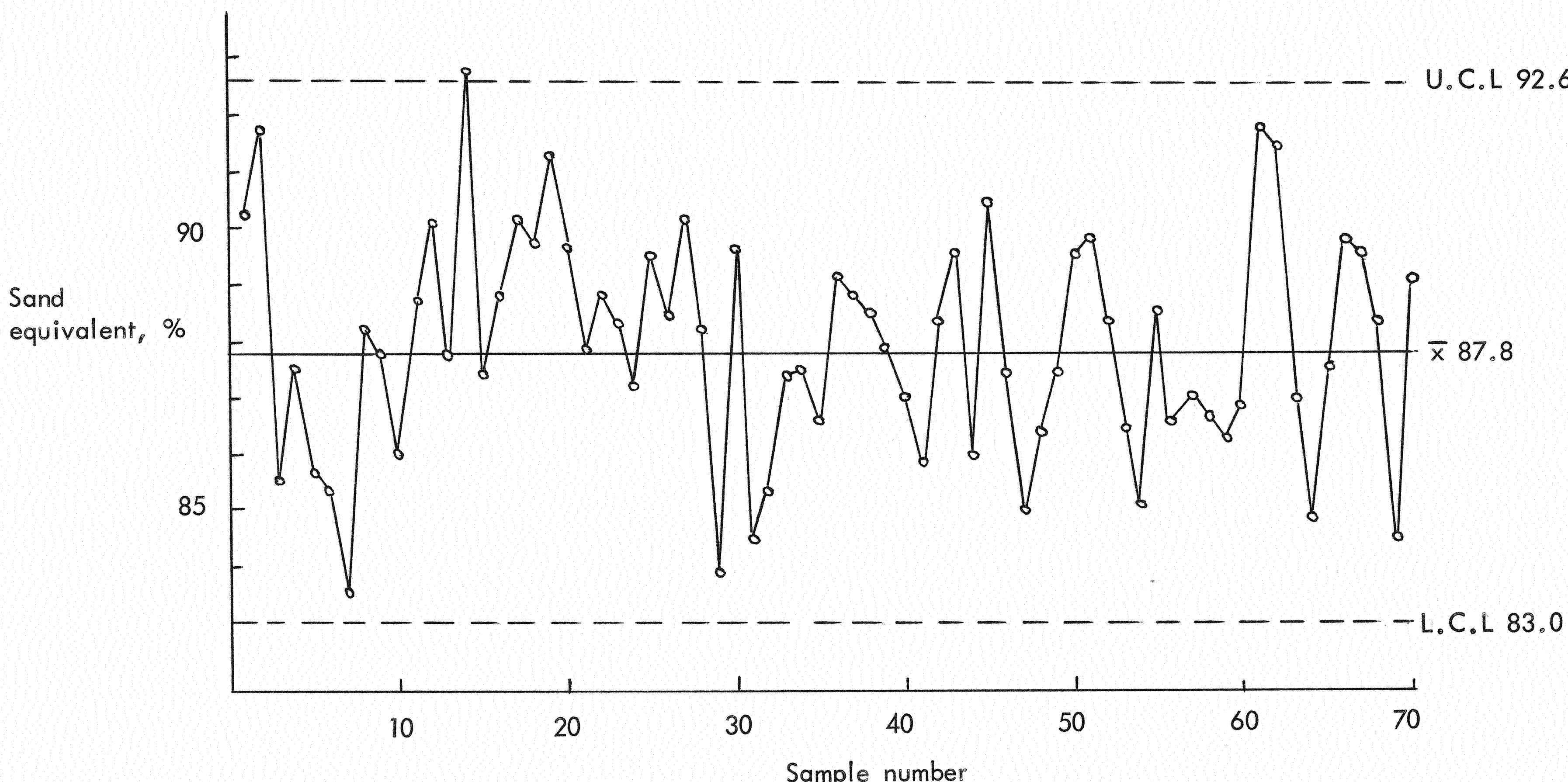


Figure I-37. Sand equivalent - quality control chart

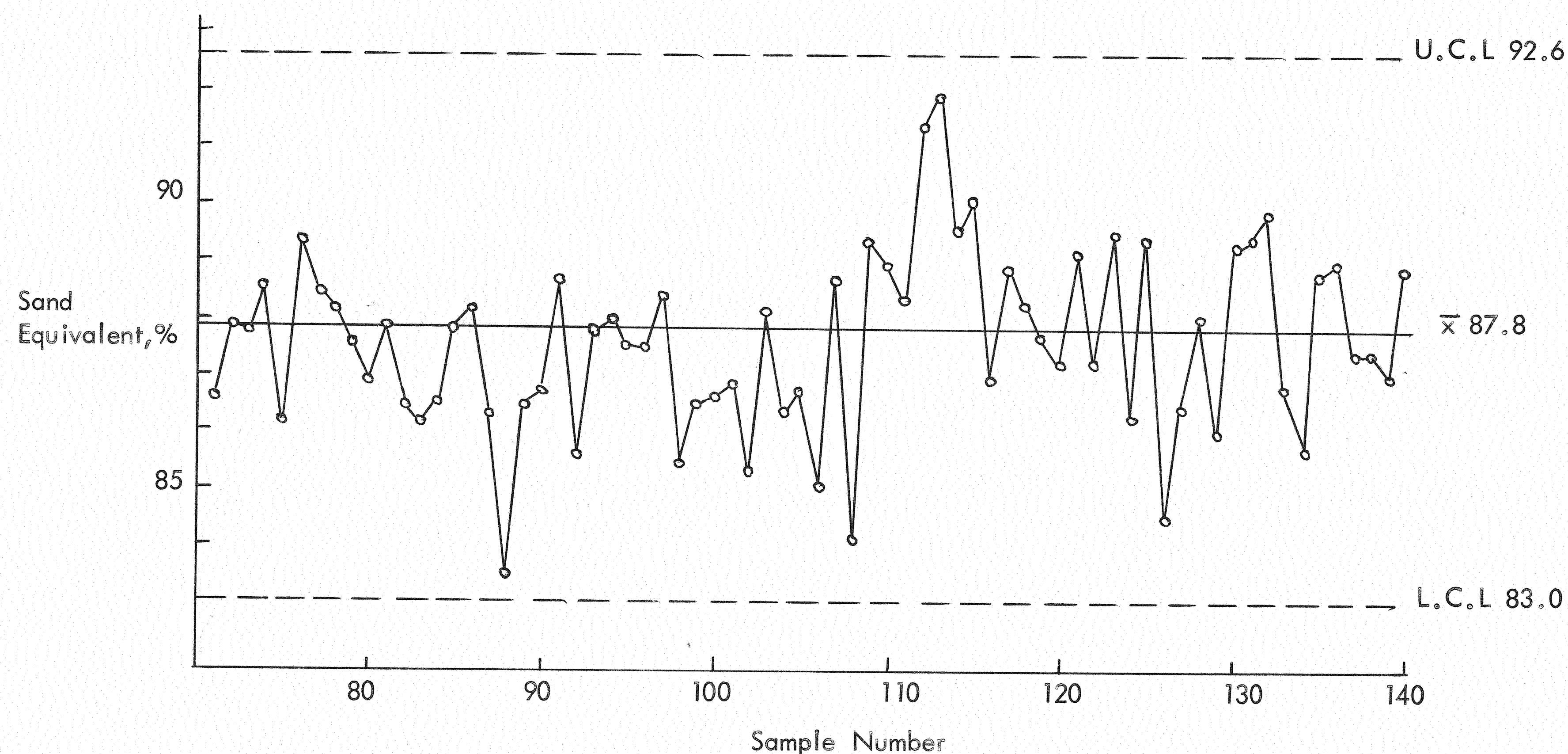


Figure I-37(cont.). Sand equivalent - quality control chart

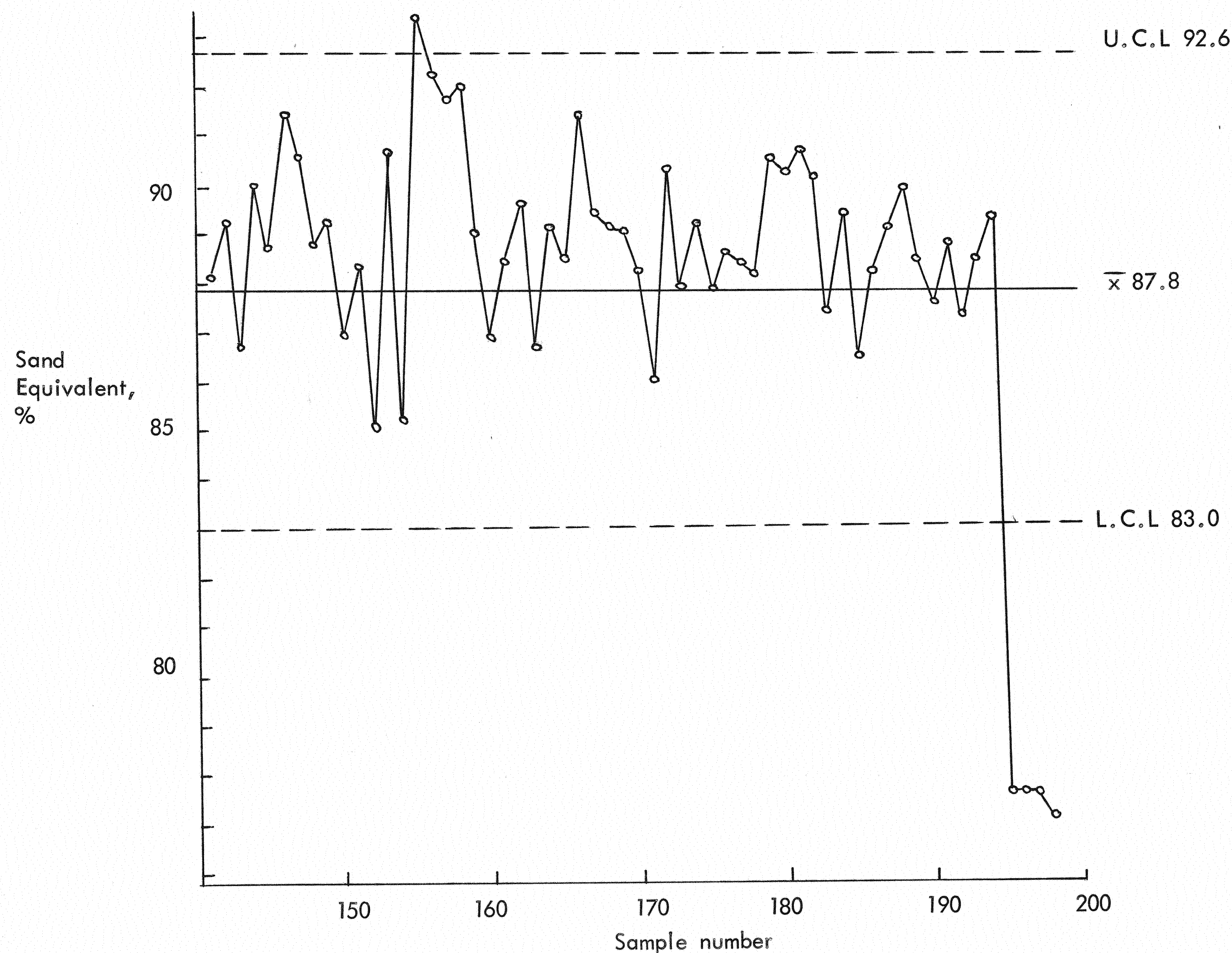


Figure I-37(cont.). Sand Equivalent - quality control chart

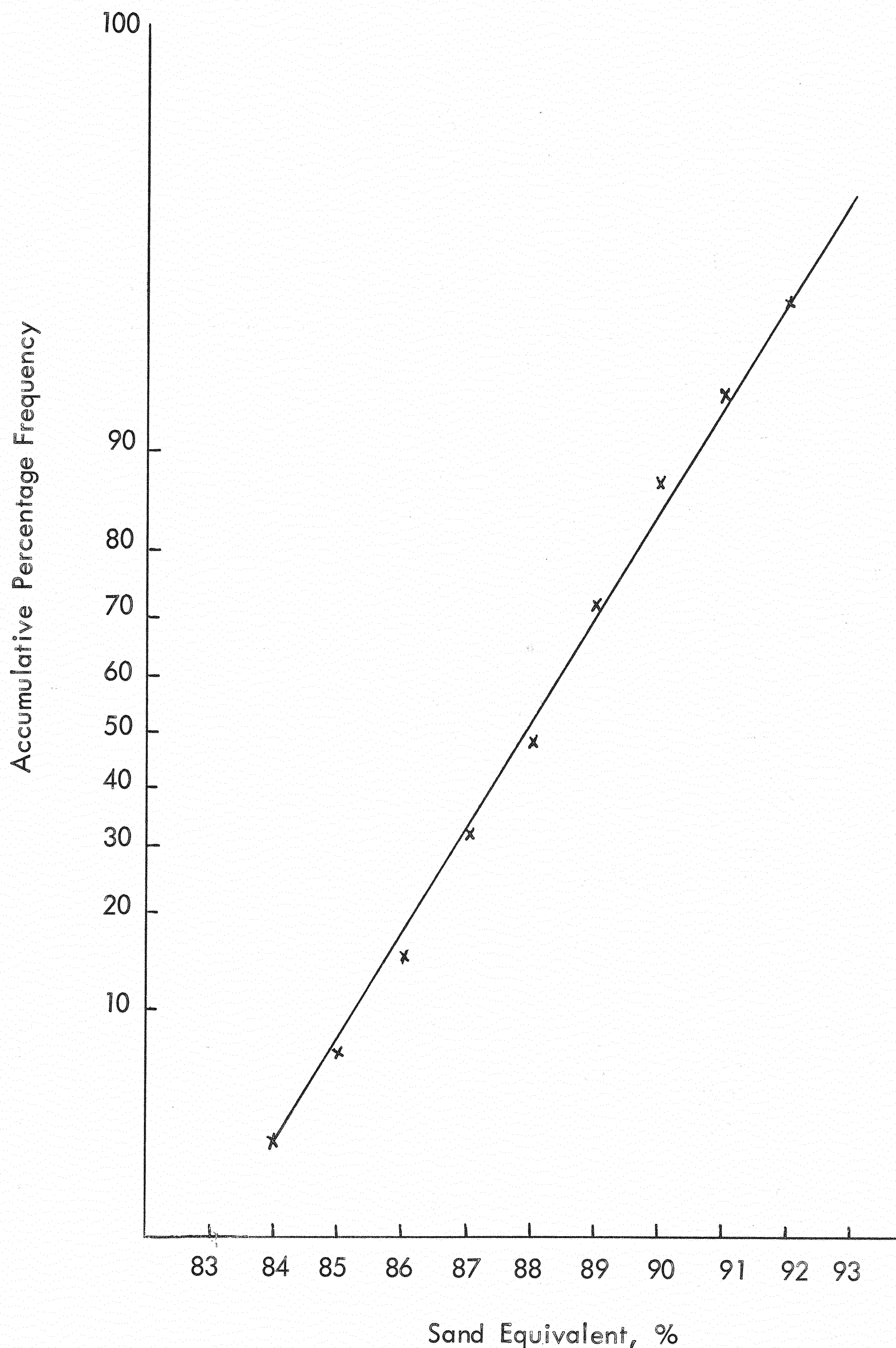


Figure I-38. Sand Equivalent - goodness of fit curve

No.	Cement Strength Range, psi	f	%	Cum%
1	550 - 650	3	6.3	6.3
2	650 - 750	3	6.3	12.6
3	750 - 850	7	14.6	27.2
4	850 - 950	11	22.9	50.1
5	950 - 1050	8	16.6	66.7
6	1050 - 1150	10	20.8	87.5
7	1150 - 1250	4	8.3	95.8
8	1250 - 1350	1	2.1	97.9
9	1350 - 1450	1	2.1	100.0
		48	100	

n	48
specs	--
$\bar{x}$	949.4
σ_T	184.8
σ_t^2	19302.7
σ_s^2	2684.4
σ_a^2	12175.7
V	19.5%

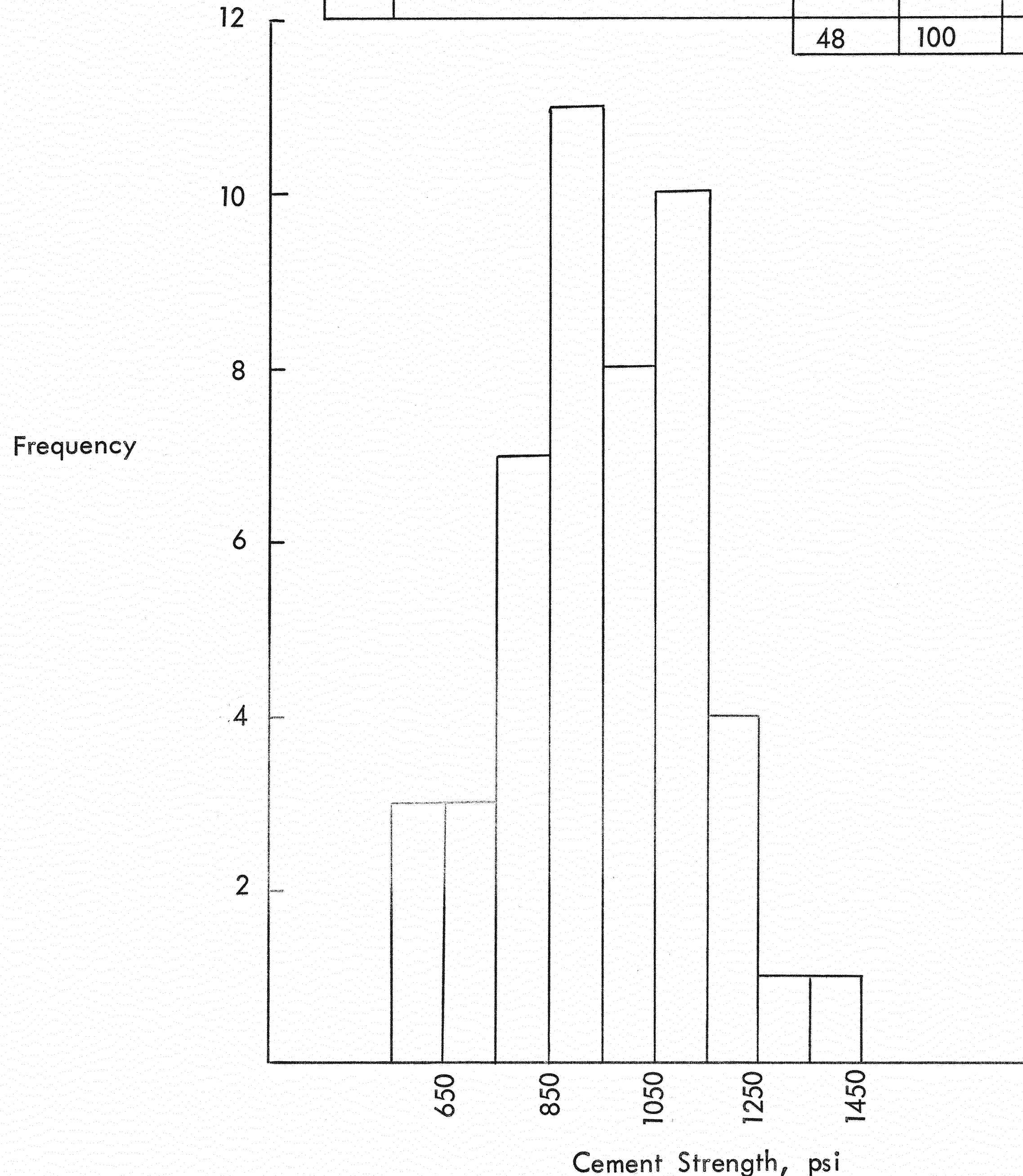
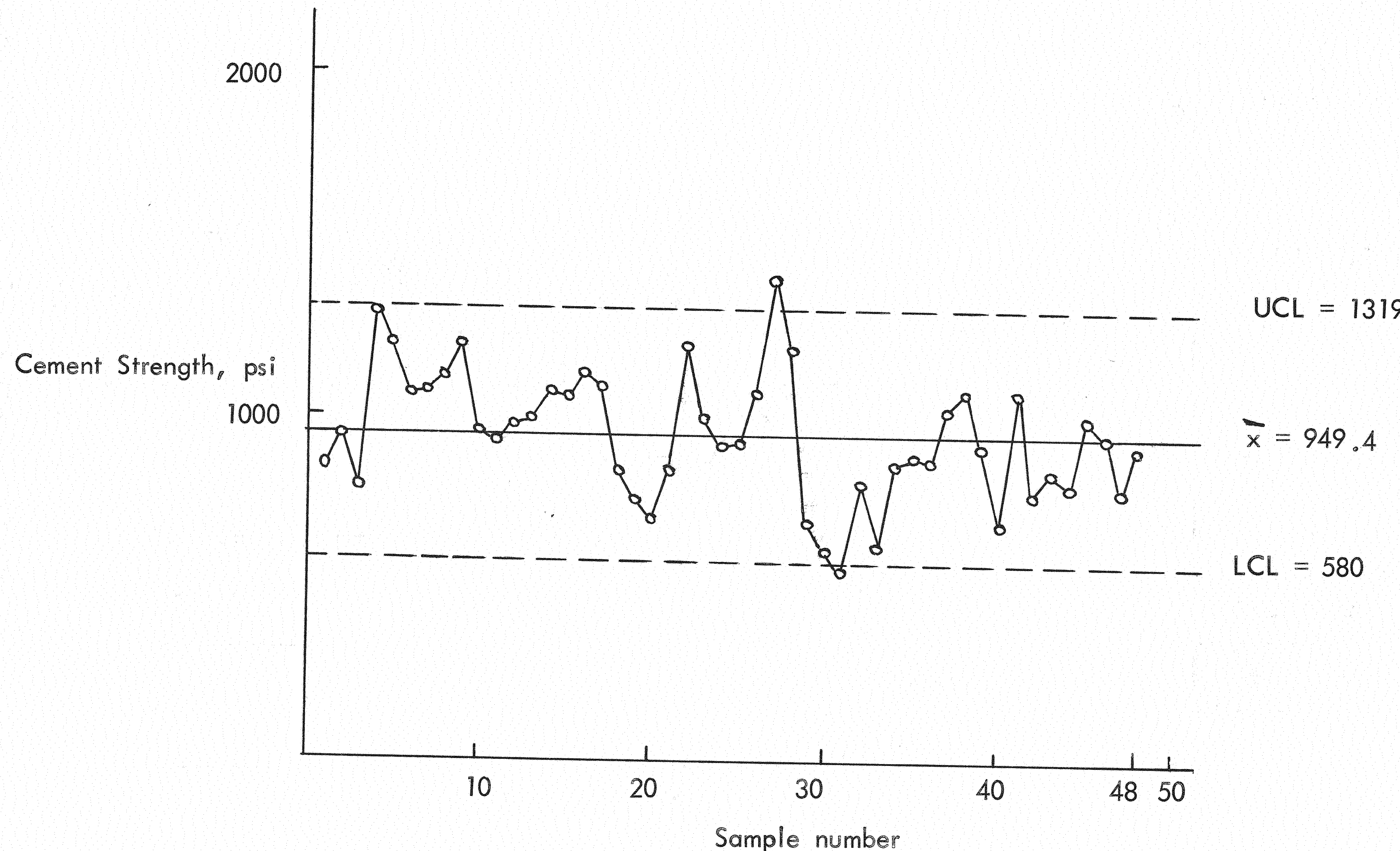


Figure I-39. Cement strength - statistical properties



Figuer I-40. Cement strength - quality control chart

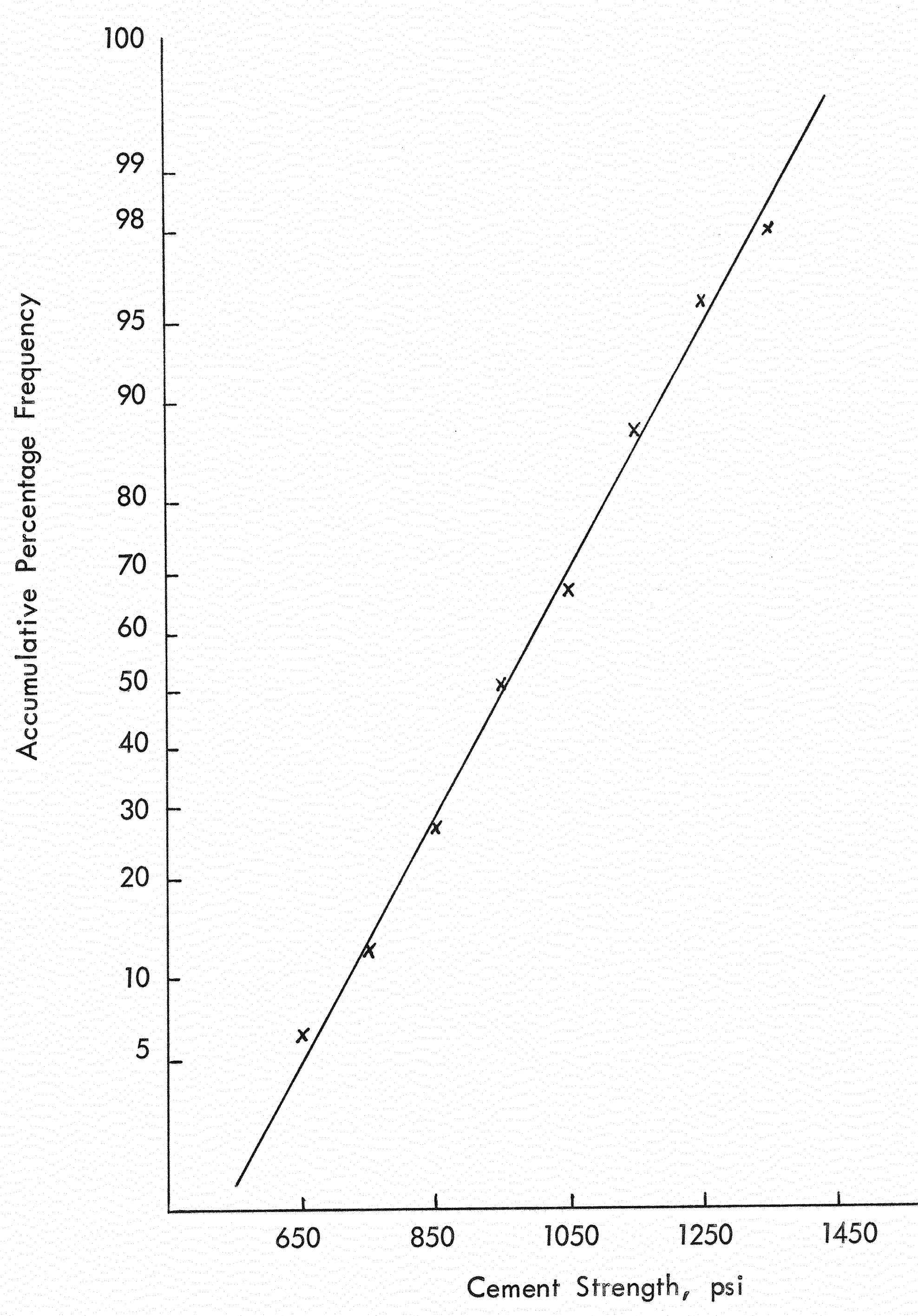


Figure I-41. Cement strength - goodness of fit curve

No.	Cement Air Content Range, %	f′	%	Cum%
1	- 350	1	2	2
2	350 - 4.00	15	30	32
3	4.00 - 4.50	17	34	66
4	4.50 - 5.00	5	10	76
5	5.00 - 5.50	2	4	80
6	5.50 - 6.00	3	6	86
7	6.00 - 6.50	1	2	88
8	6.50 - 7.00	2	4	92
9	7.00 - 7.50	1	2	94
10	7.50 - 8.00	1	2	96
11	8.00 - 8.50	2	4	100
		50	100	

n	50
specs	--
$\bar{x}$	4.0
σ_T	0.77
σ_t^2	0.03
σ_s^2	0.01
σ_a^2	0.54
V	19.3%

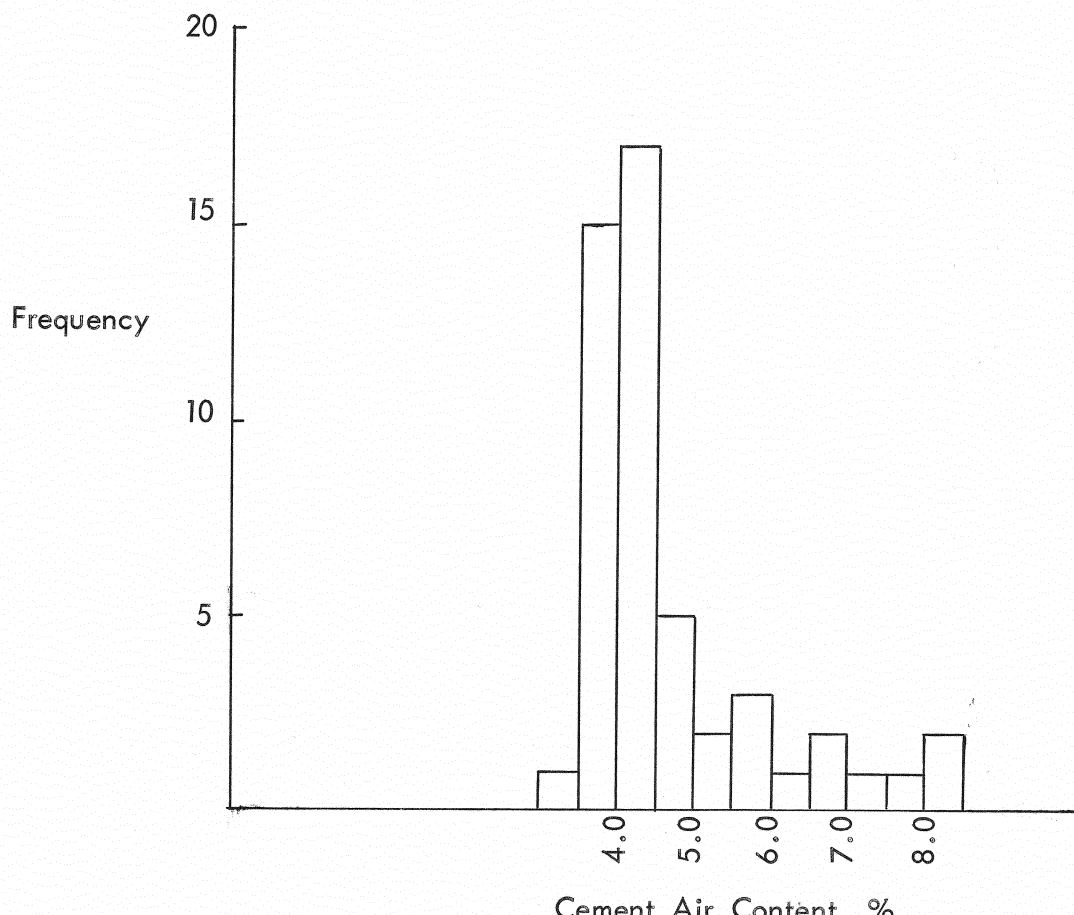


Figure I-42. Cement air content - statistical properties

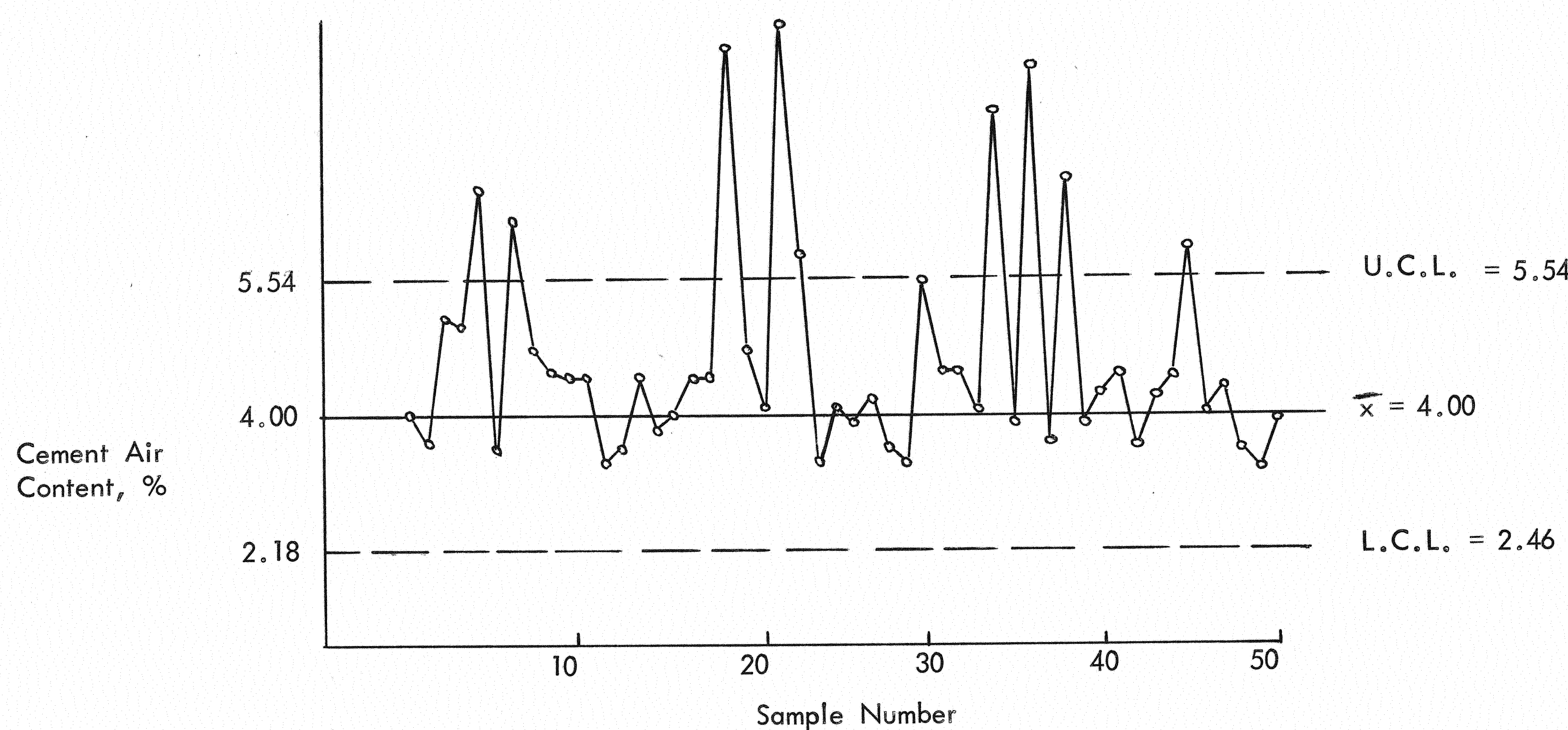


Figure I-43. Cement Air Content - quality control chart

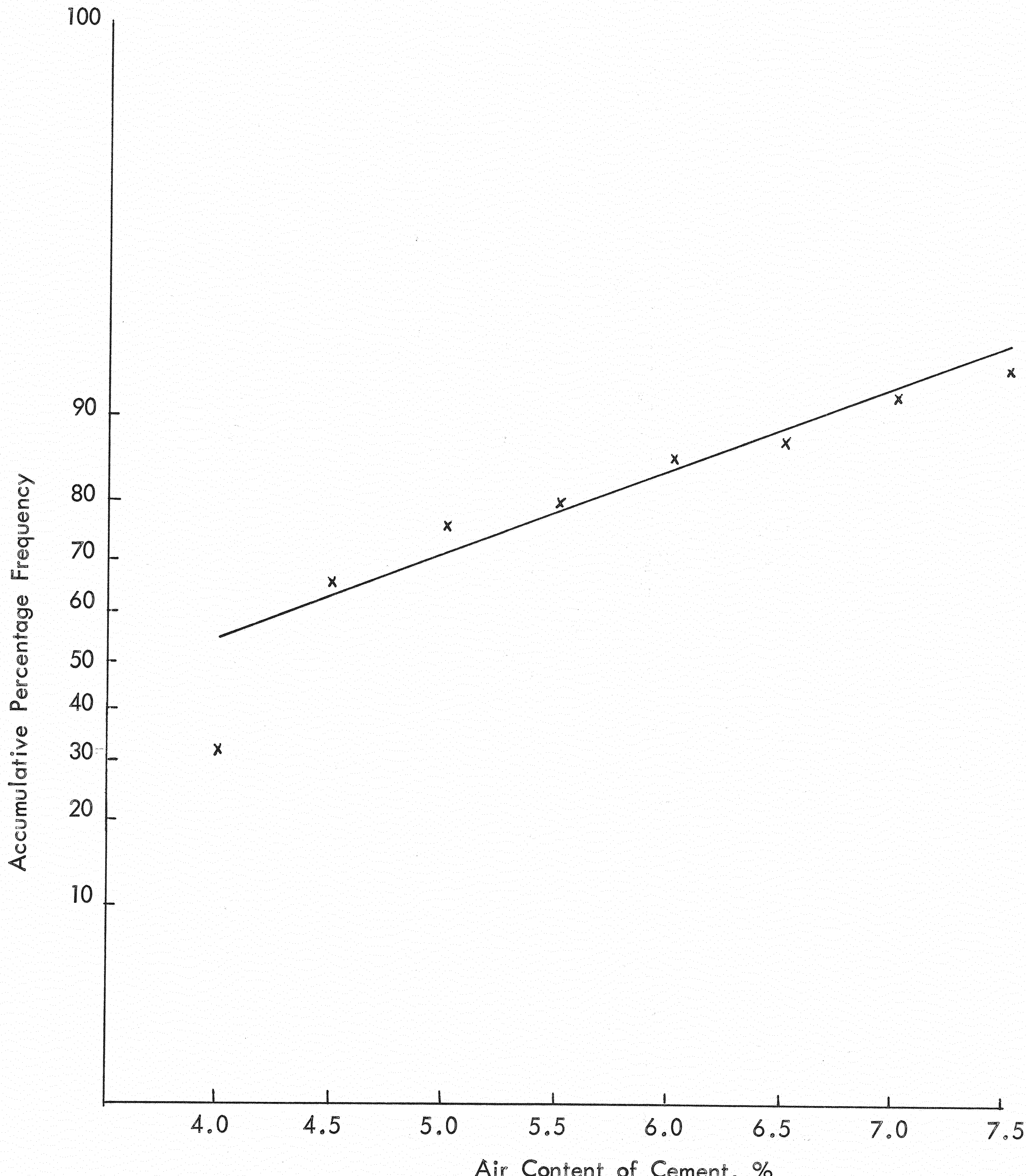


Figure I-44. Cement Air Content - goodness of fit curve

No.	Alkali Content Range, %	f	%	Cum%
1	0.15 - 0.18	5	10.4	10.4
2	0.18 - 0.21	2	4.2	14.6
3	0.21 - 0.24	9	18.7	33.3
4	0.24 - 0.27	19	39.6	72.9
5	0.27 - 0.30	7	14.6	87.5
6	0.30 - 0.33	6	12.5	100.0
		48	100	

n	48
specs	--
$\bar{x}$	0.245
σ_T	0.043
σ_t^2	0.0012
σ_s^2	0.0003
σ_a^2	0.0004
V	17.6 %

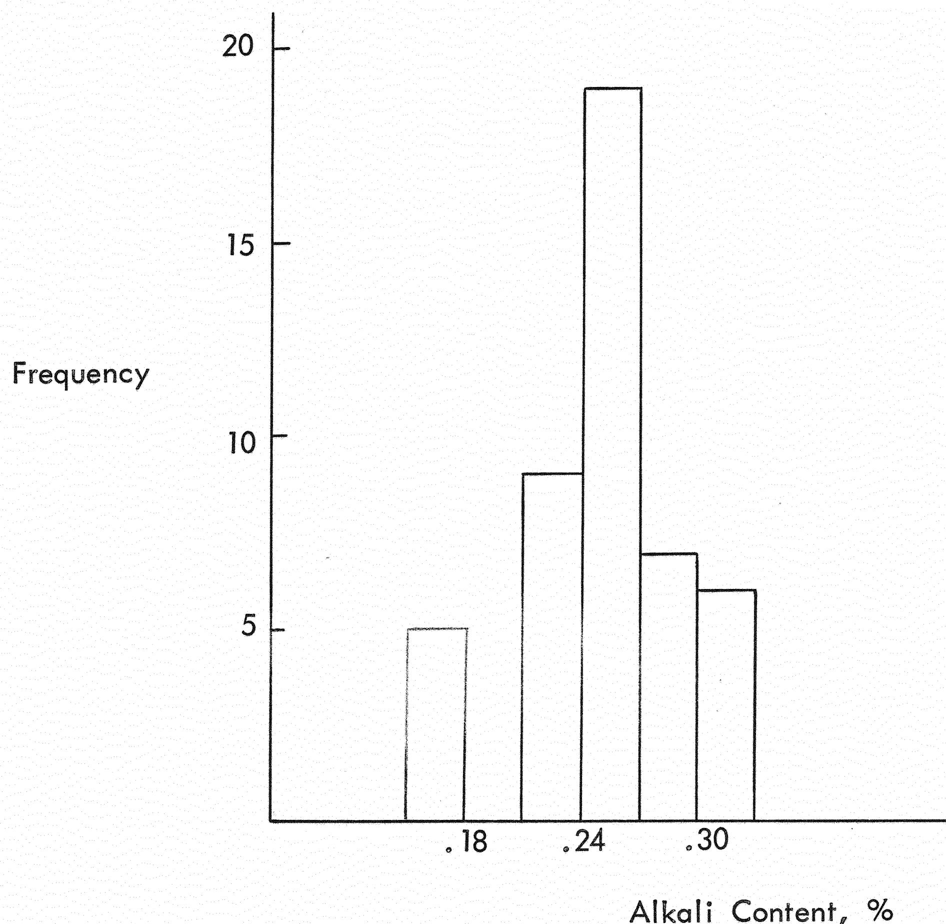


Figure I-45. Alkali Content - statistical properties

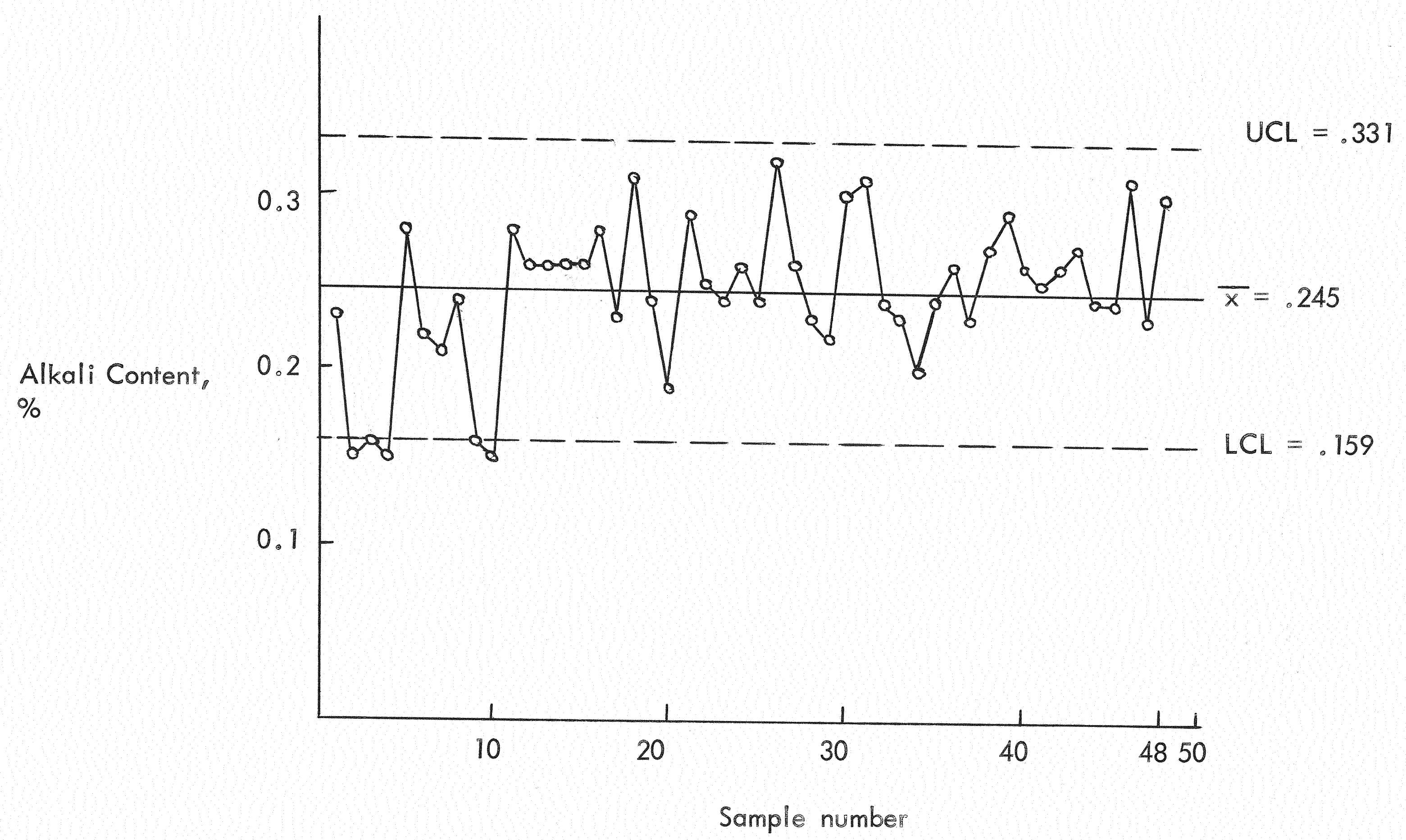


Figure I-46. Alkali Content - quality control chart

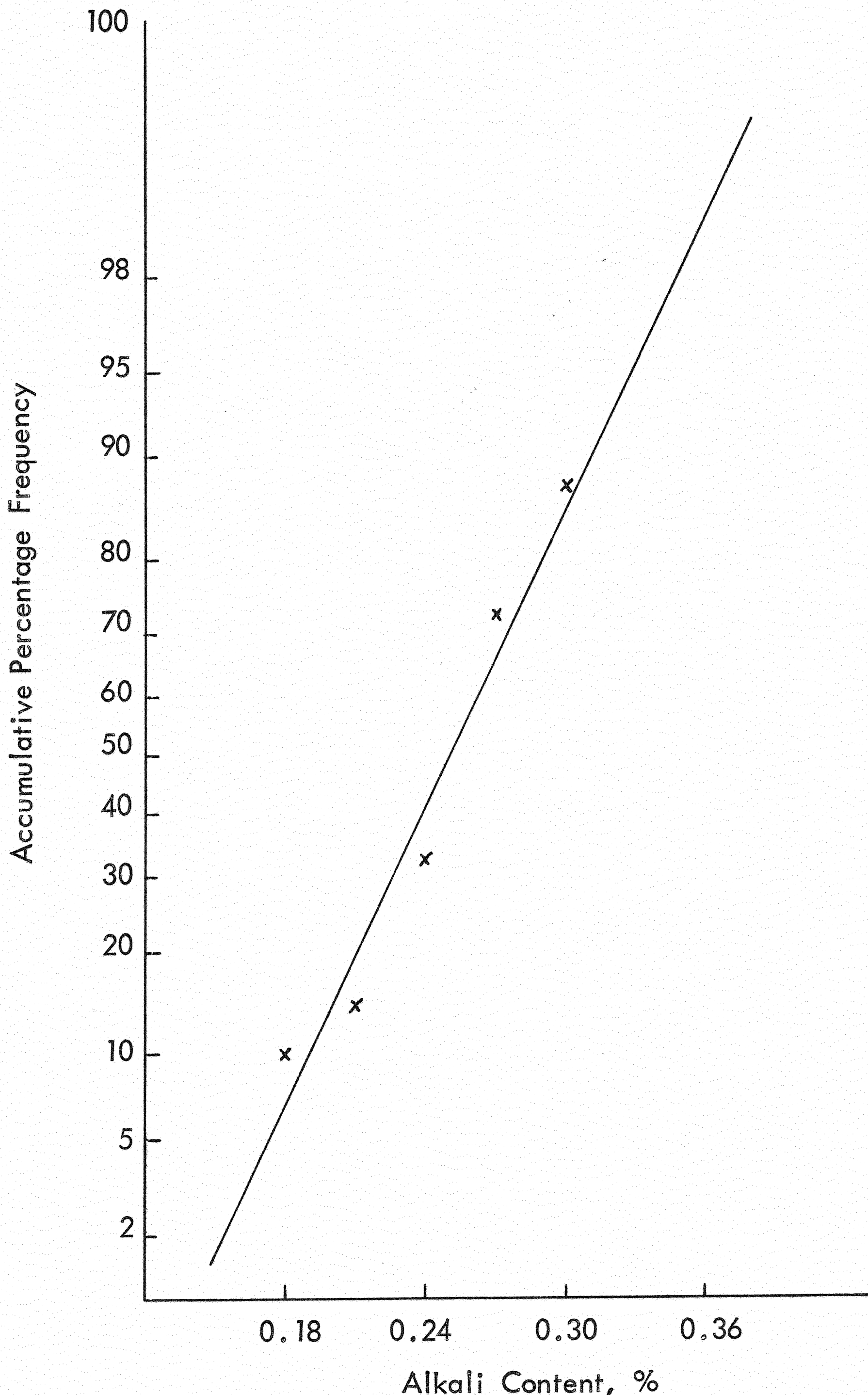


Figure I-47. Alkali Content - goodness of fit curve

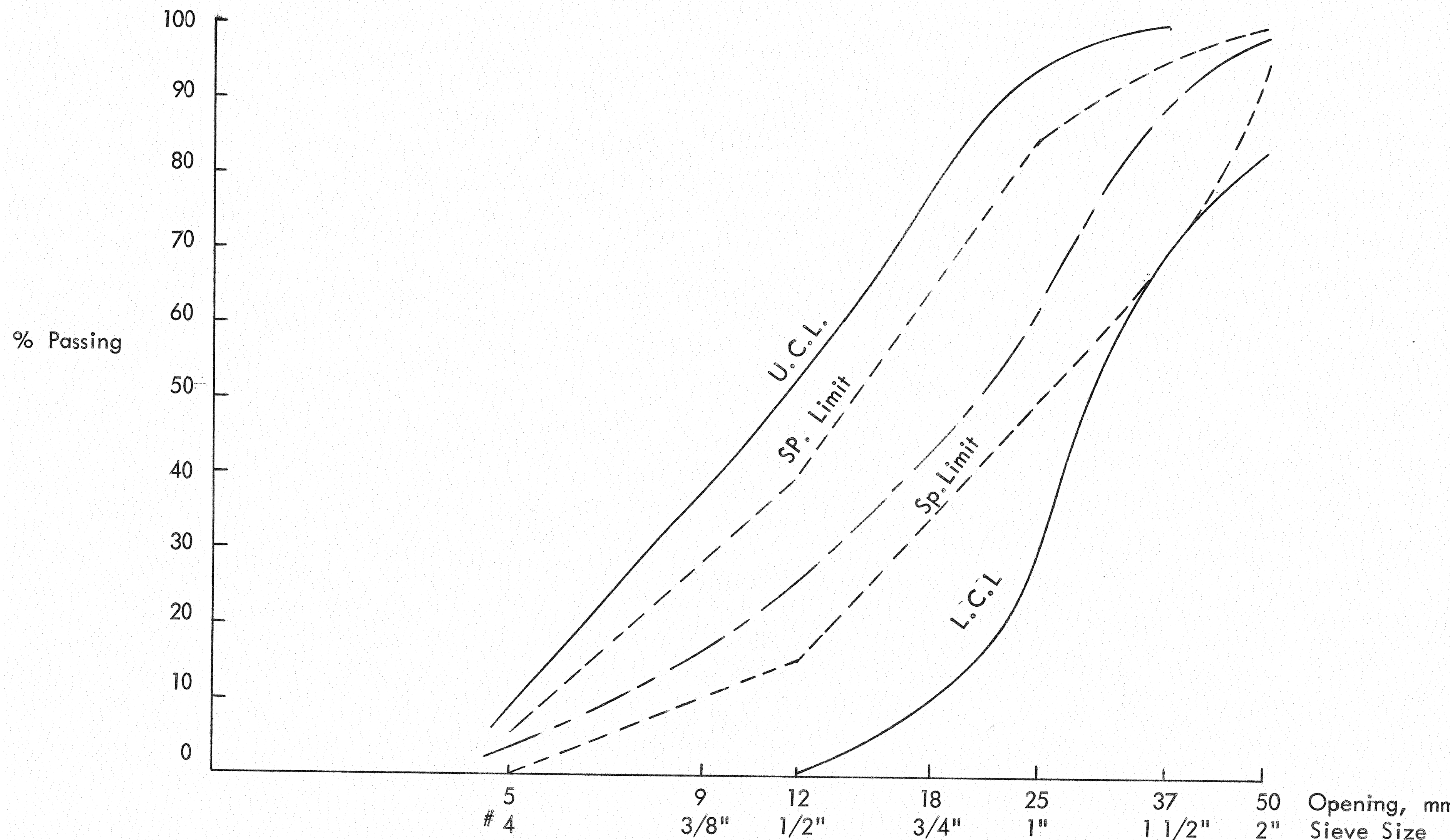


Figure I-48. Gradation analysis for coarse aggregate

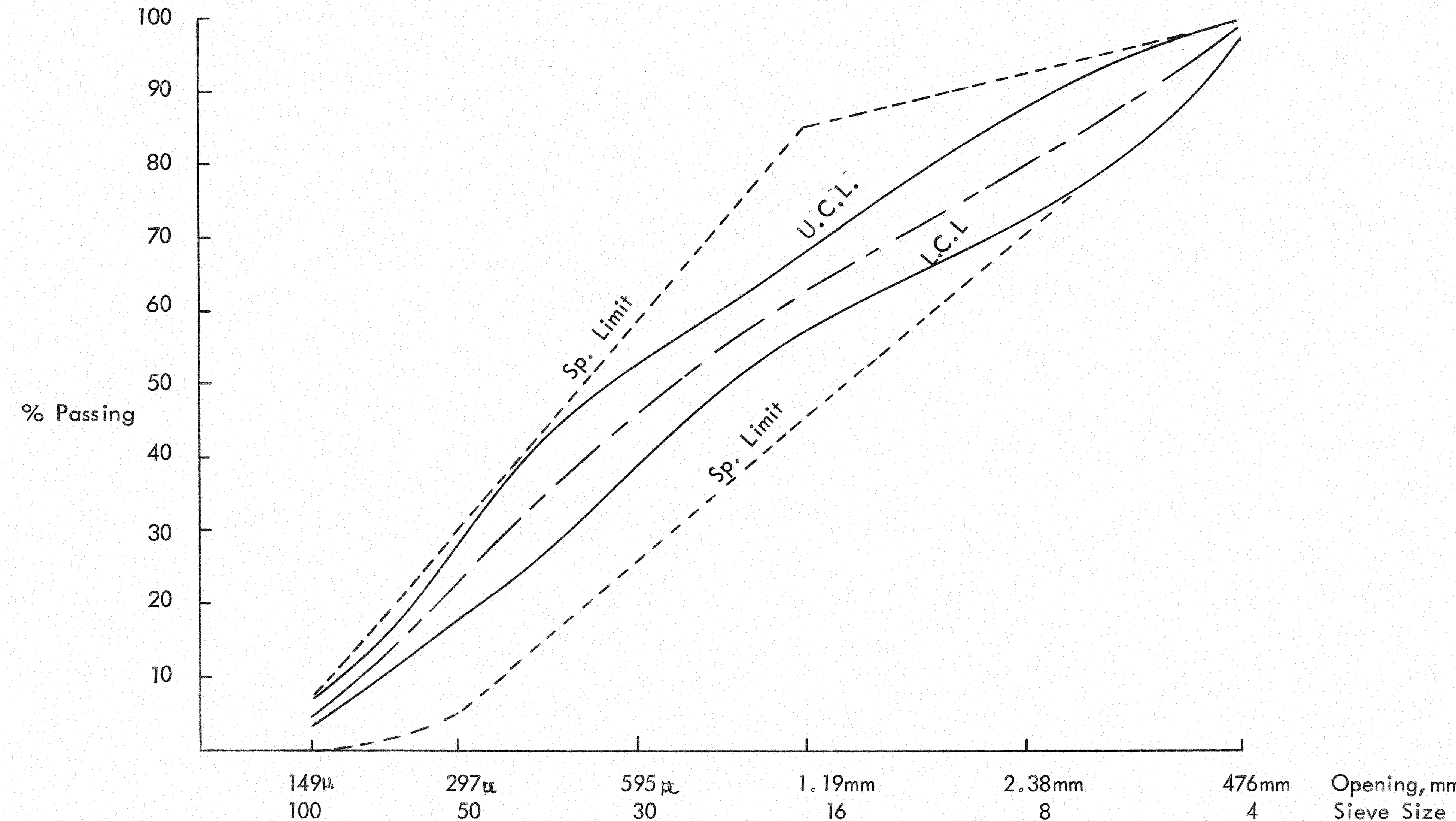
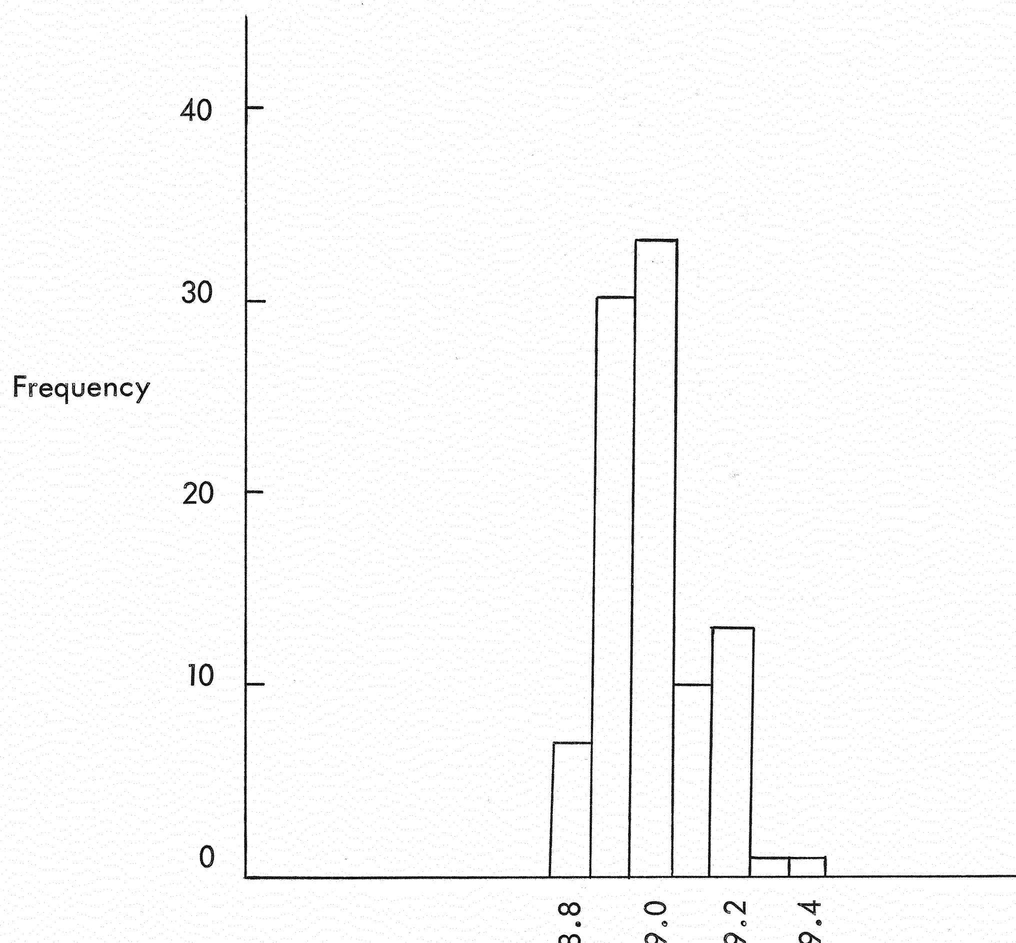


Figure I-49. Gradation analysis for fine aggregate

No.	Thickness Range, in.	f	%	Cum%
1	- 8.8	7	7.4	7.4
2	- 8.9	30	31.6	39.0
3	- 9.0	33	34.8	73.8
4	- 9.1	10	10.5	84.3
5	- 9.2	13	13.7	98.0
6	- 9.3	1	1.0	99.0
7	- 9.4	1	1.0	100.0
		95	100	

n	95
specs	9.0in.
$\overline{x}$	8.9
σ_T	0.1
σ_t^2	--
σ_s^2	--
σ_a^2	--
V	1.1%



Thickness Distribution, Inch

Figure II-50. Thickness - statistical properties

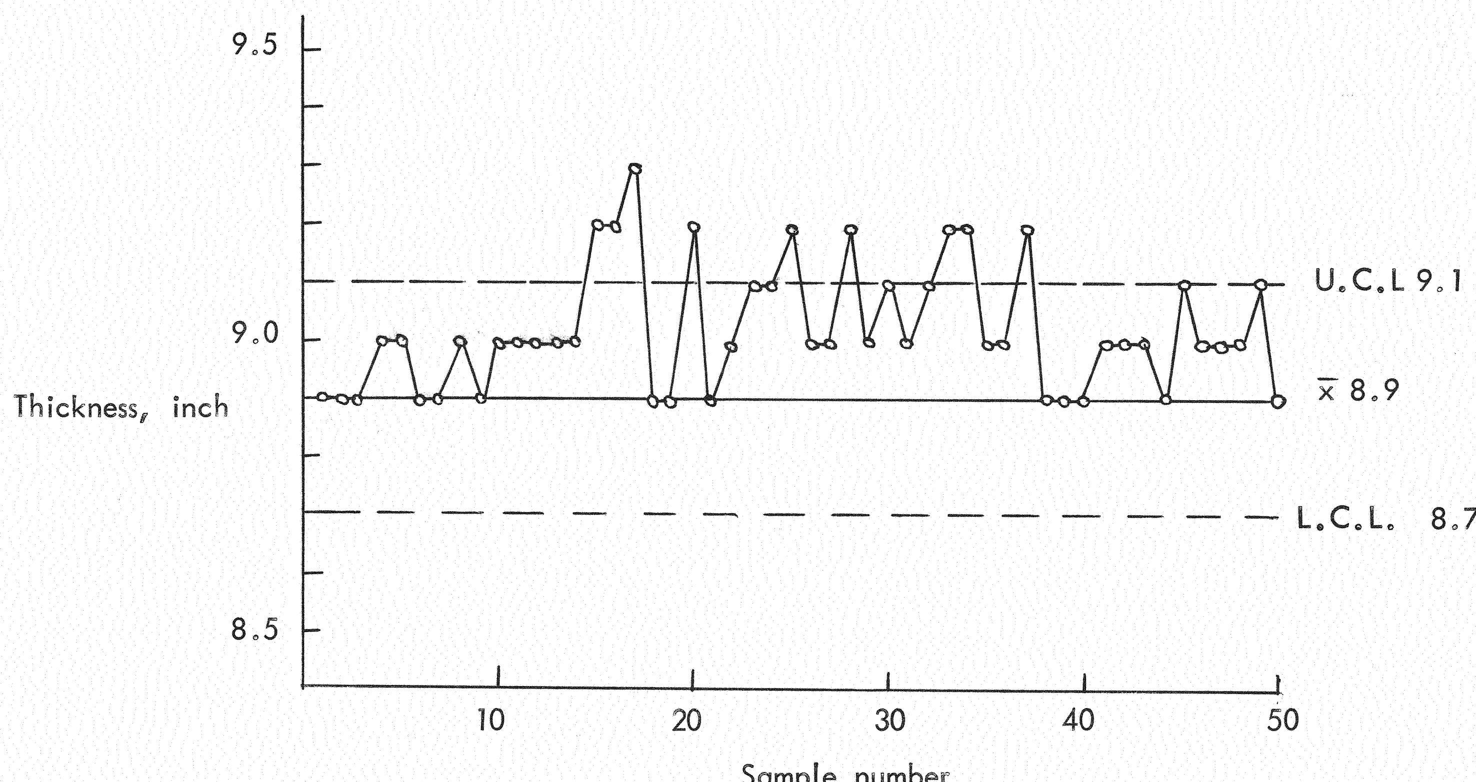


Figure II-51. Thickness - quality control chart

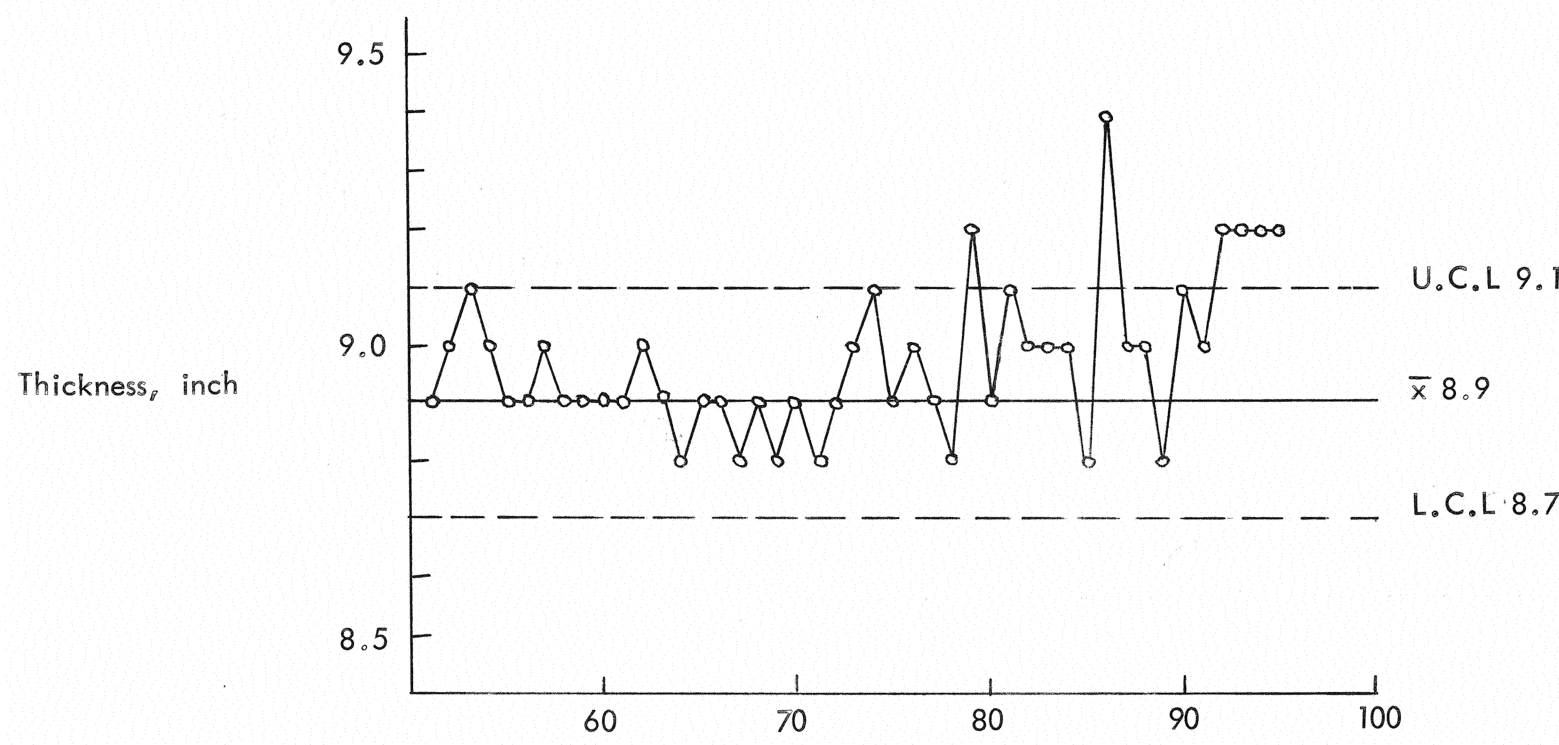


Figure II-51.(cont.). Thickness - quality control chart

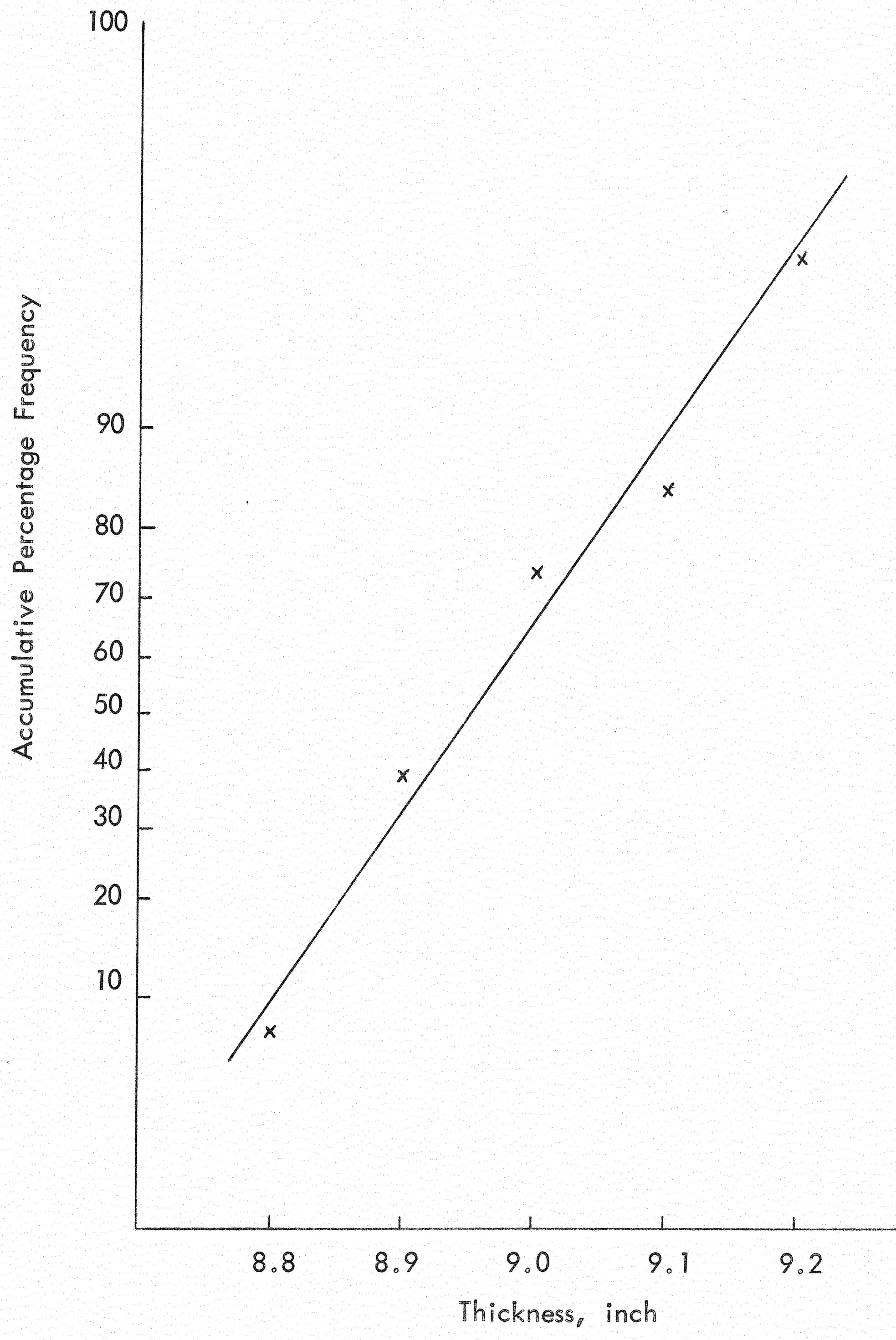


Figure II-52. Thickness - goodness of fit curve

No.	Slump Range, in.	f	%	Cum %
1	- 0.5	16	3.0	8.0
2	0.5 - 1.0	43	21.5	29.5
3	1.0 - 1.5	52	26.0	55.5
4	1.5 - 2.0	54	27.0	82.5
5	2.0 - 2.5	16	8.0	90.5
6	2.5 - 3.0	9	4.5	95.0
7	3.0 - 3.5	3	1.5	96.5
8	3.5 - 4.0	7	3.5	100.0
		200	100	

n	200
specs	0.5-3.5 in.
$\overline{x}$	1.5
σ_T	0.8
σ_t^2	0.13
σ_s^2	0.02
σ_a^2	0.45
V	53.3%

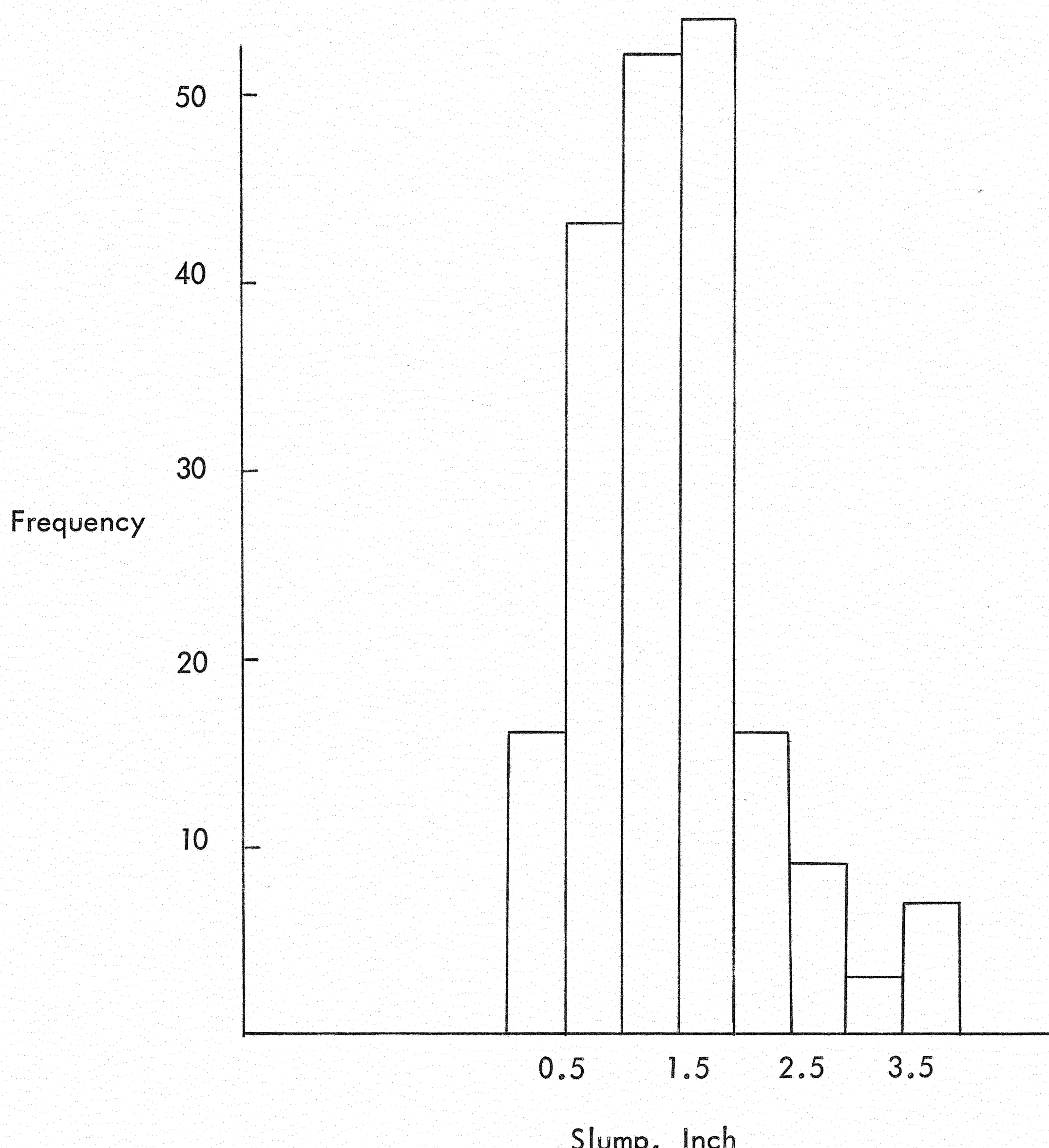


Figure II-53. Slump - statistical properties

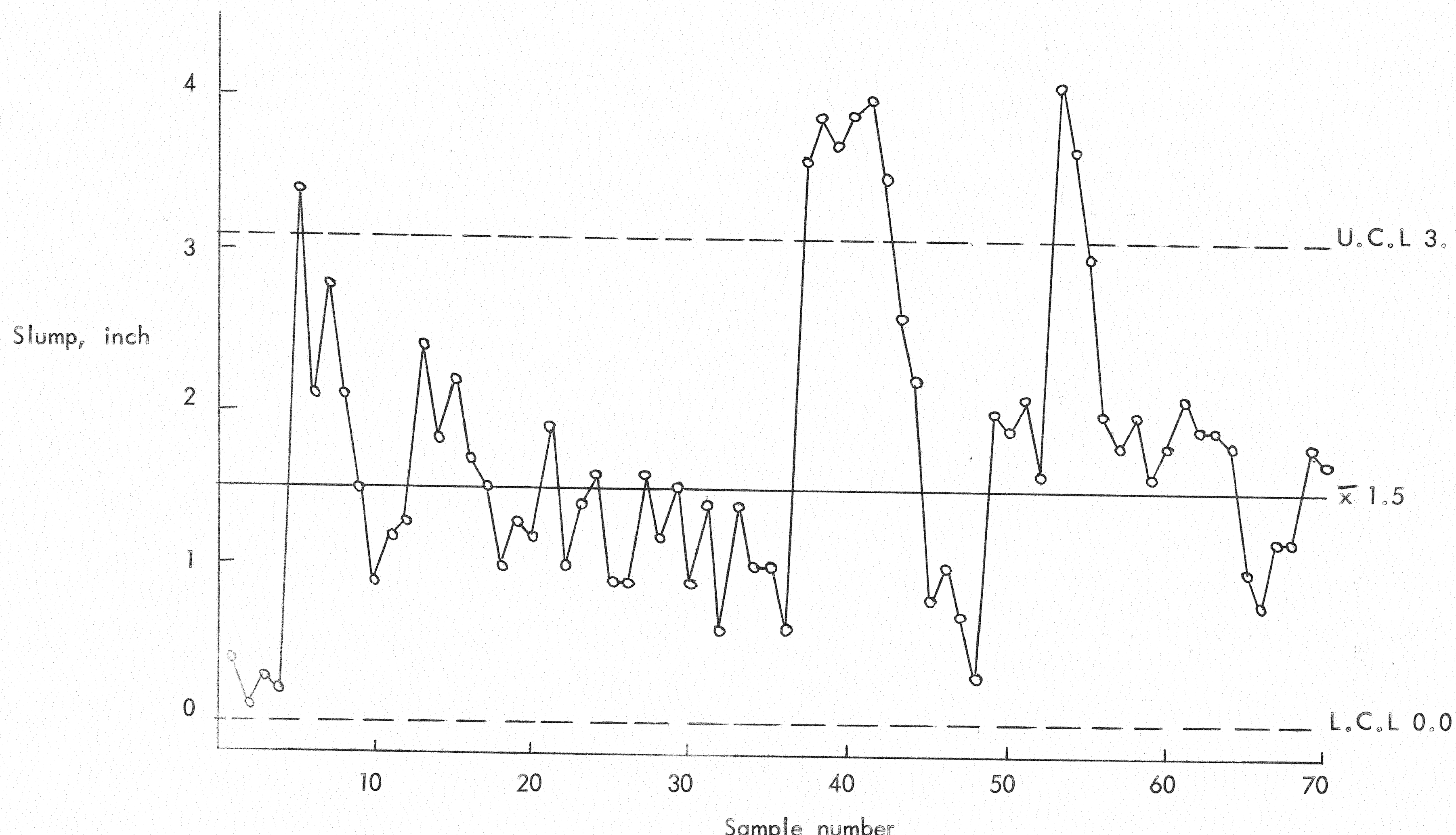


Figure II-54 Slump – quality contorl chart

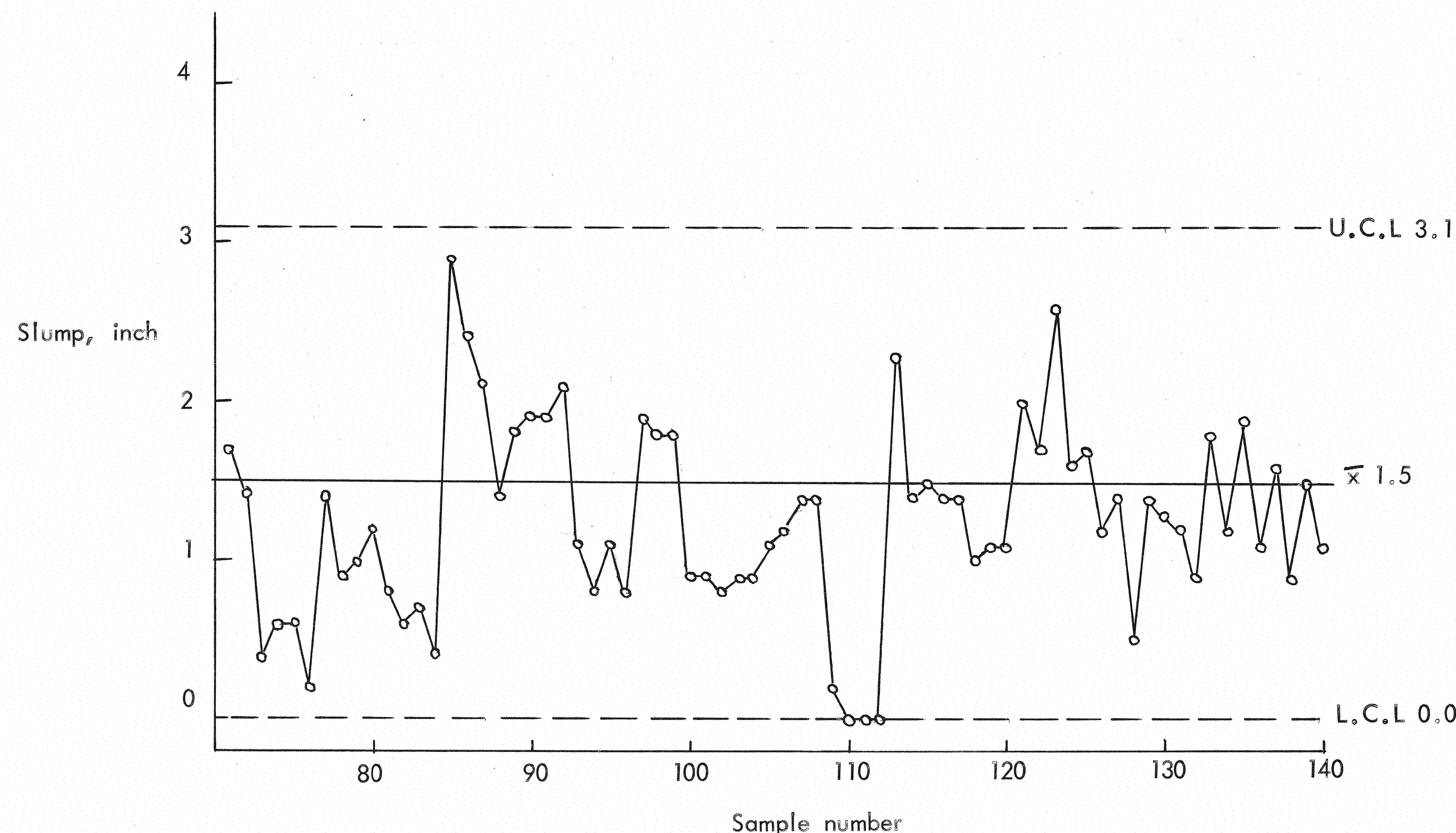


Figure II-54.(cont.). Slump - quality control chart

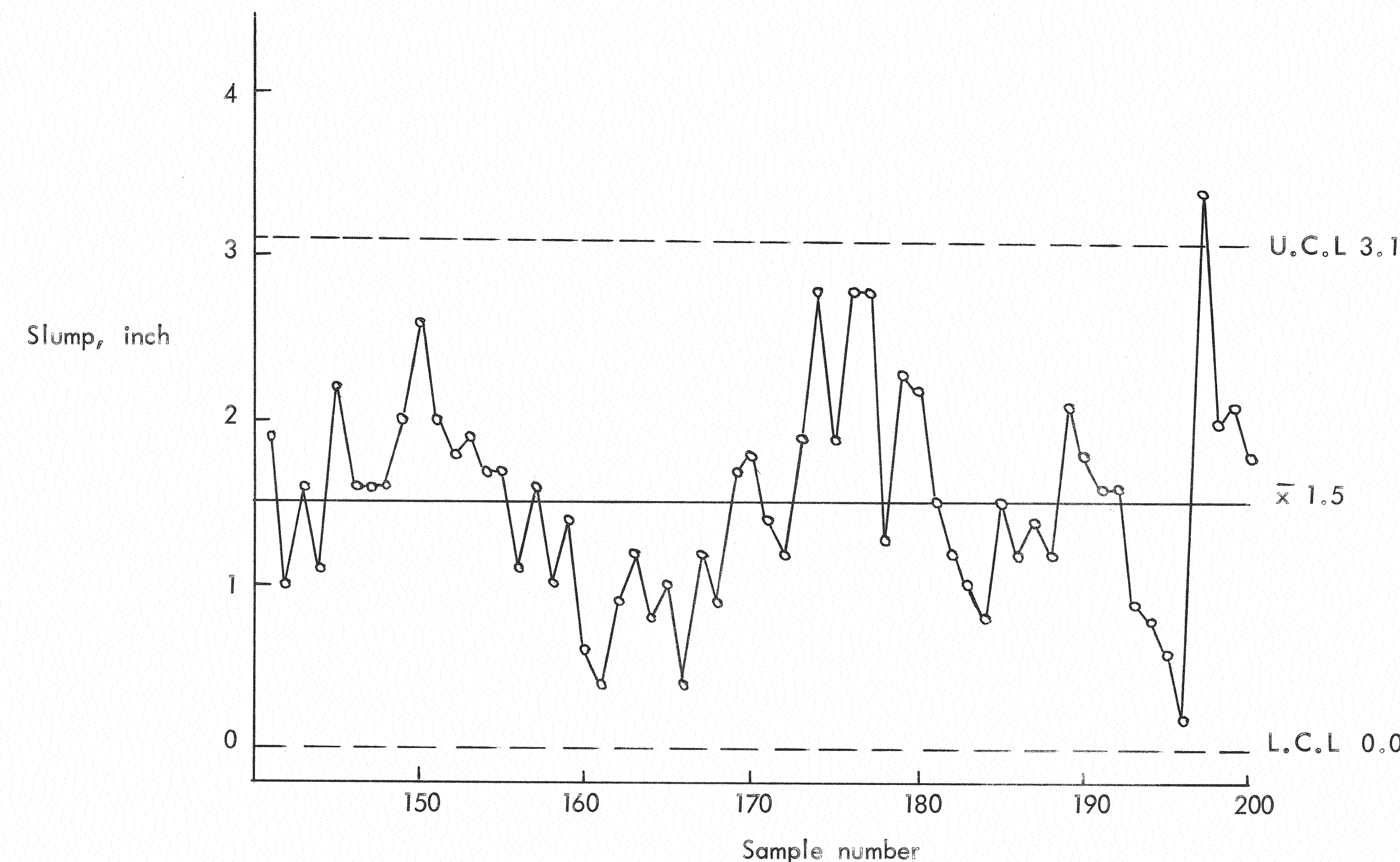


Figure II-54(cont.). Slump – quality control chart

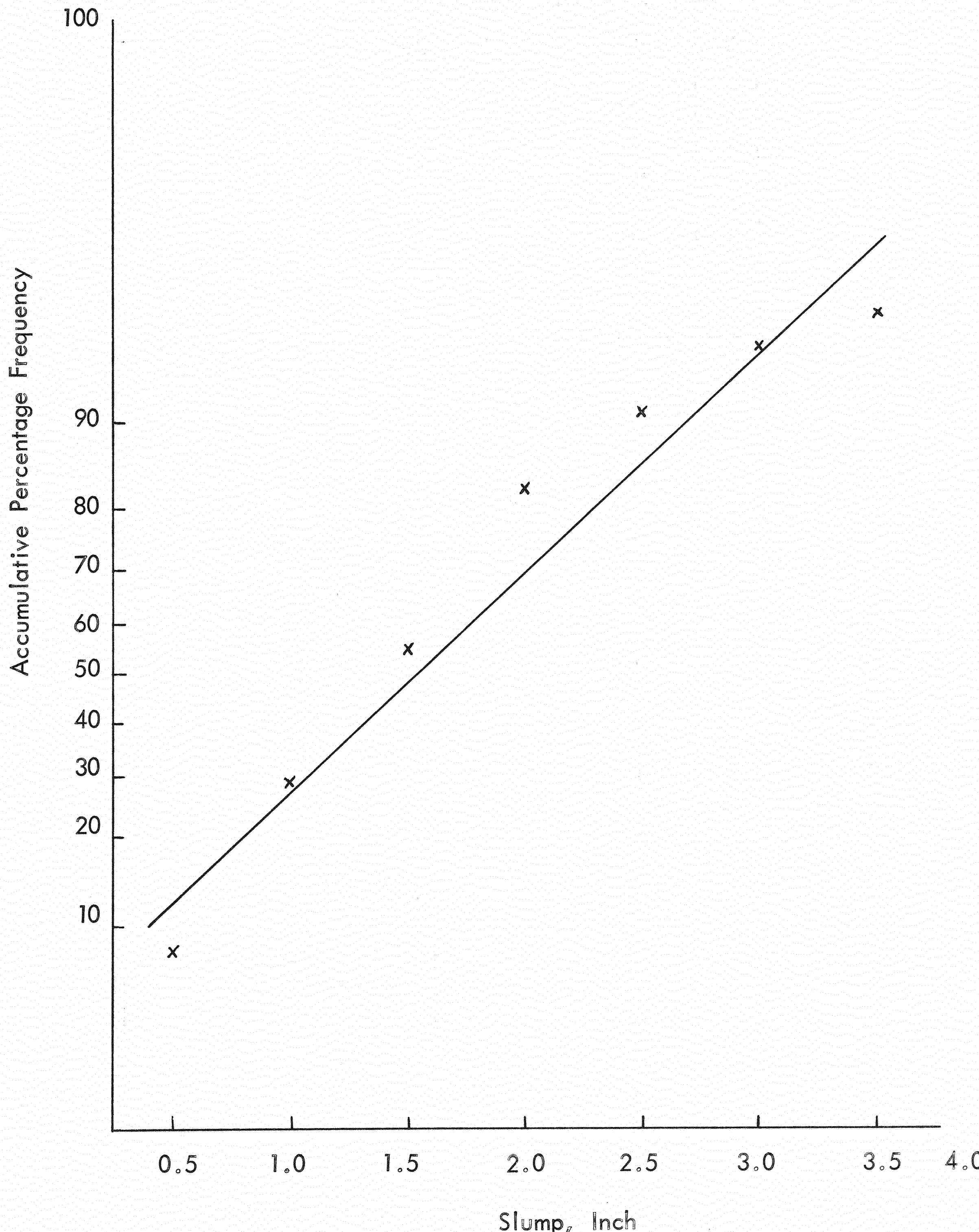
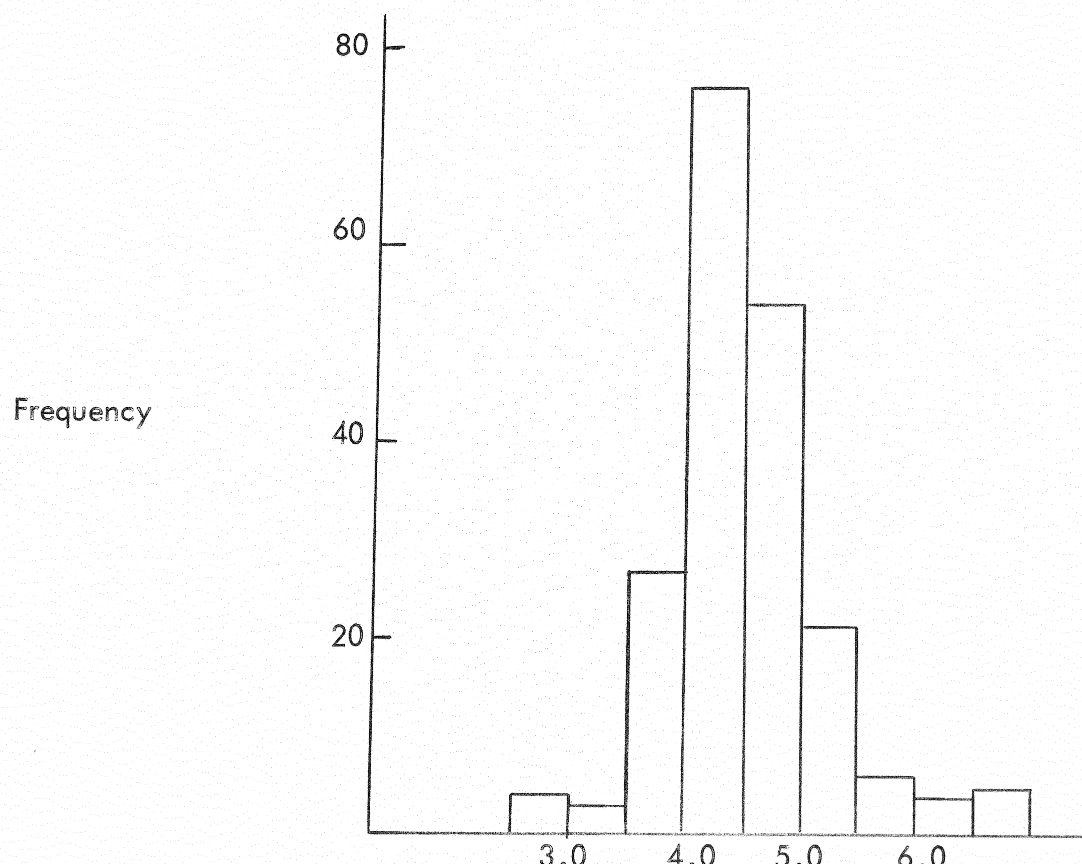


Figure II-55. Slump - goodness of fit curve

No.	Concrete Air Cont. Range, %	f	%	Cum%
1	- 3.0	4	2.0	2.0
2	3.0 - 3.5	3	1.5	3.5
3	3.5 - 4.0	27	13.5	17.0
4	4.0 - 4.5	76	38.0	55.0
5	4.5 - 5.0	54	27.0	82.0
6	5.0 - 5.5	21	10.5	92.5
7	5.5 - 6.0	6	3.0	95.5
8	6.0 - 6.5	4	2.0	97.5
9	6.5 -	2	2.5	100.0
		200	100.0	



n	200
specs	3-6%
$\bar{x}$	4.6
σ_T	0.8
σ_t^2	0.08
σ_s^2	0.12
σ_a^2	0.46
V	17.4%

Figure II-56. Concrete Air Content - statistical properties

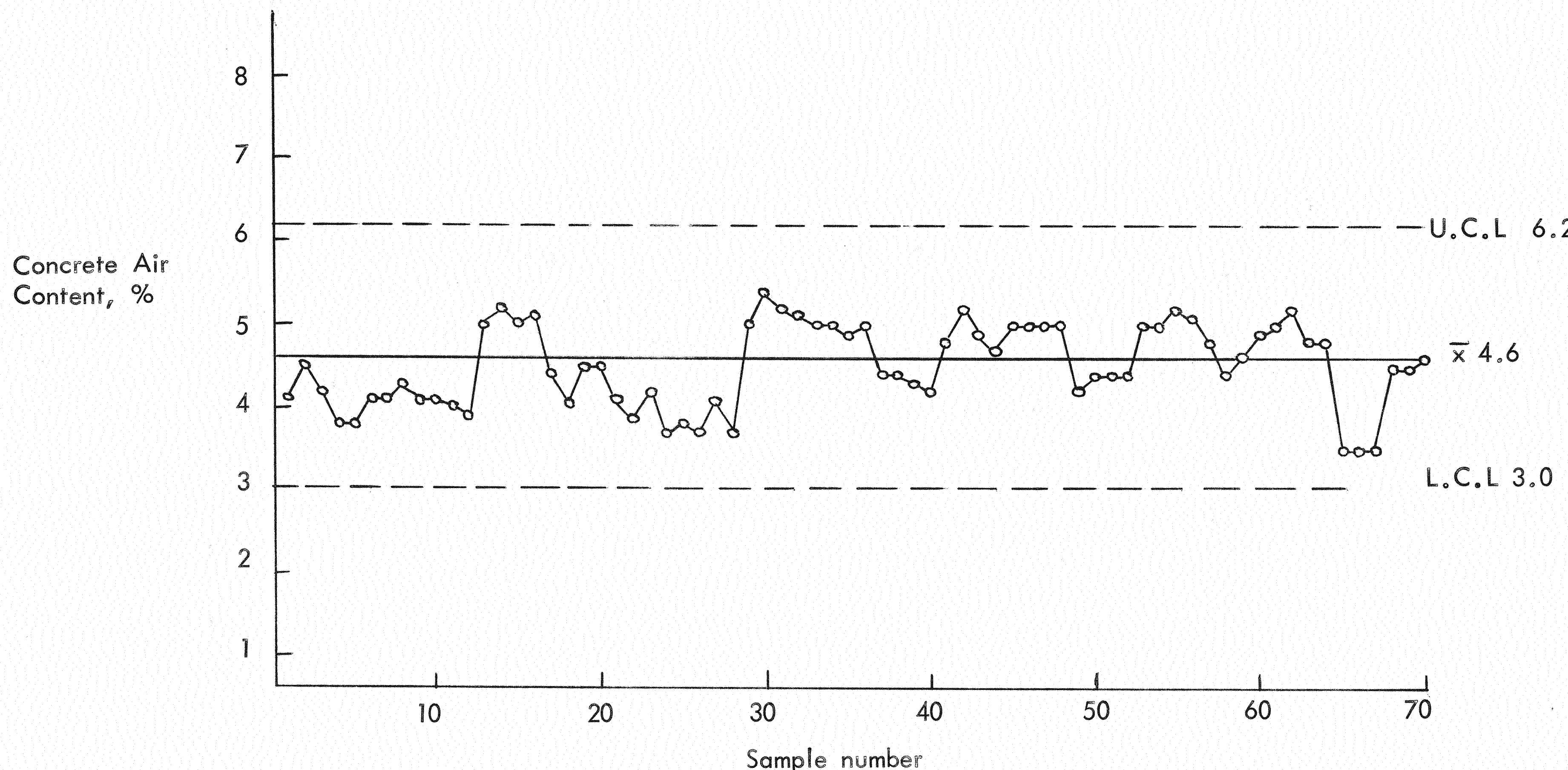


Figure II-57. Concrete Air Content - quality control chart

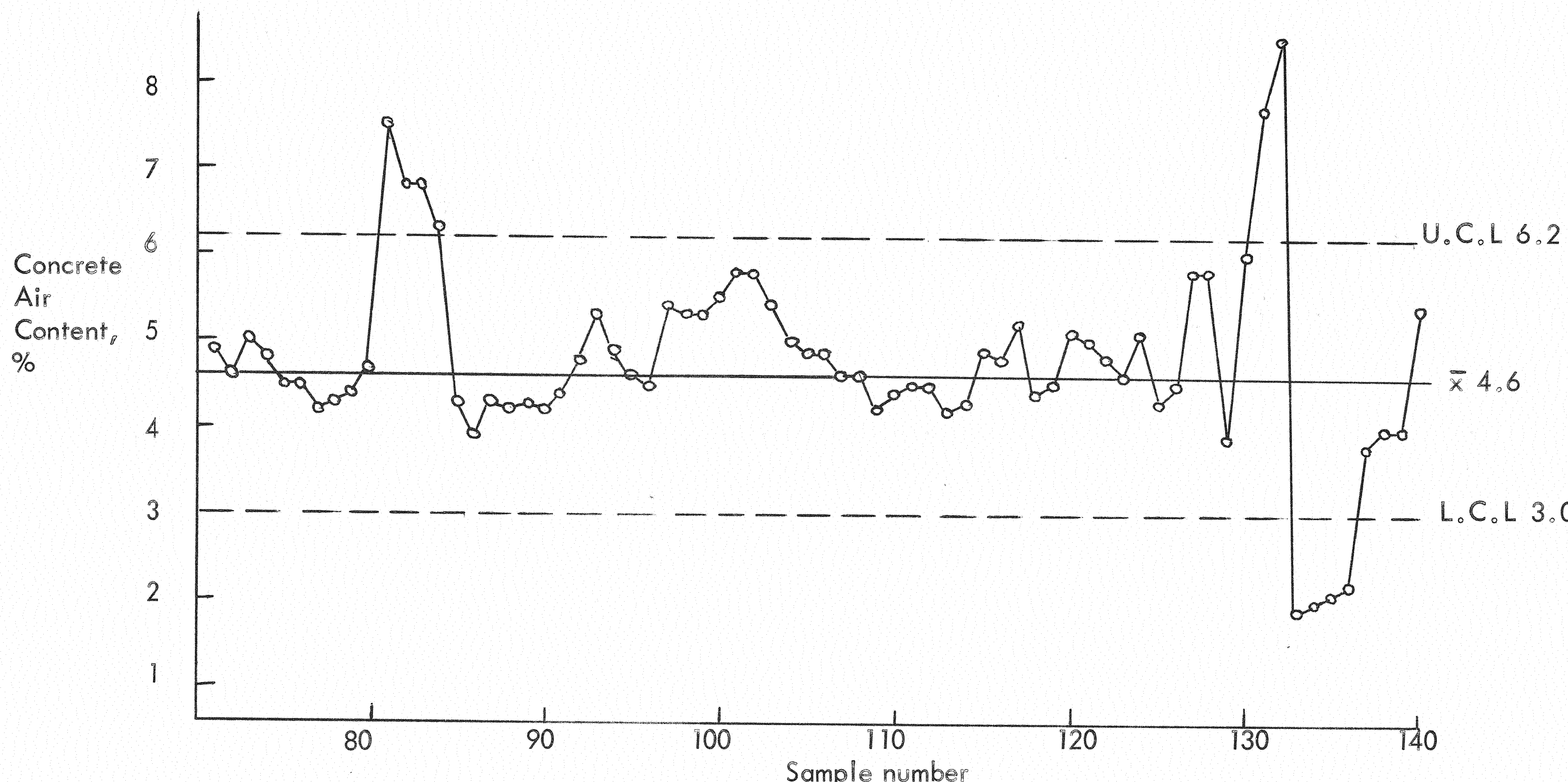


Figure II-57 (cont.). Concrete Air Content - quality control chart

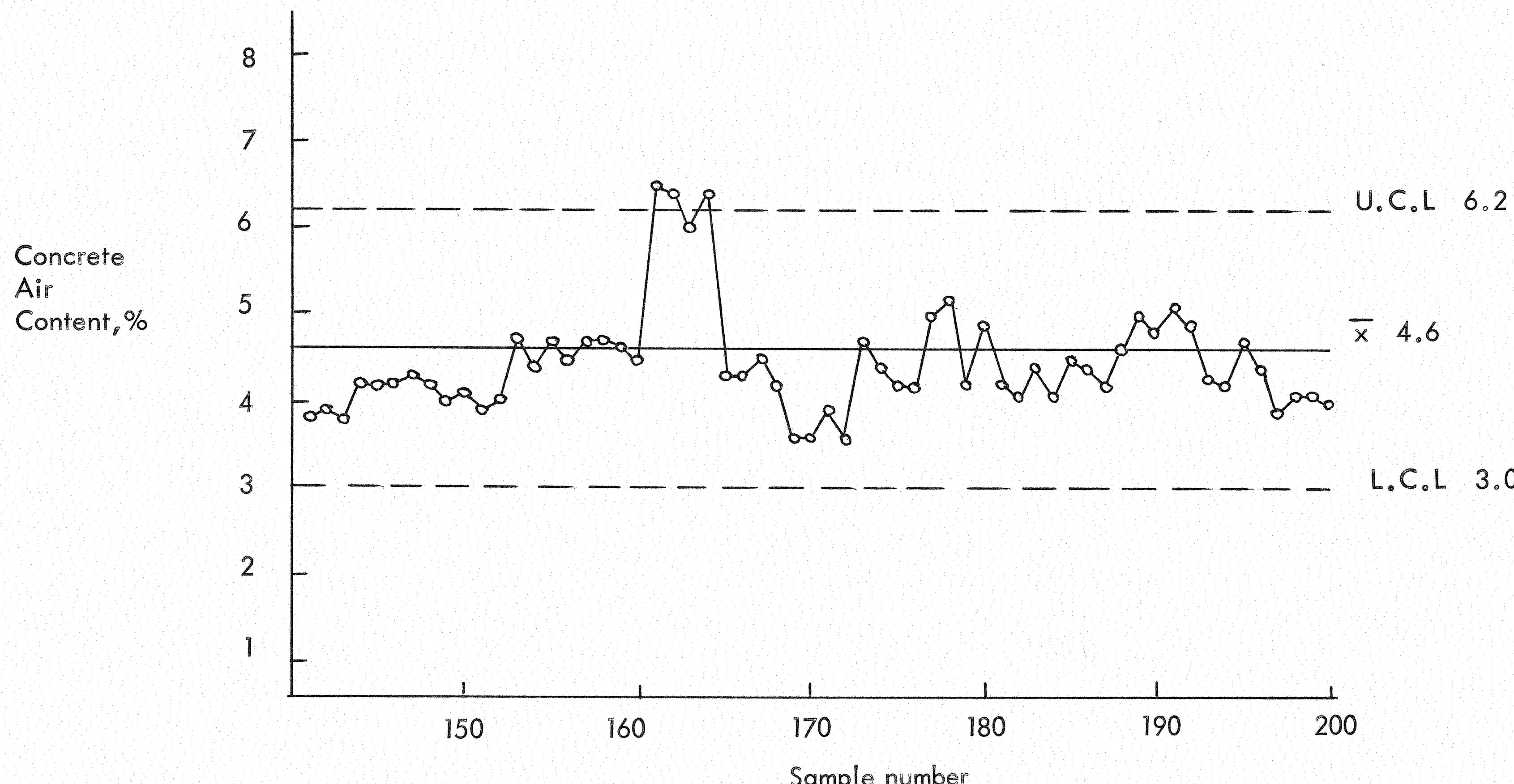


Figure II-57 (cont.). Concrete Air Content - quality control chart

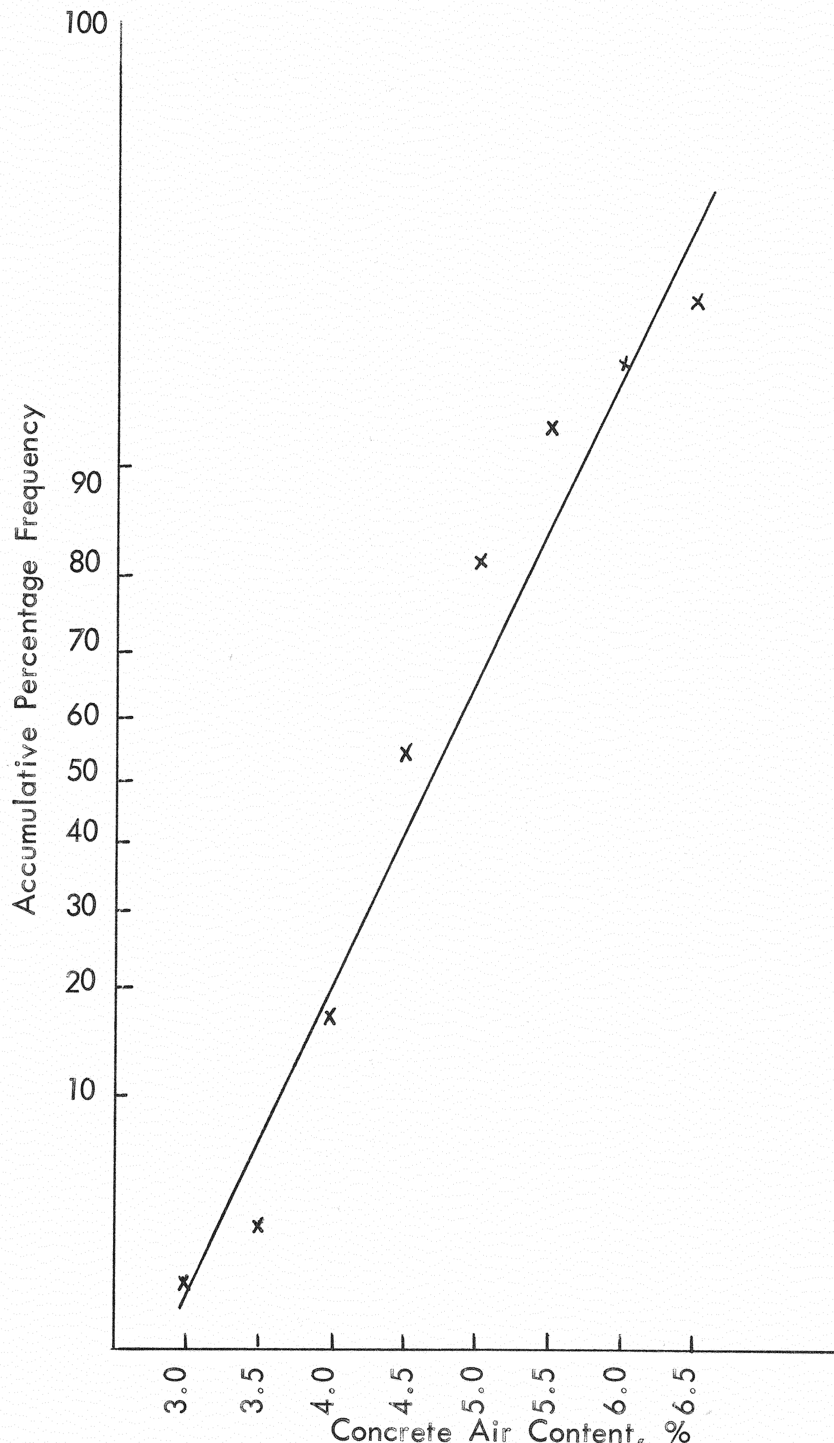
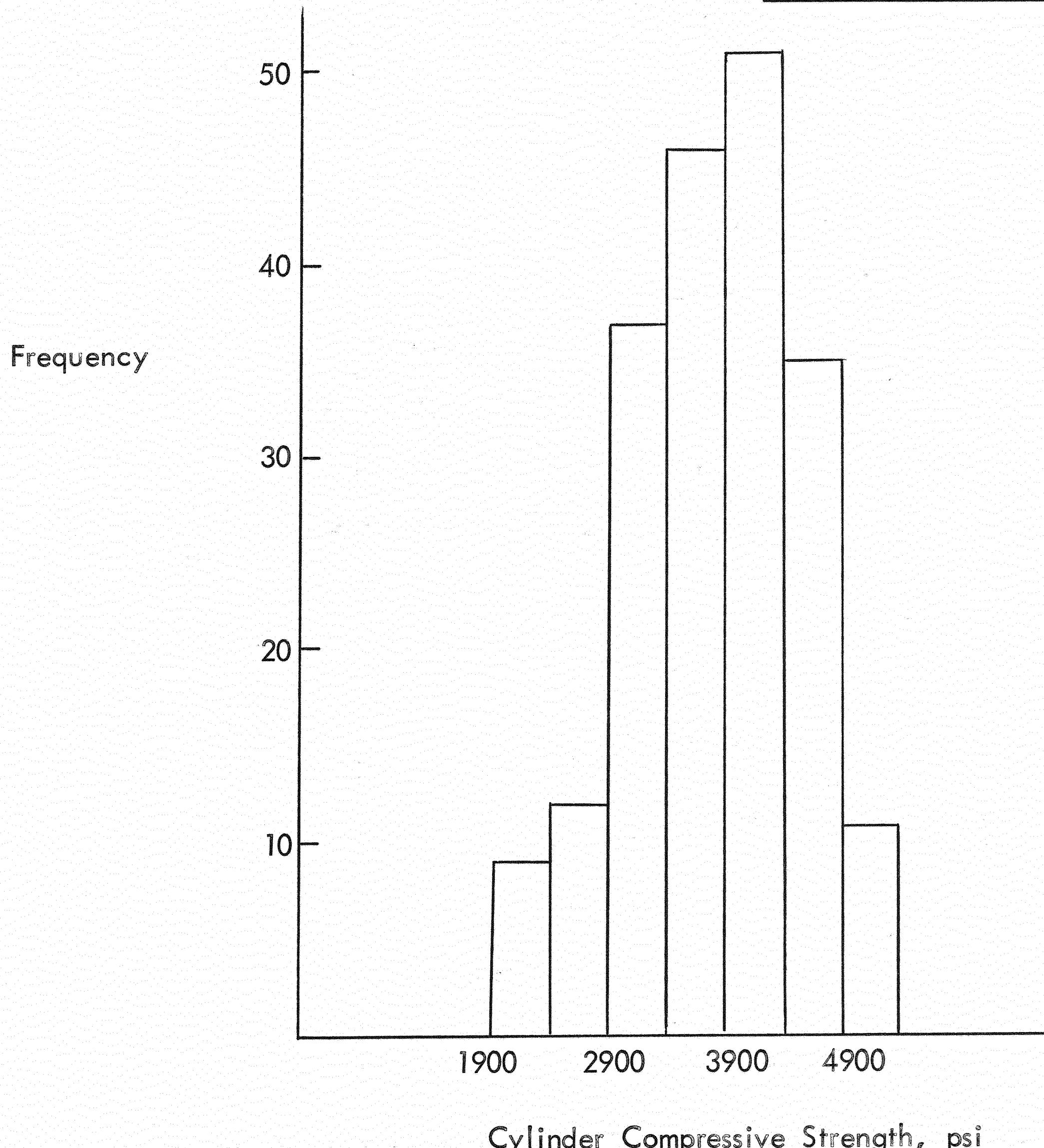


Figure II-58. Concrete Air Content - goodness of fit curve

No.	Concrete Compressive Strength Range, psi	f	%	Cum%
1	1900 - 2400	8	4	4
2	2400 - 2900	12	6	10
3	2900 - 3400	37	18.5	28.5
4	3400 - 3900	46	23	51.5
5	3900 - 4400	51	25.5	77.0
6	4400 - 4900	35	17.5	94.5
7	4900 - 5400	11	5.5	100.0
		200	100	



n	400
specs.	--
$\bar{x}$	3803
σ_T	721
σ_t^2	264,694
σ_s^2	0.0
σ_a^2	254,840
V	19.0%

Figure II-59. Cylinder Compressive Strength - statistical properties

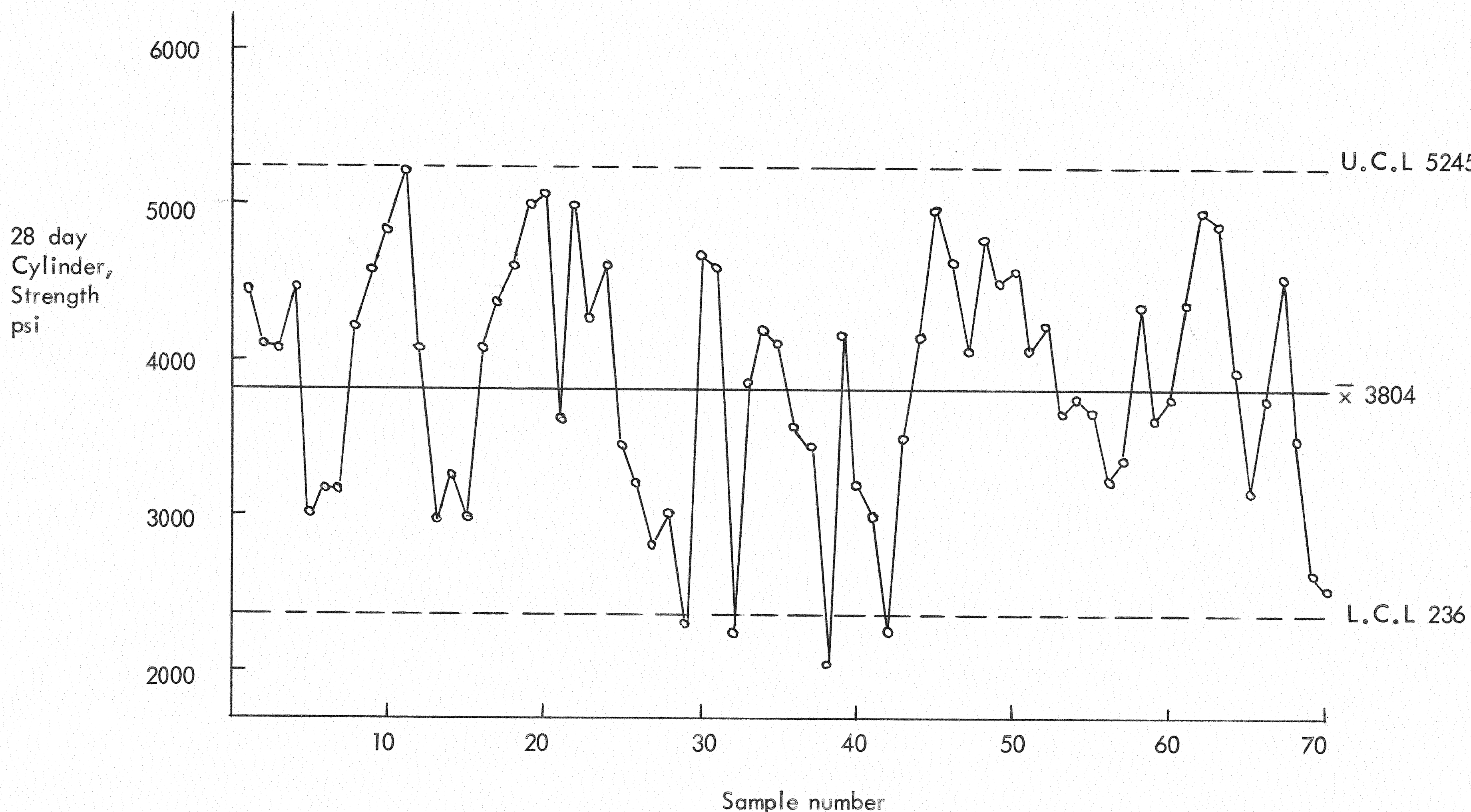


Figure II-60. Cylinder Compressive Strength - quality control chart

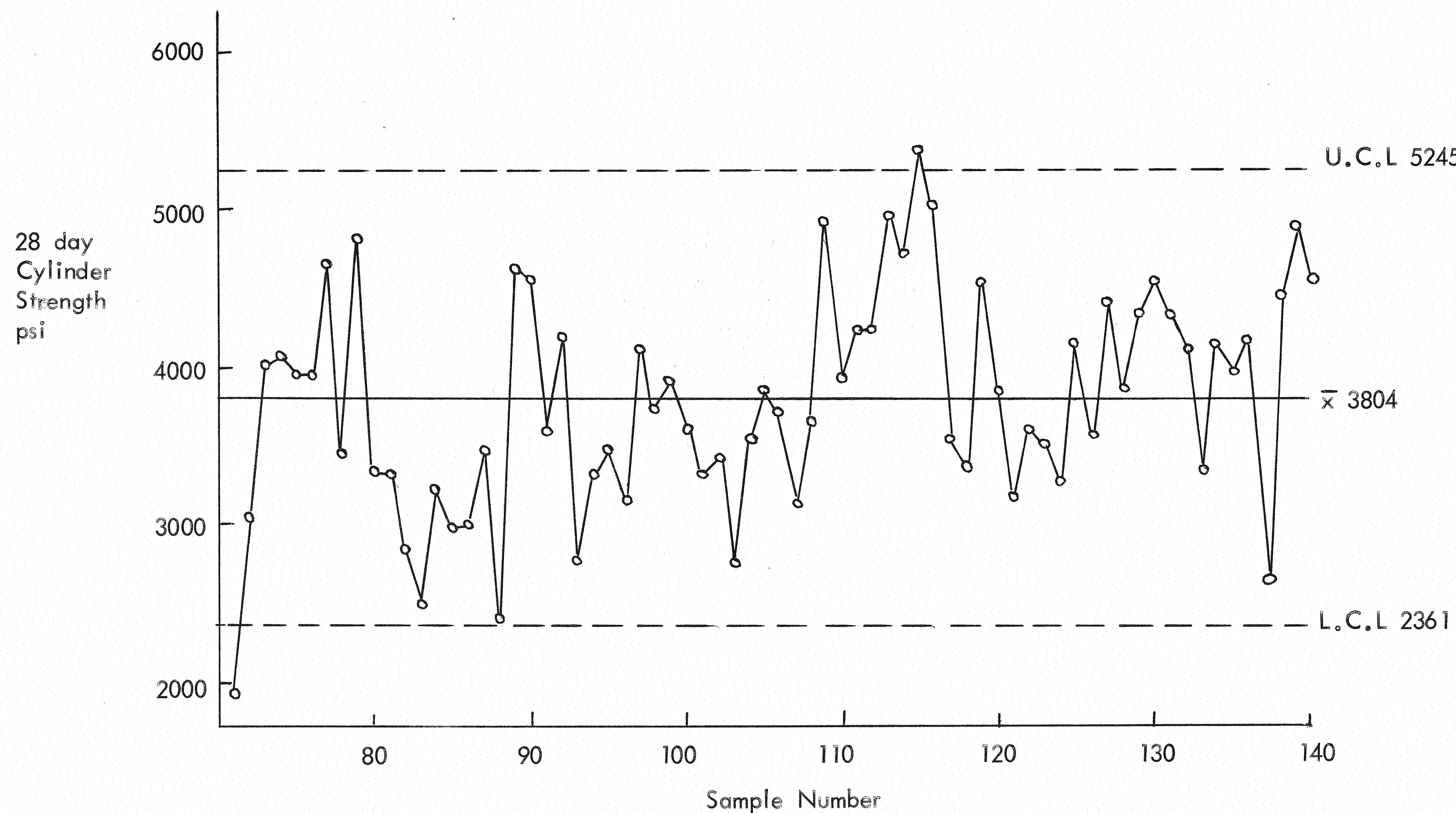


Figure II-60(cont.). Cylinder Compressive Strength - quality control chart

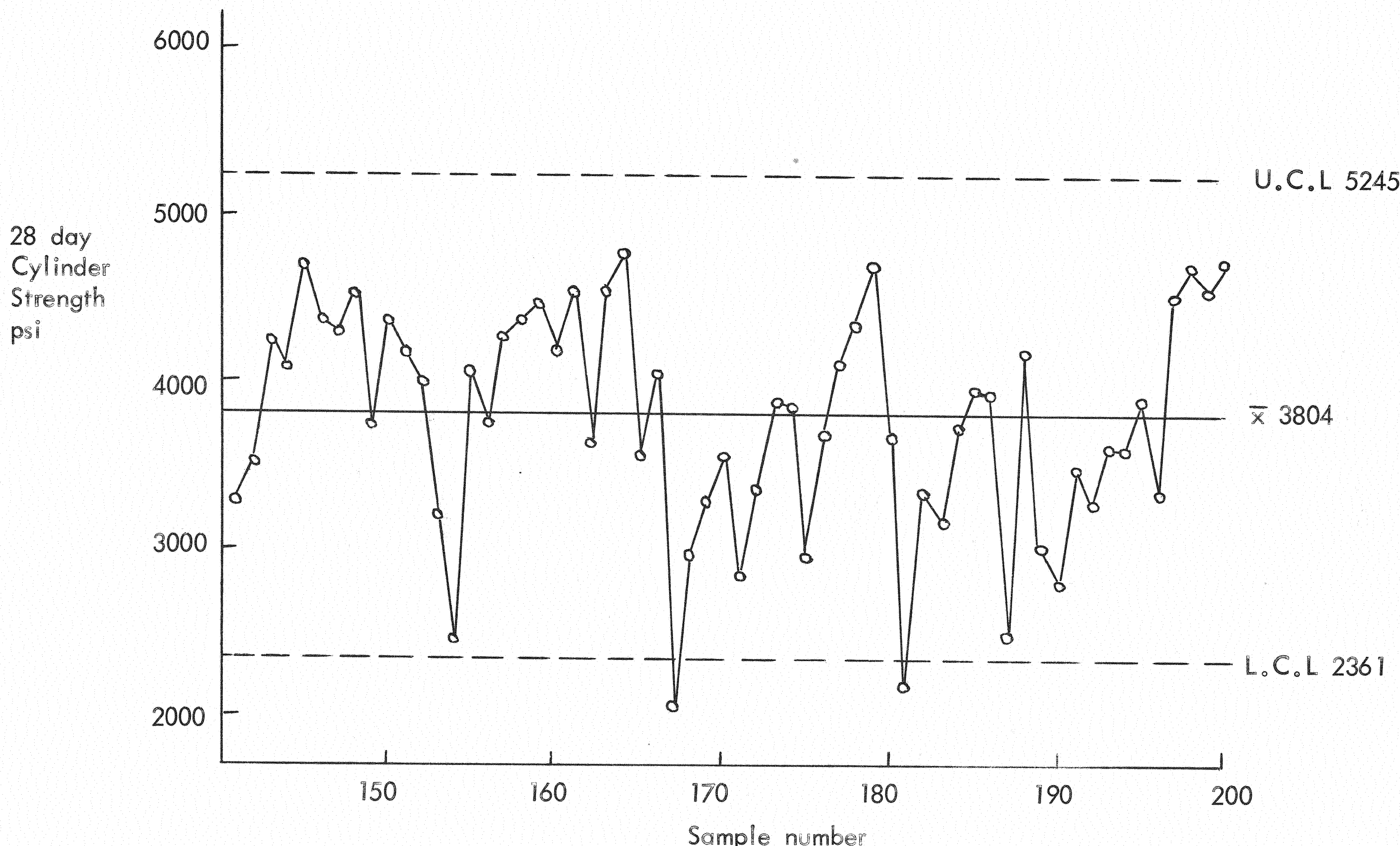


Figure II-60(cont.). Cylinder Compressive Strength - quality control chart

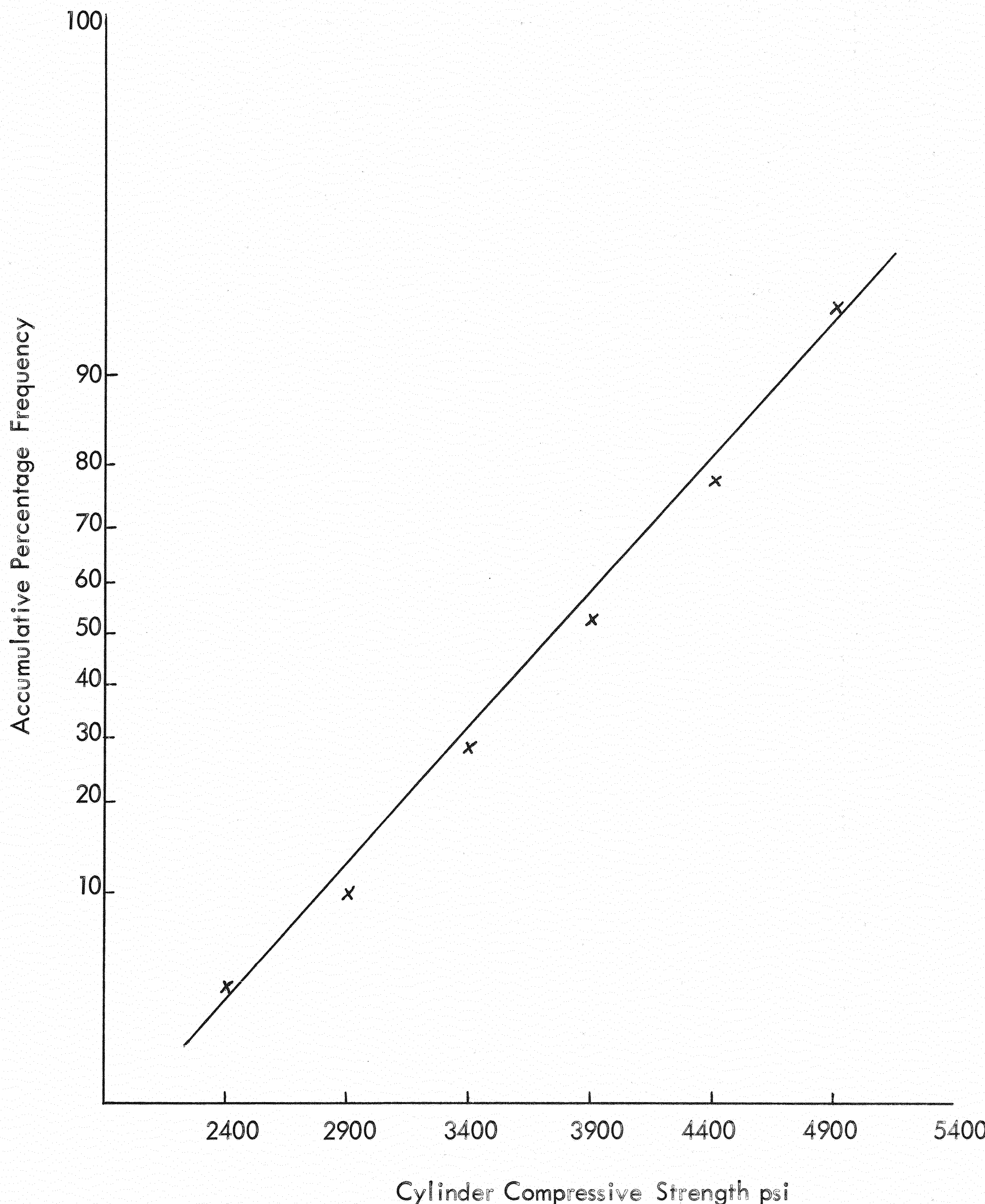


Figure II-61. Cylinder Compressive Strength – goodness of fit curve

No.	Cement Content of Hardened Content Range	f	%	Cum%
1	94 - 98	8	16.7	16.7
2	98 - 102	20	41.6	58.3
3	102 - 106	12	25.0	83.3
4	106 - 110	5	10.4	93.7
5	110 - 114	1	2.1	95.8
6	114 - 118	2	4.2	100.0
		48	100	

n	48
specs	--
$\bar{x}$	101.7
σ_T	4.7
σ_t^2	14.4
σ_s^2	0.0
σ_a^2	7.99
V	4.6%

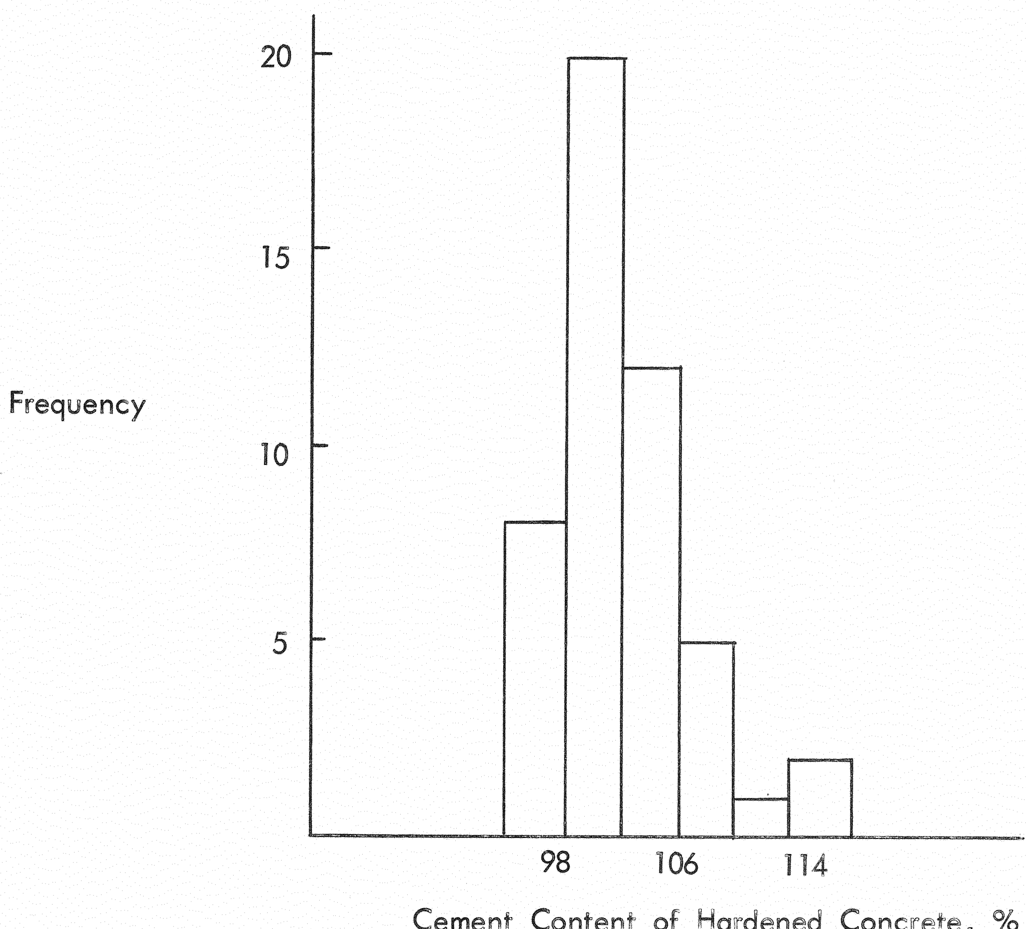


Figure II-62. Cement Content of Hardened Concrete - statistical properties

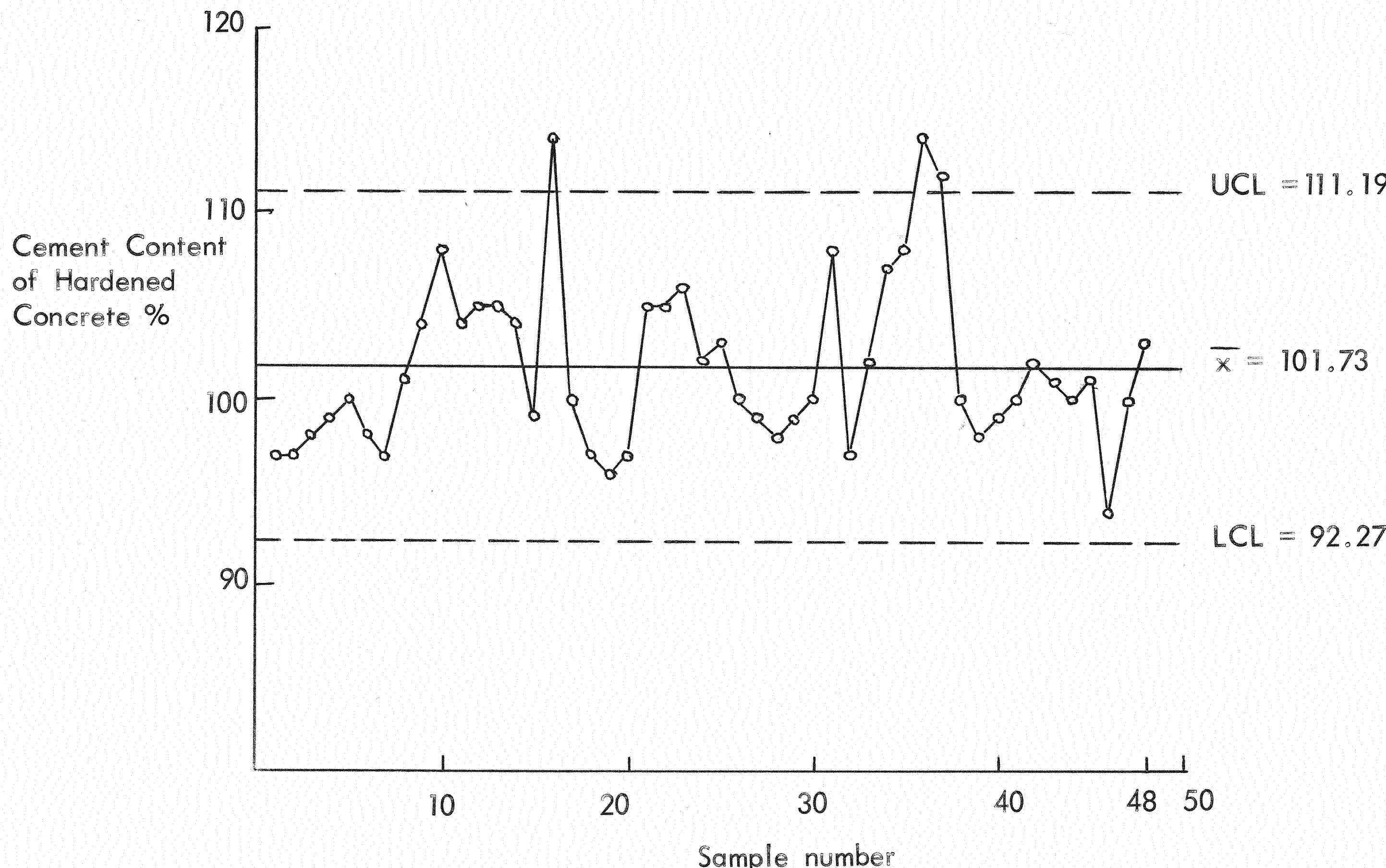


Figure II-63. Cement Content of Hardened Concrete - quality control chart

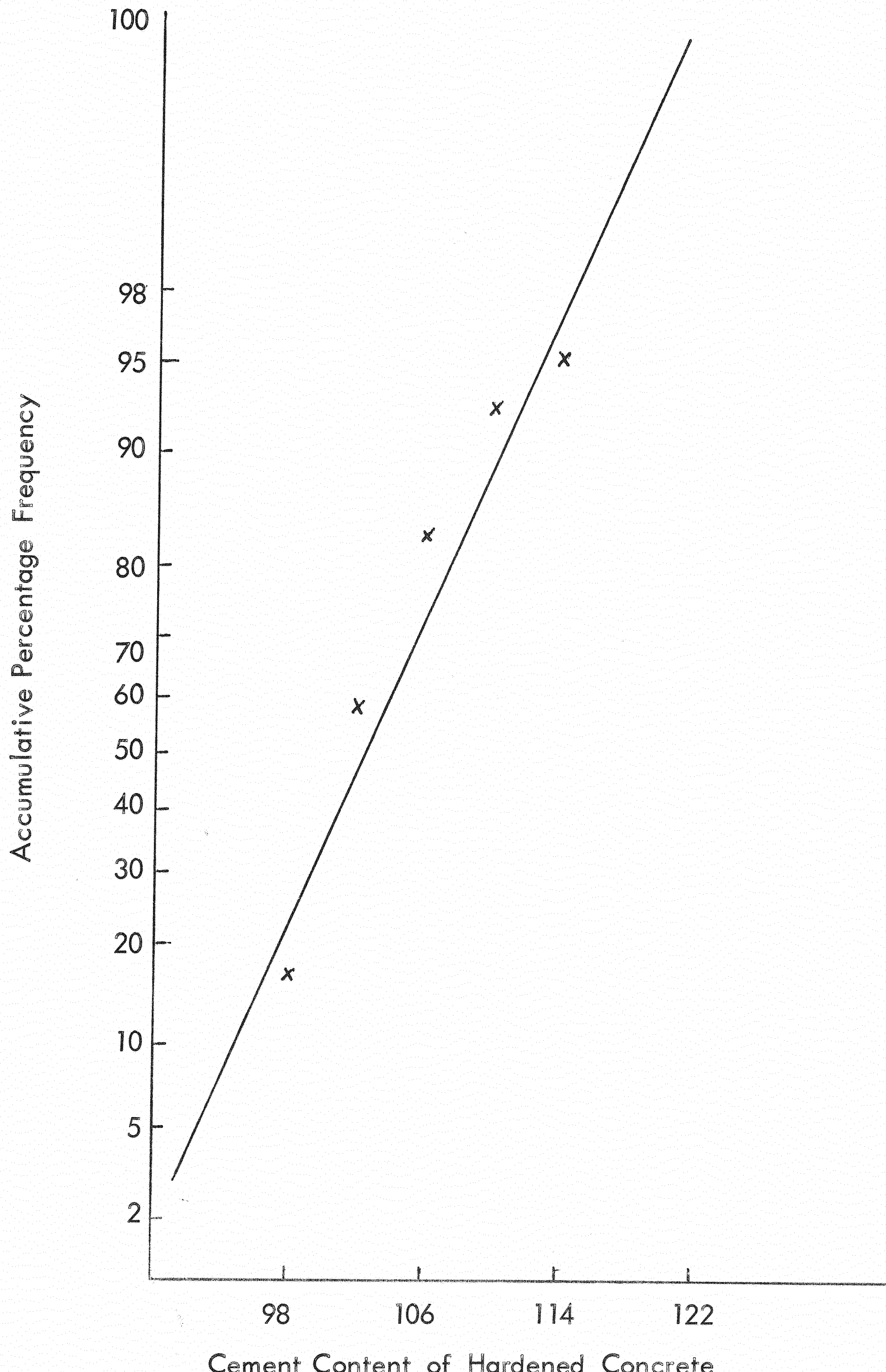


Figure II-64. Cement Content of Hardened Concrete - goodness of fit curve

No.	Durability Range, %	f	%	Cum %
1	- 37	2	1.3	1.3
2	37 - 42	3	1.9	3.2
3	42 - 47	5	3.2	6.4
4	47 - 52	6	3.9	10.3
5	52 - 57	10	6.4	16.7
6	57 - 62	30	19.2	35.9
7	62 - 67	51	32.6	68.5
8	67 - 72	40	25.7	94.2
9	72 -	9	5.8	100.0
		156	100	

n	156
specs	--
$\bar{x}$	63.0
σ_T	7.9
σ_t^2	37.5
σ_s^2	3.0
σ_a^2	21.9
V	12.5%

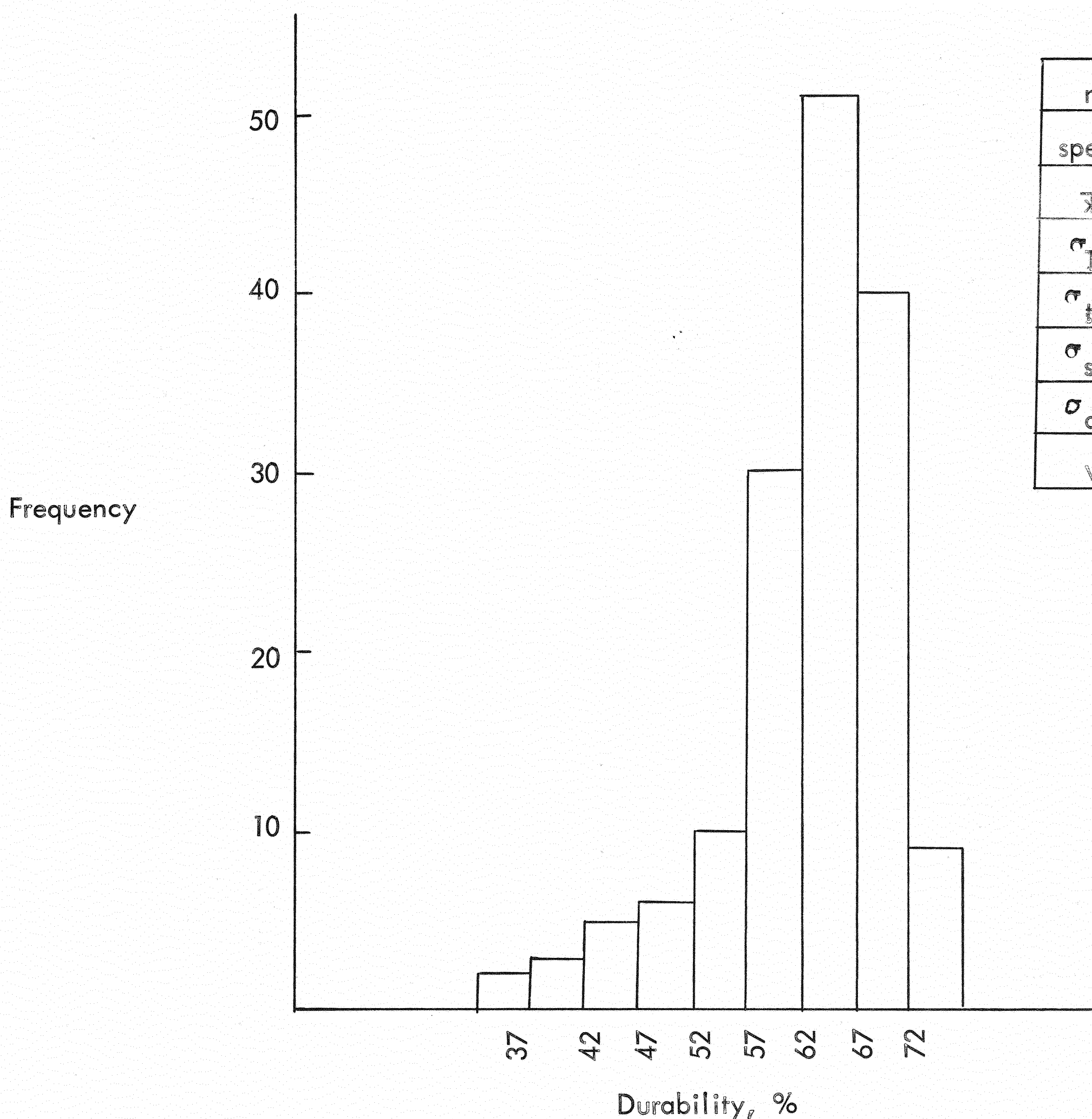


Figure II-65. Durability - statistical properties

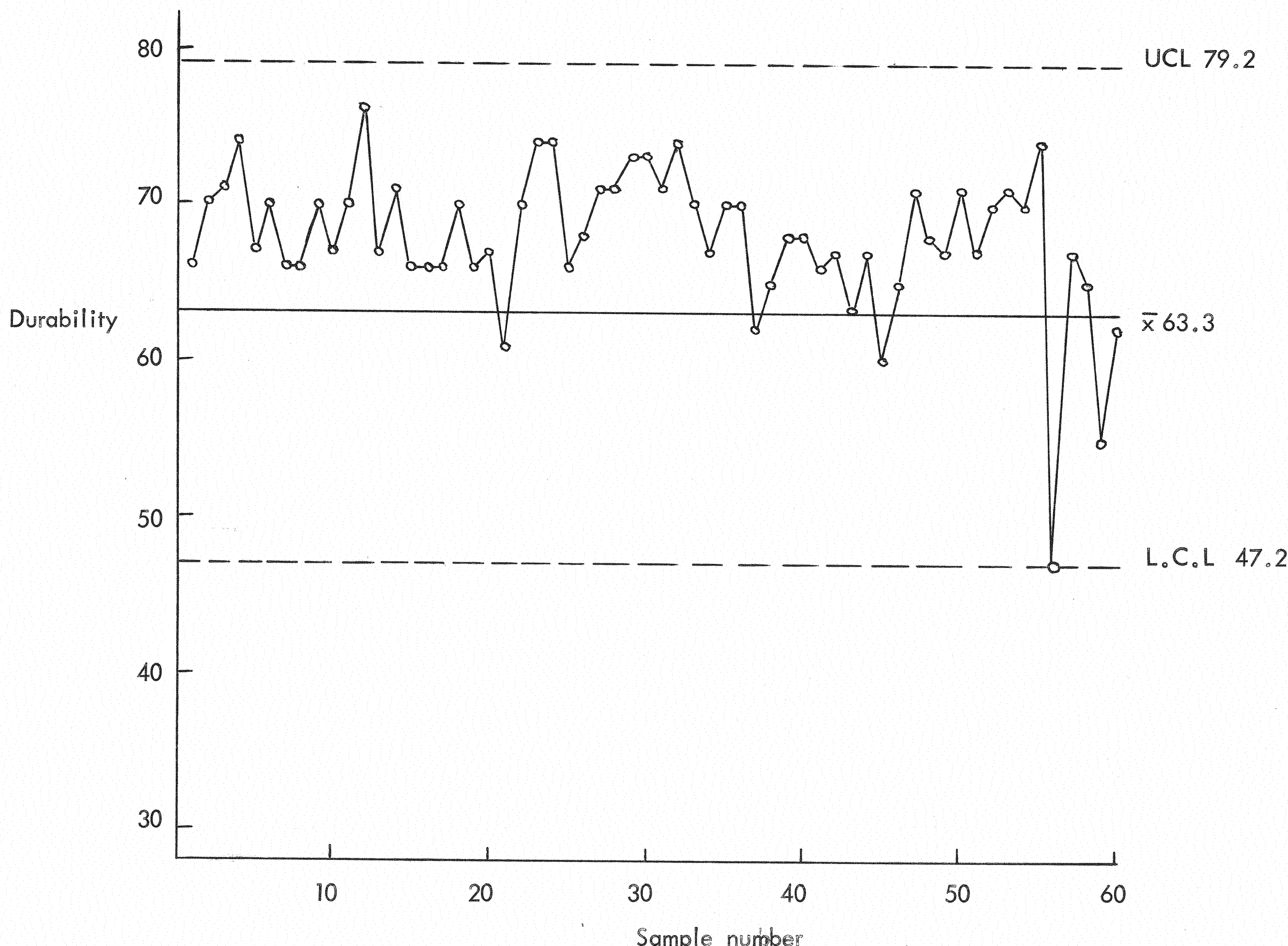


Figure II-66. Durability - quality control chart

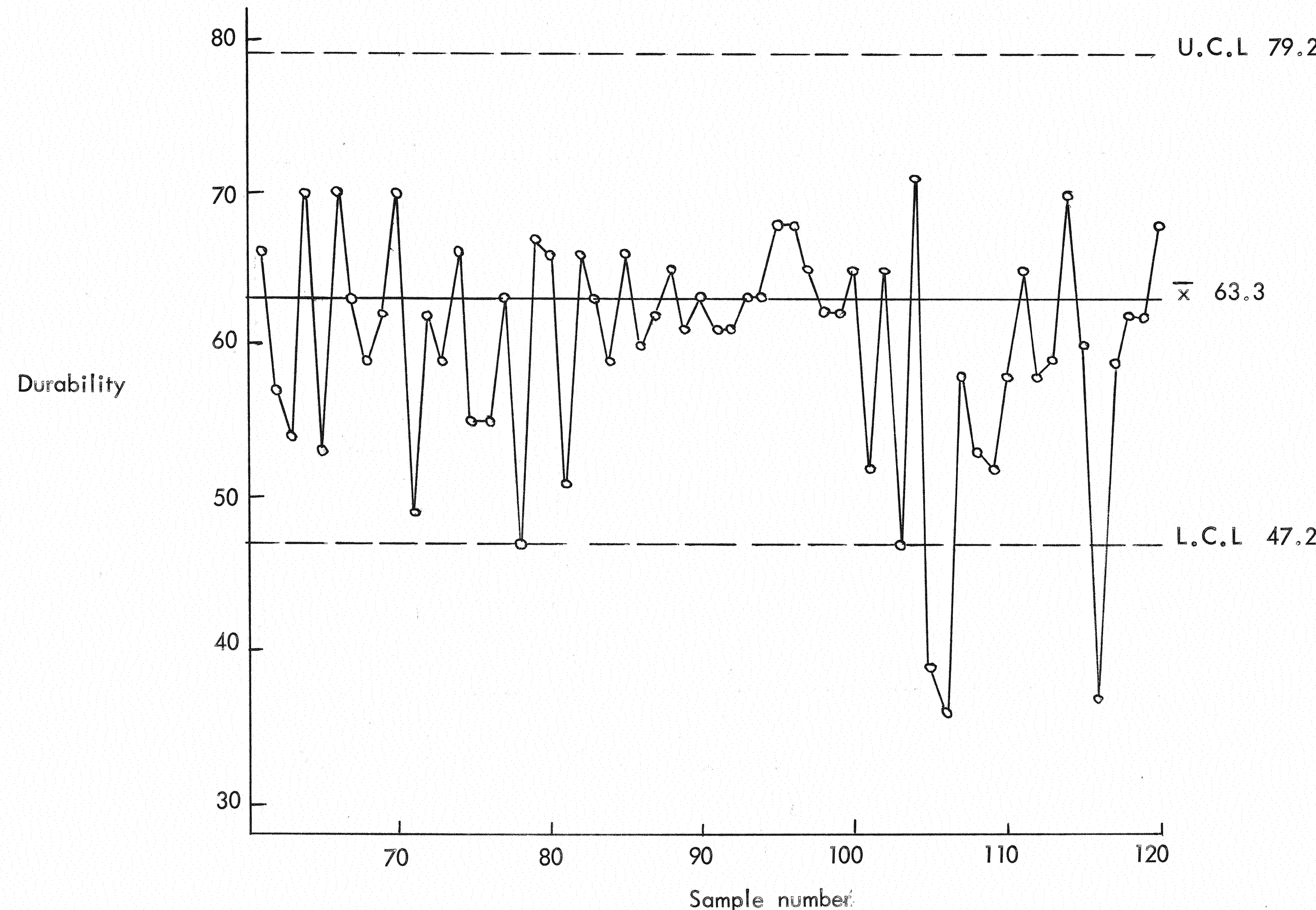


Figure II-66.(cont.) Durability - quality control chart

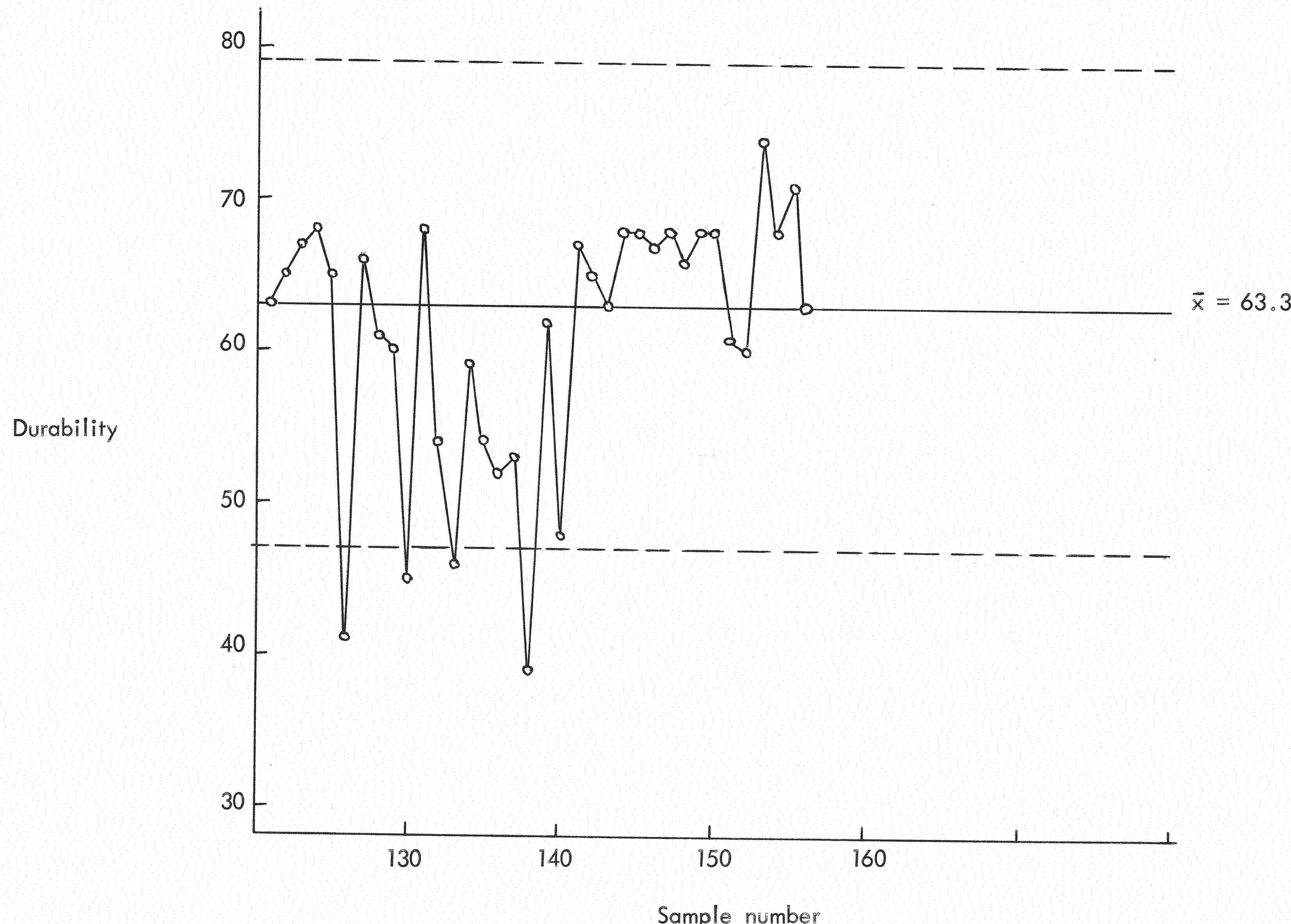


Figure II-66(cont.). Durability - quality control chart

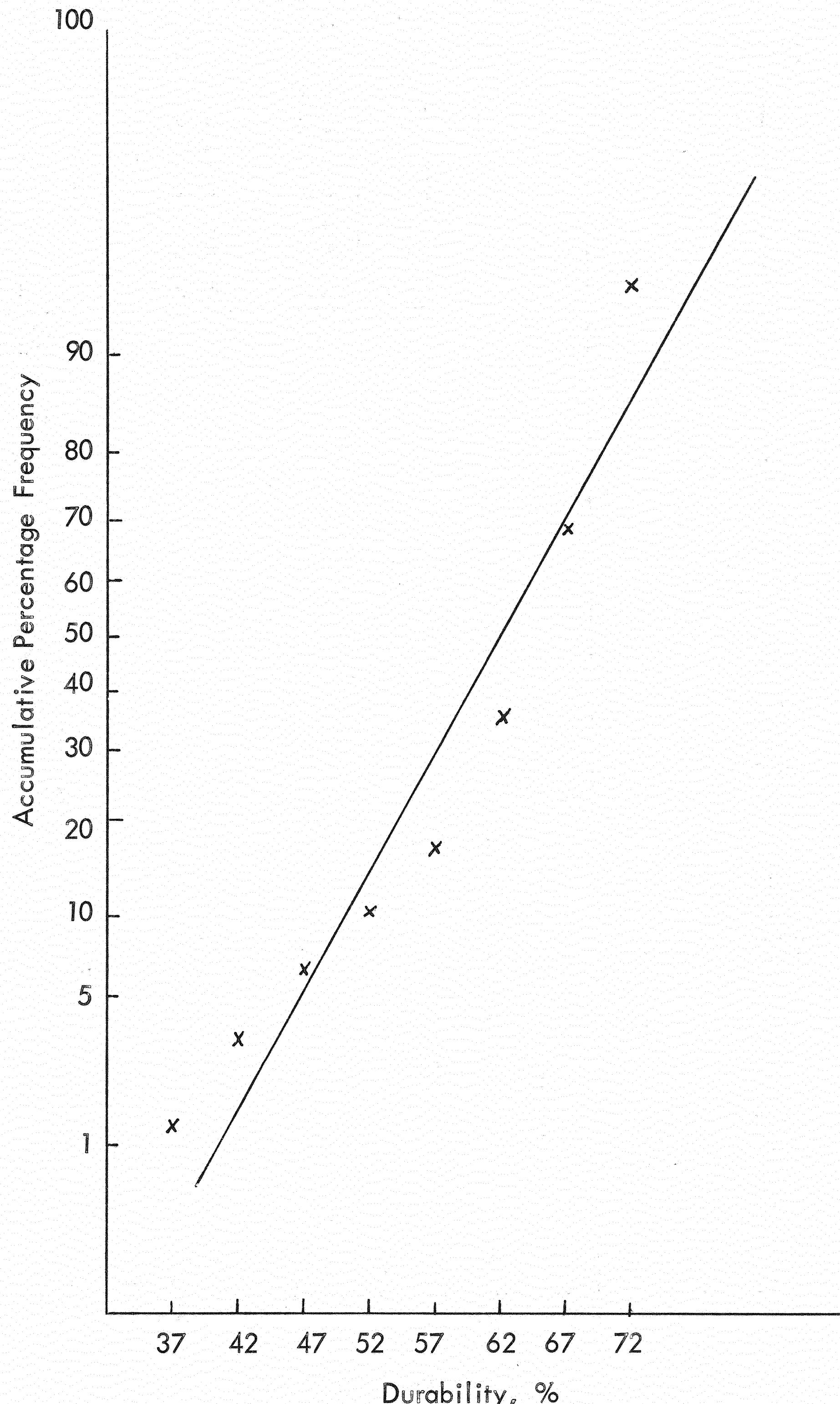


Figure II-67. Durability - goodness of fit curve

No.	C.A. Passing No. 200 Range, %	f	%	Cum%
1	0.2 - 0.8	27	15.0	15
2	0.8 - 1.4	66	36.6	51.6
3	1.4 - 2.0	49	27.2	78.8
4	2.0 - 2.6	17	9.5	88.3
5	2.6 - 3.2	11	6.1	94.4
6	3.2 - 3.8	7	3.9	98.3
7	3.8 - 4.4	-	0	98.3
8	4.4 - 5.0	-	0	98.3
9	5.0 - 5.6	2	1.1	99.4
10	5.6 - 6.2	1	6	100.0
		180	100	

n	180
specs	2%max
$\bar{x}$	1.66
σ_T	1.57
σ_t^2	1.90
σ_s^2	0.41
σ_a^2	0.16
V	94.6%

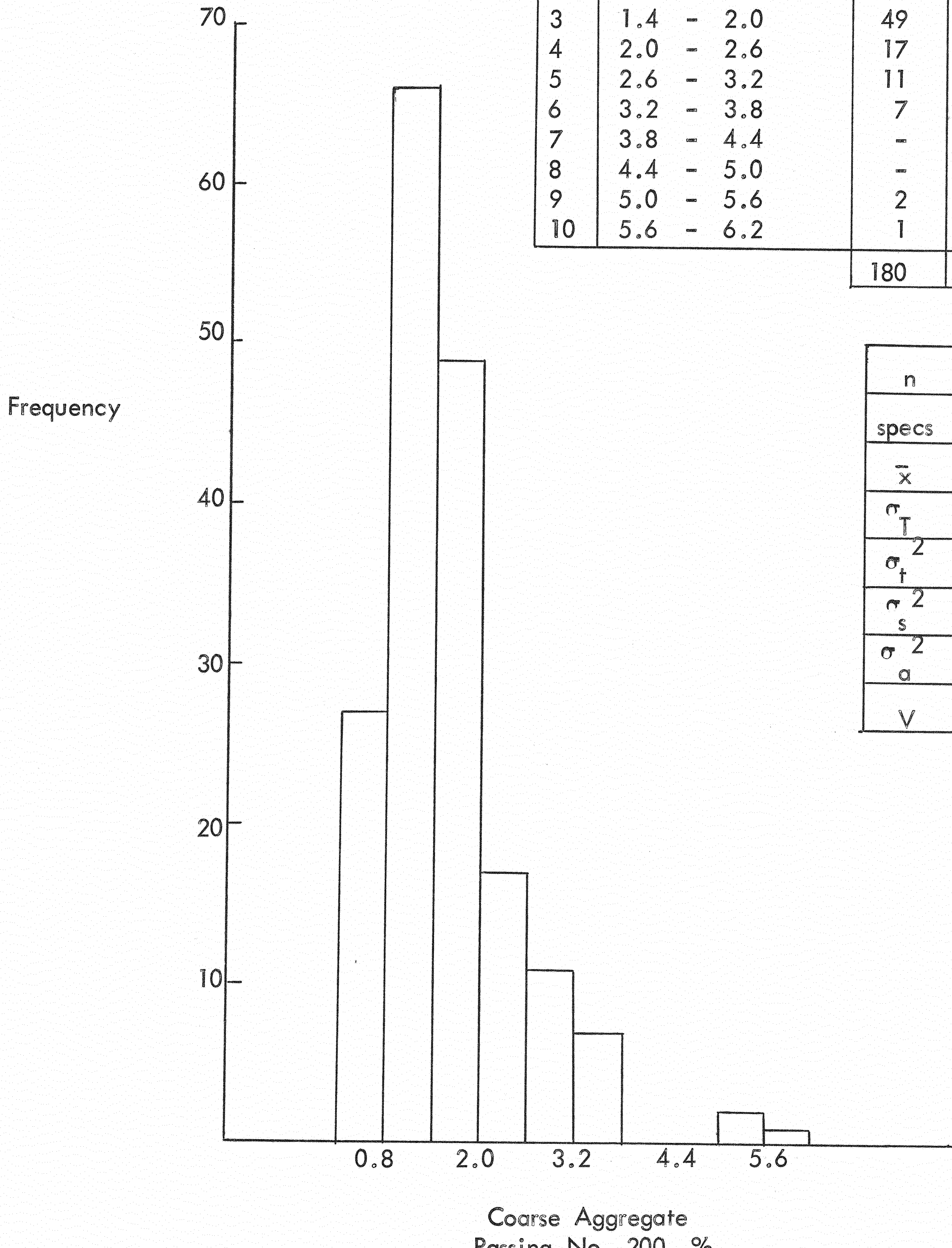


Figure II-68. % Passing No. 200 C.A. - statistical properties

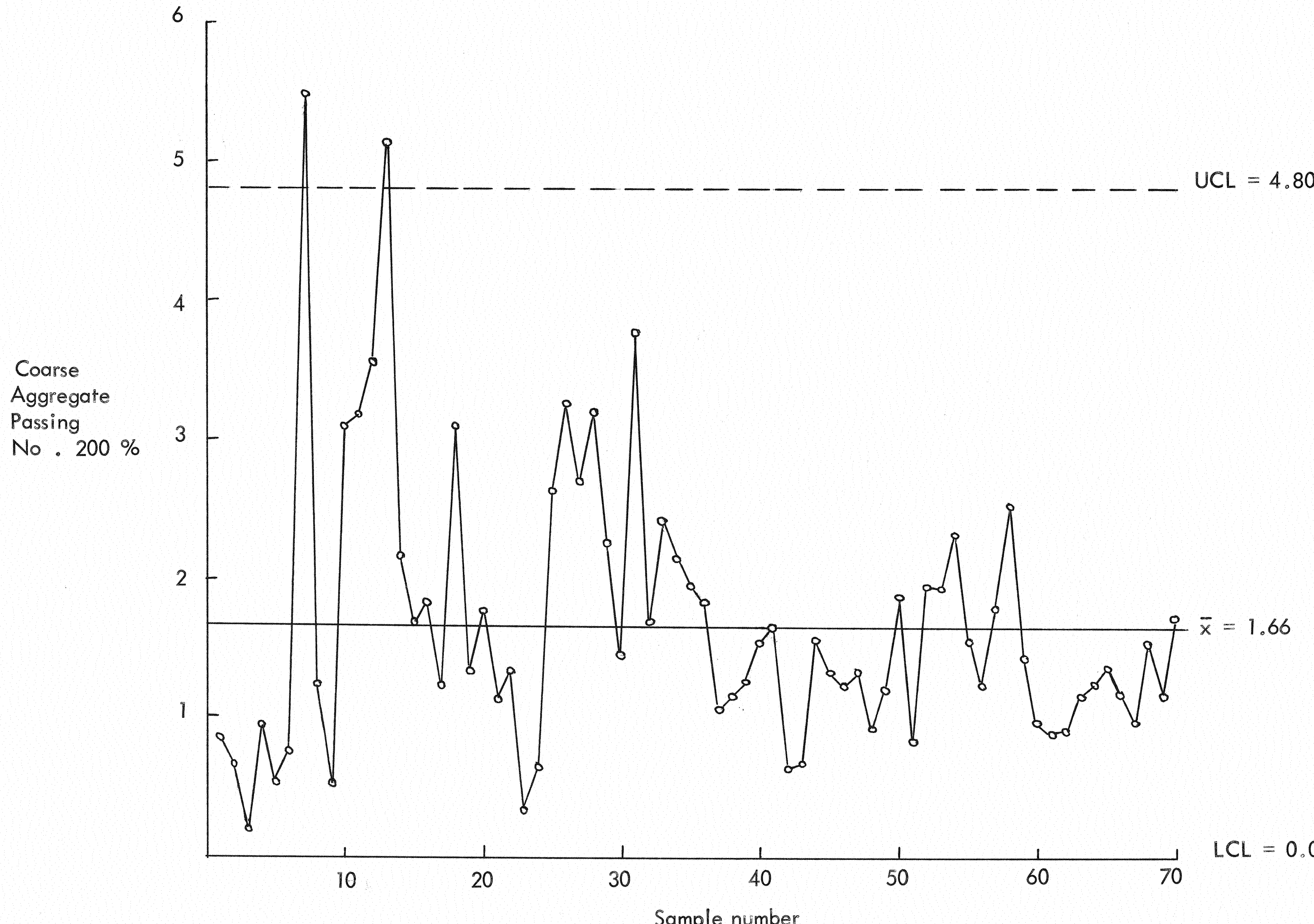


Figure II-69. % Passing No. 200 C.A. - quality control chart

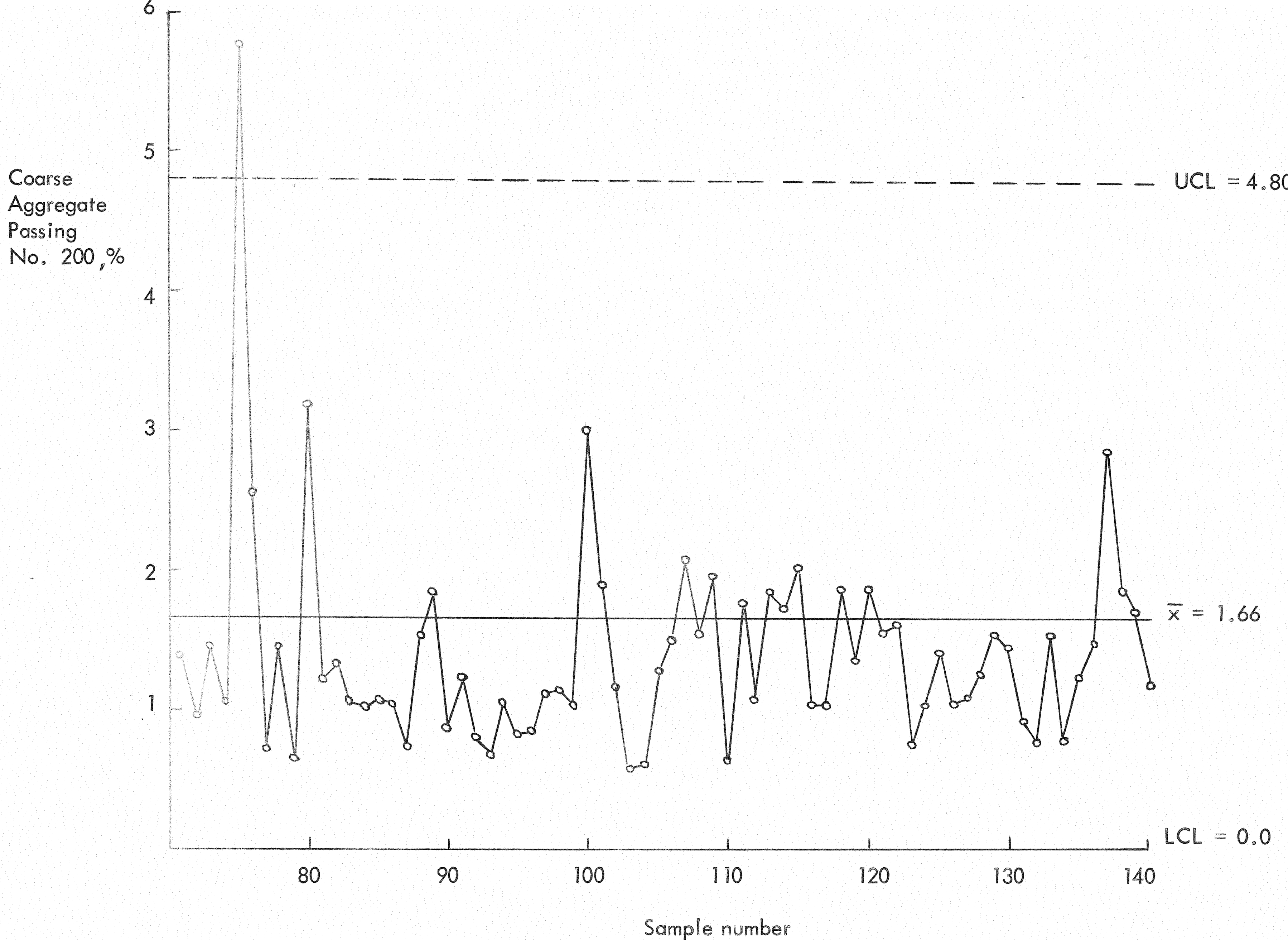


Figure II-69(cont.) % Passing No. 200 C.A. - quality control chart

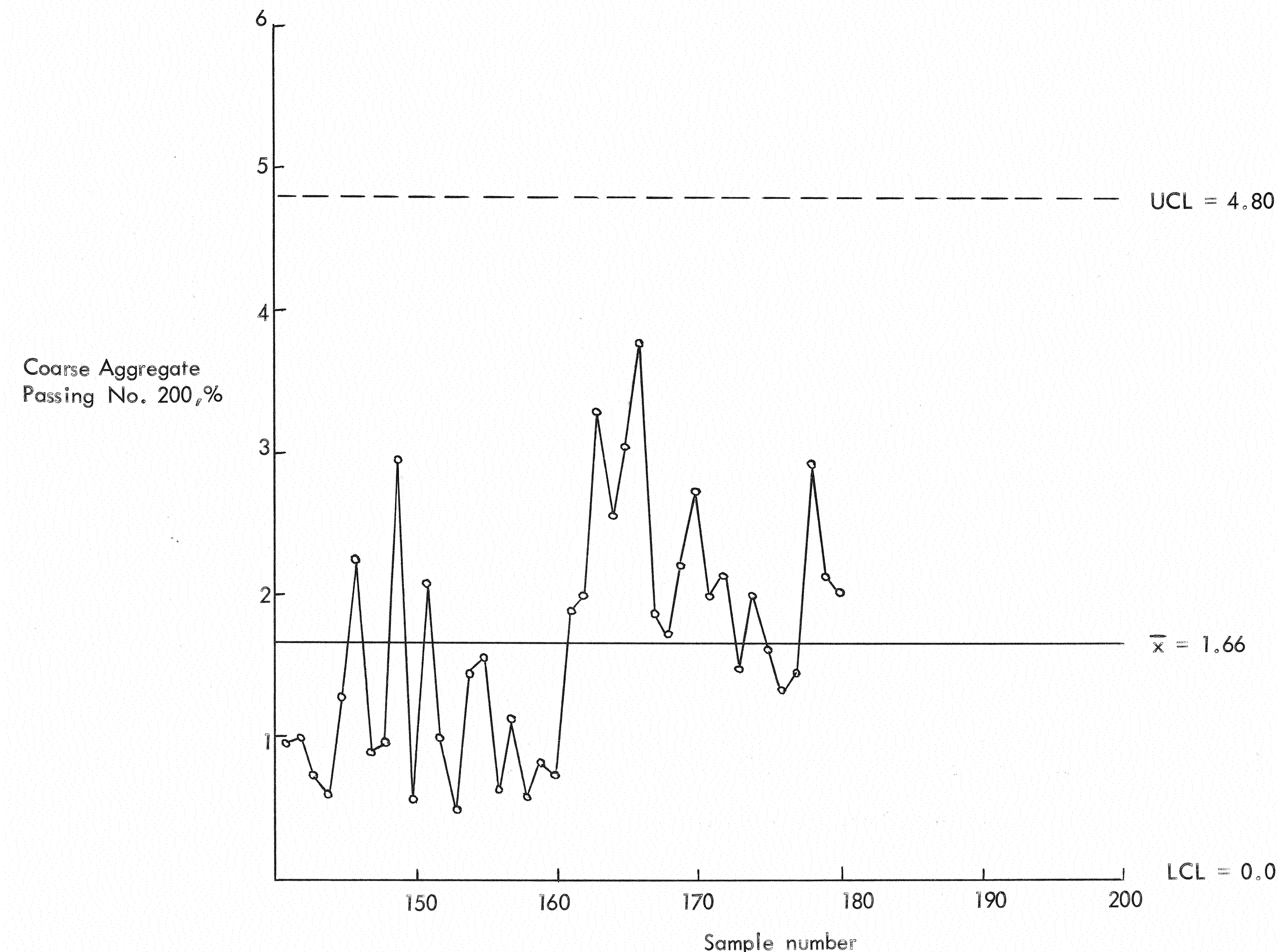


Figure II-69(cont.). % Passing No. 200 C.A. - quality control chart

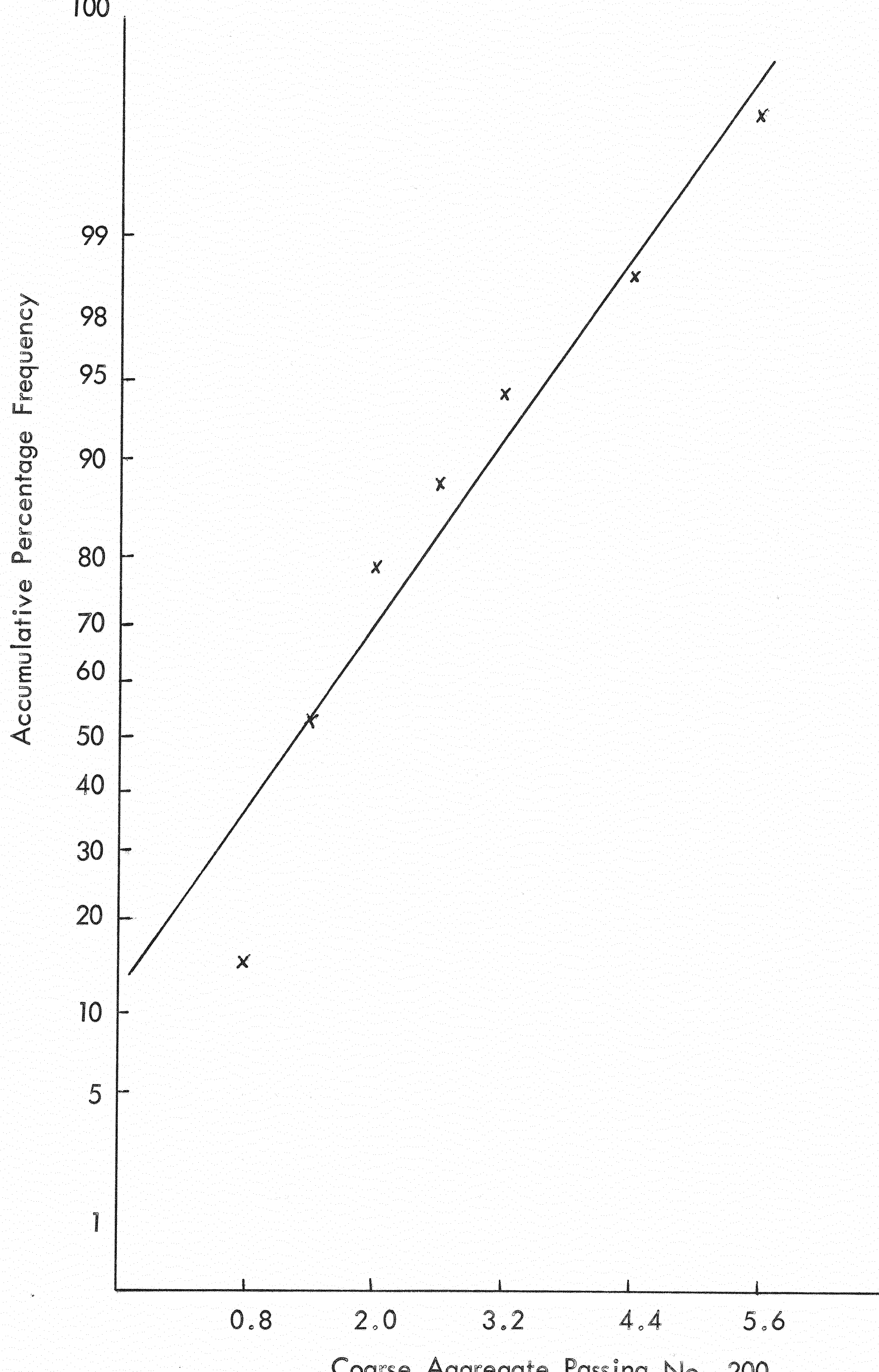


Figure II-70. % Passing No. 200 C.A. - goodness of fit curve

No.	Los Angeles Range, %	f	%	Cum%
1	- 25	10	5.2	5.2
2	25 - 28	80	41.7	46.9
3	28 - 31	57	29.7	76.6
4	31 - 34	24	12.5	89.1
5	34 - 37	18	9.4	98.5
6	37 -	3	1.5	100.0
		192	100	

n	192
specs	40%max
$\bar{\bar{x}}$	29.2
σ_T	4.2
σ_t^2	12.2
σ_s^2	0.1
σ_a^2	5.4
V	14.4%

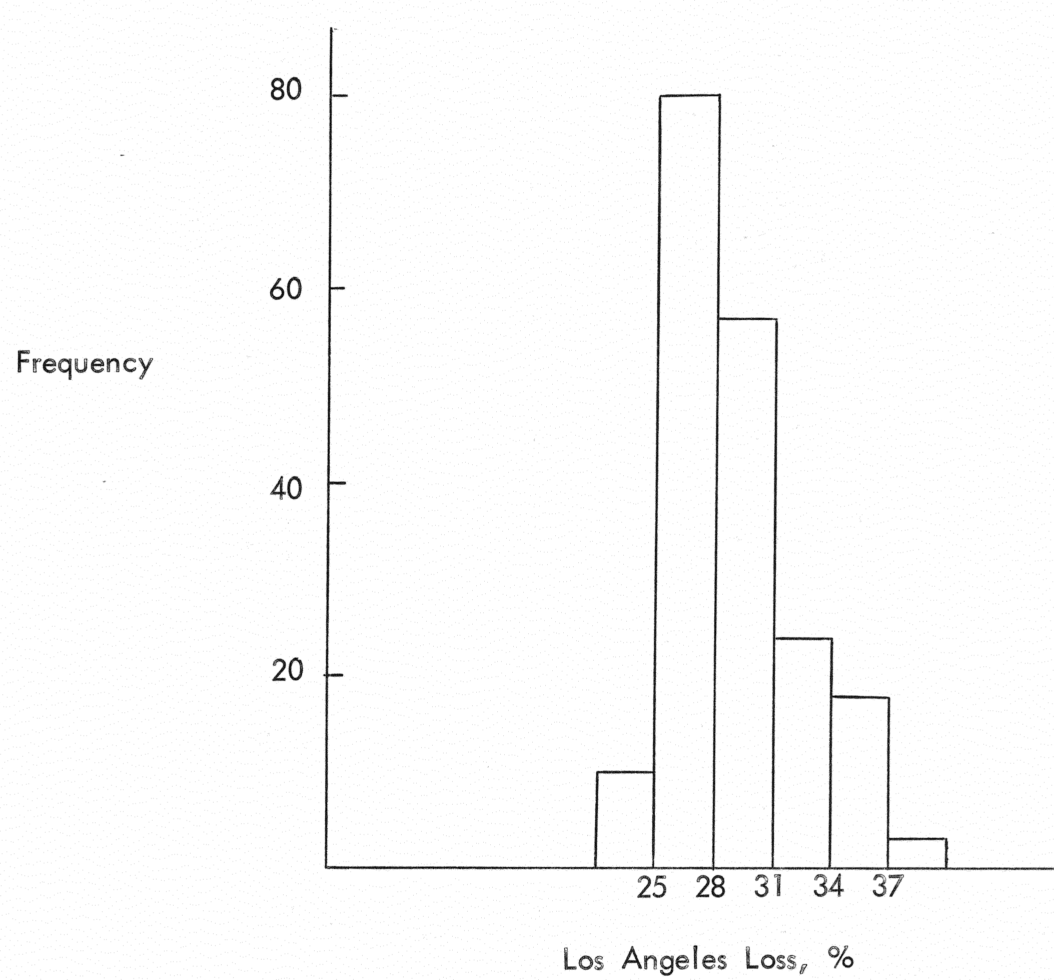


Figure II-71. Los Angeles Loss - statistical properties

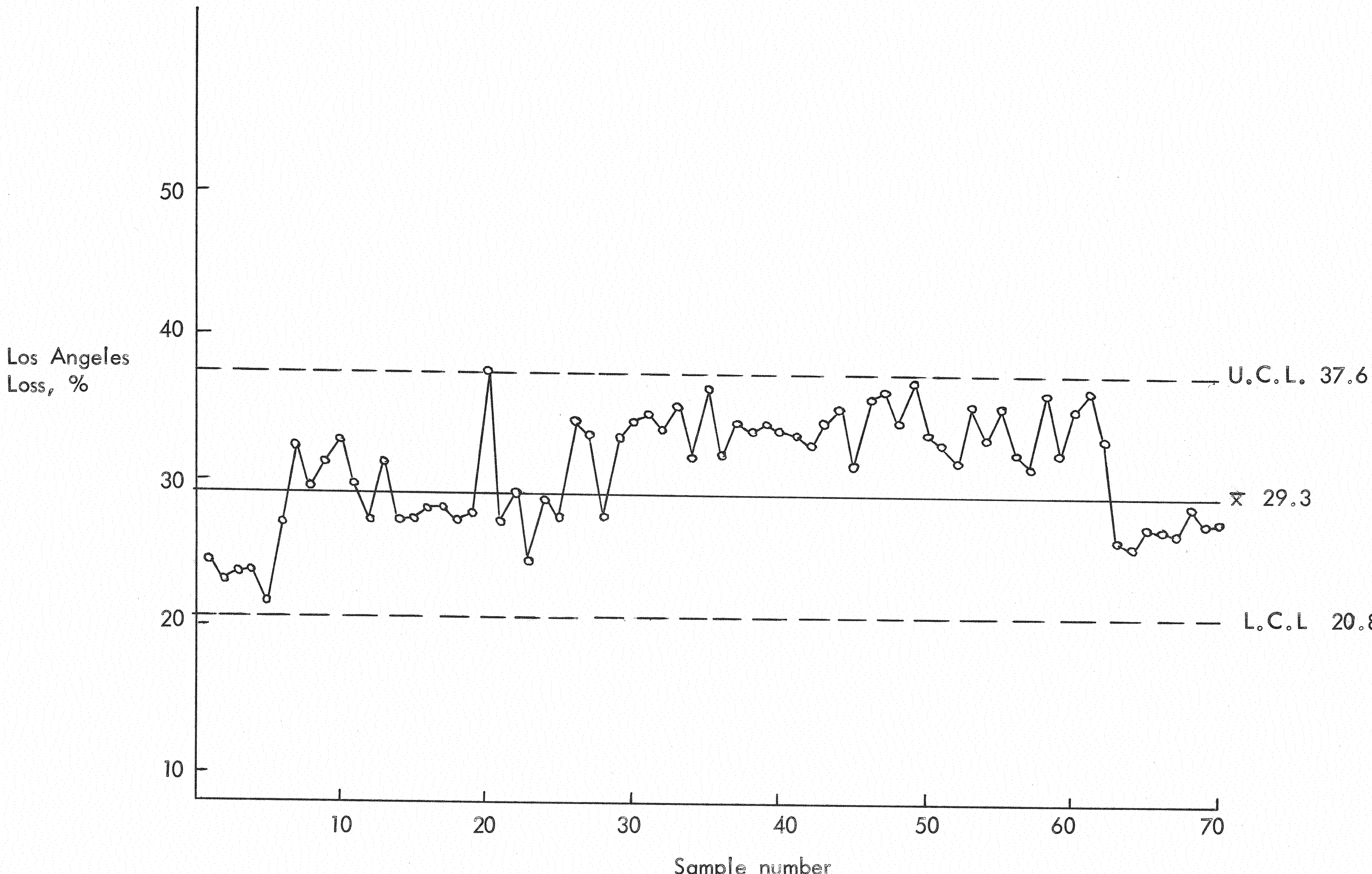


Figure II-72. Los Angeles Loss - quality control chart

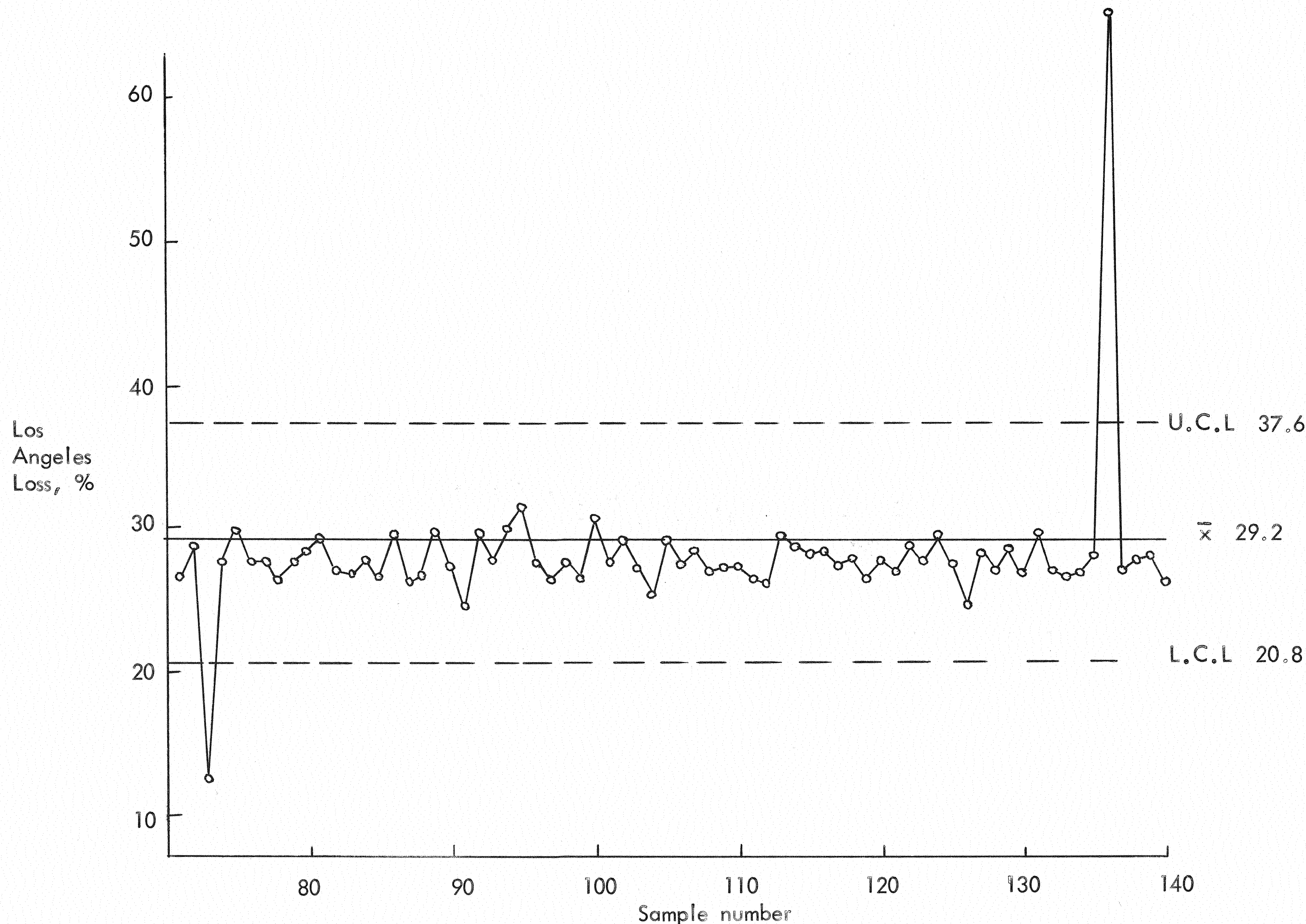


Figure II-72 (cont.) Los Angeles Loss - quality control chart

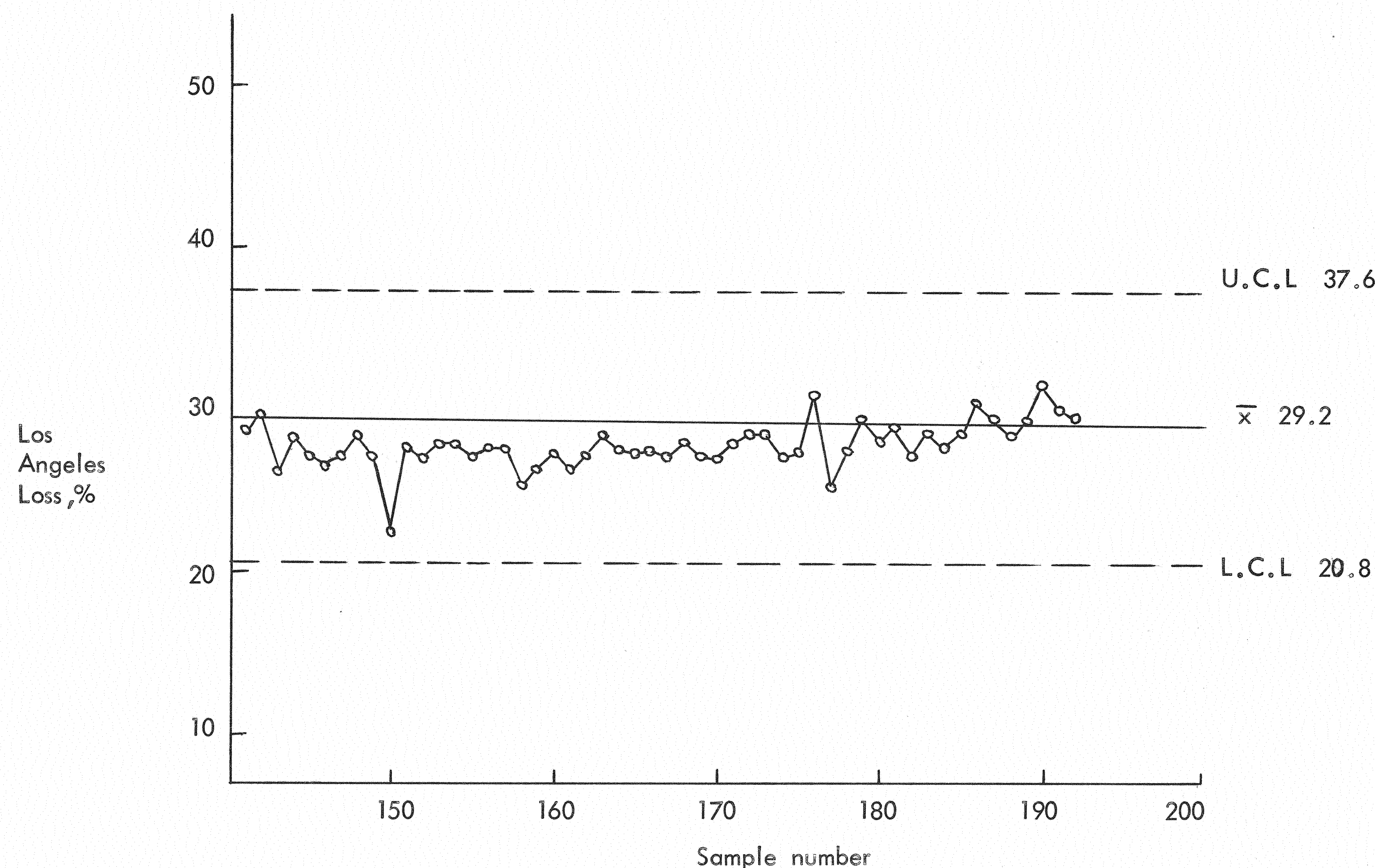


Figure II-72(cont.) Los Angeles Loss - quality control chart

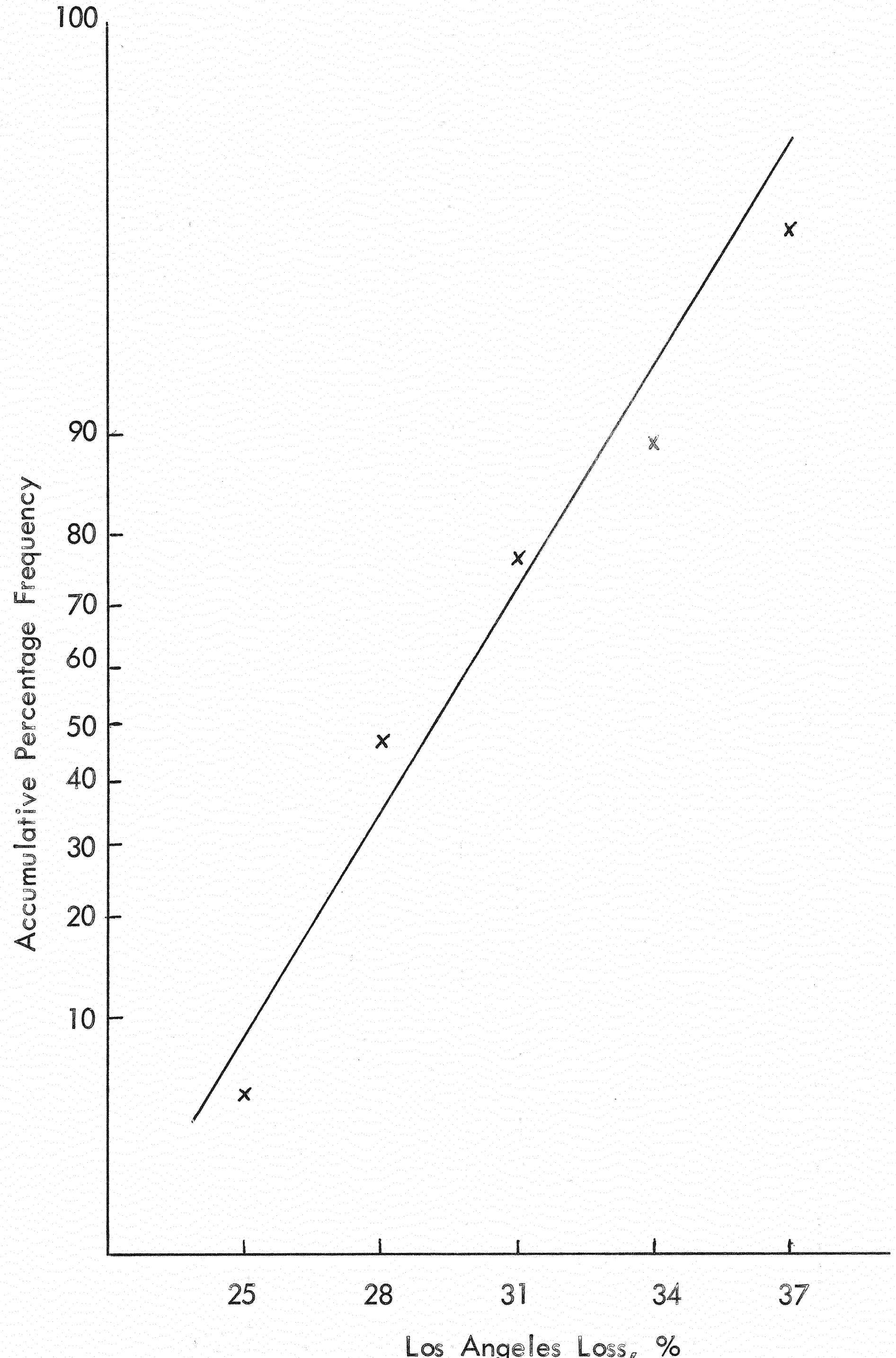


Figure II-73. Los Angeles Loss - goodness of fit curve

No.	Fineness Modulus Range %	f	%	Cum%
1	2.10 - 2.20	2	.9	.9
2	2.21 - 2.30	1	.4	1.3
3	2.31 - 2.40	9	4.4	5.7
4	2.41 - 2.50	36	17.7	23.4
5	2.51 - 2.60	67	33.0	56.4
6	2.61 - 2.70	45	22.2	78.6
7	2.71 - 2.80	30	14.8	93.4
8	2.81 - 2.90	12	5.9	99.3
9	2.91 - 3.00	1	.4	99.7
		203	100	

n	203
specs	---
$\bar{x}$	2.60
σ_T	0.15
σ_t^2	0.009
σ_s^2	0.001
σ_a^2	0.012
V	5.8%

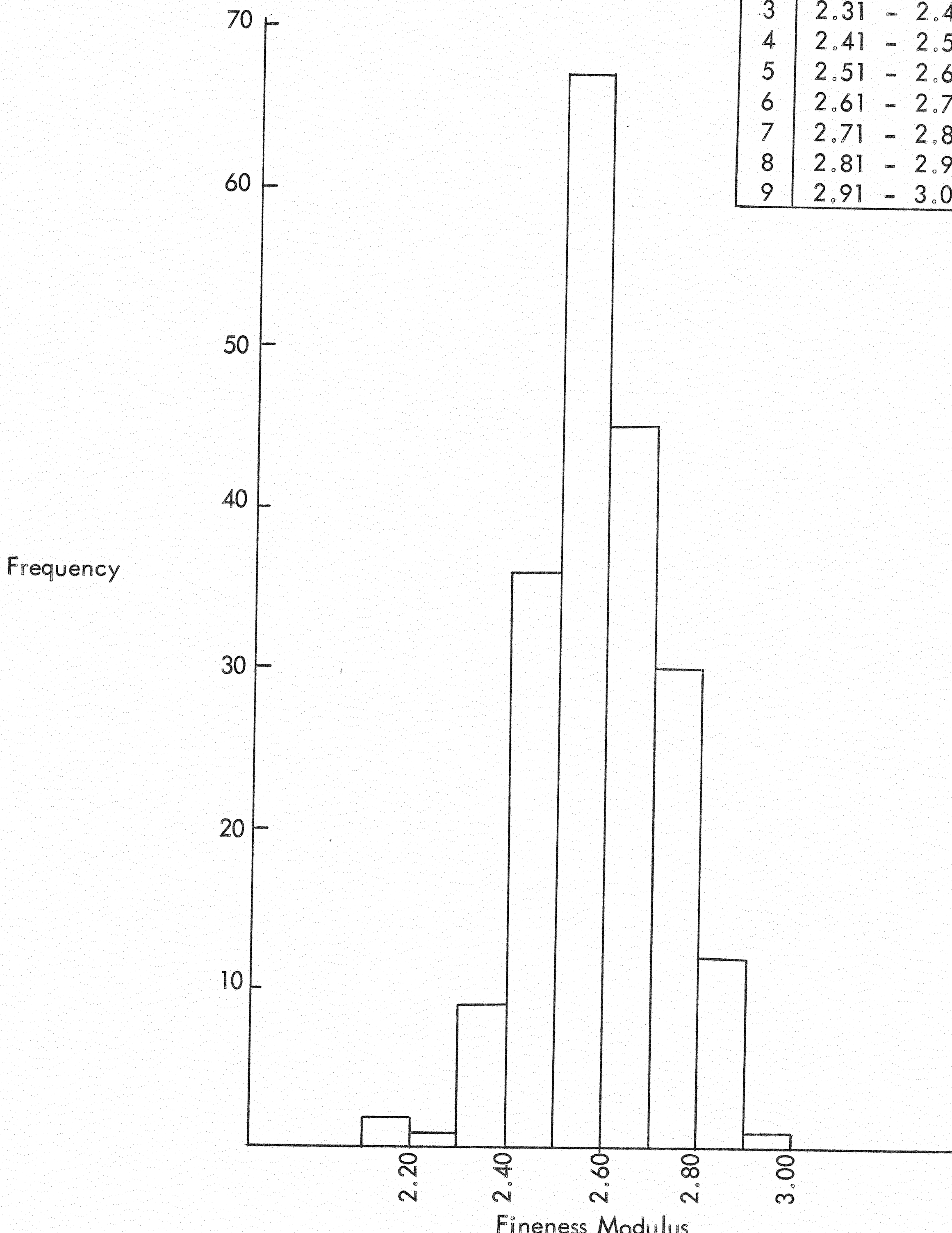


Figure II-74. Fineness Modulus - statistical properties

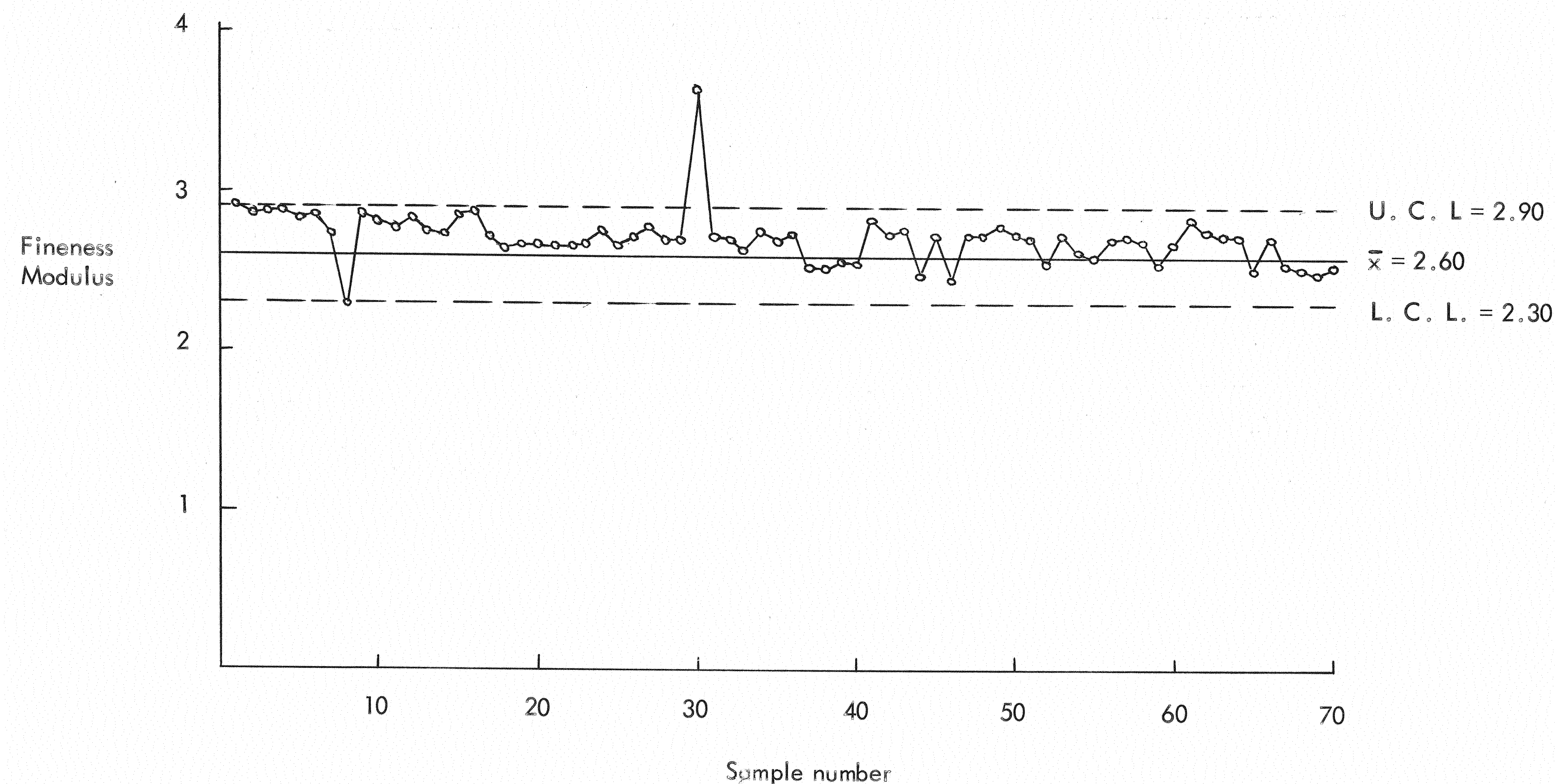


Figure II-75. Fineness Modulus - quality control chart

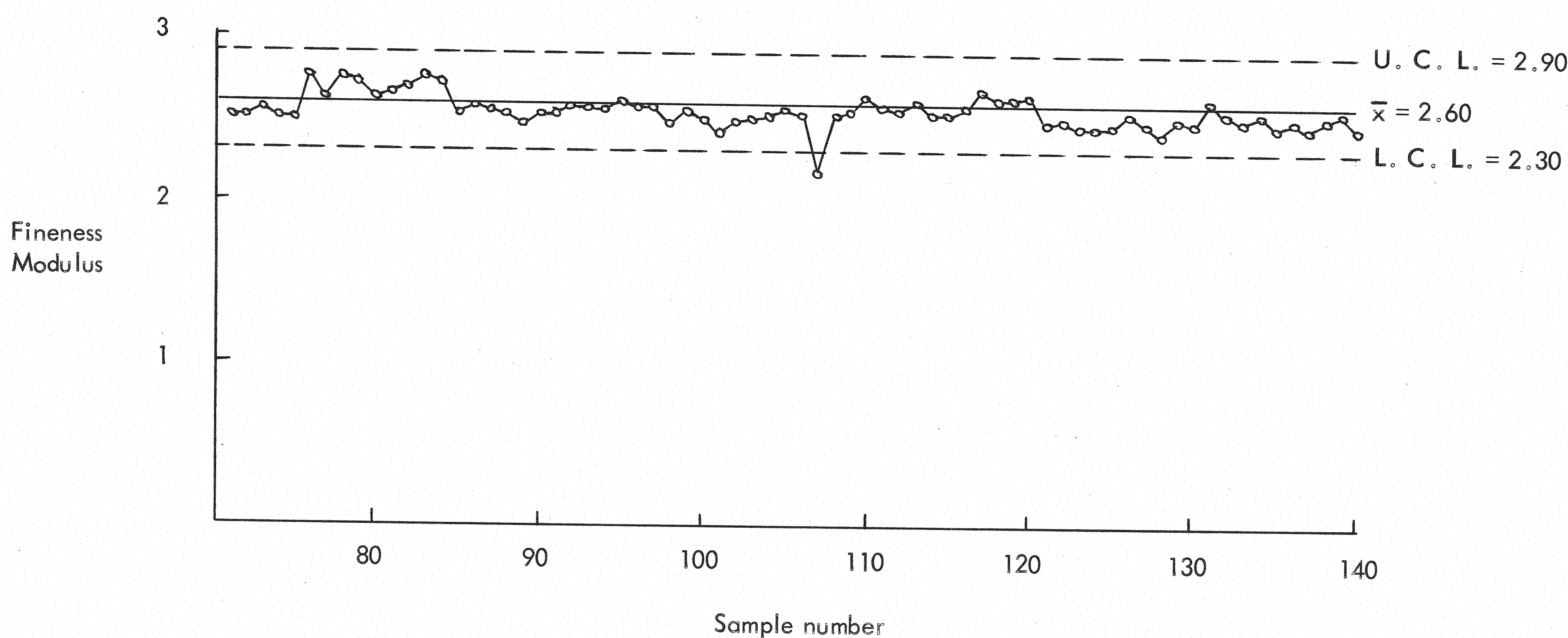


Figure II-75 (cont.). Fineness Modulus - quality control chart

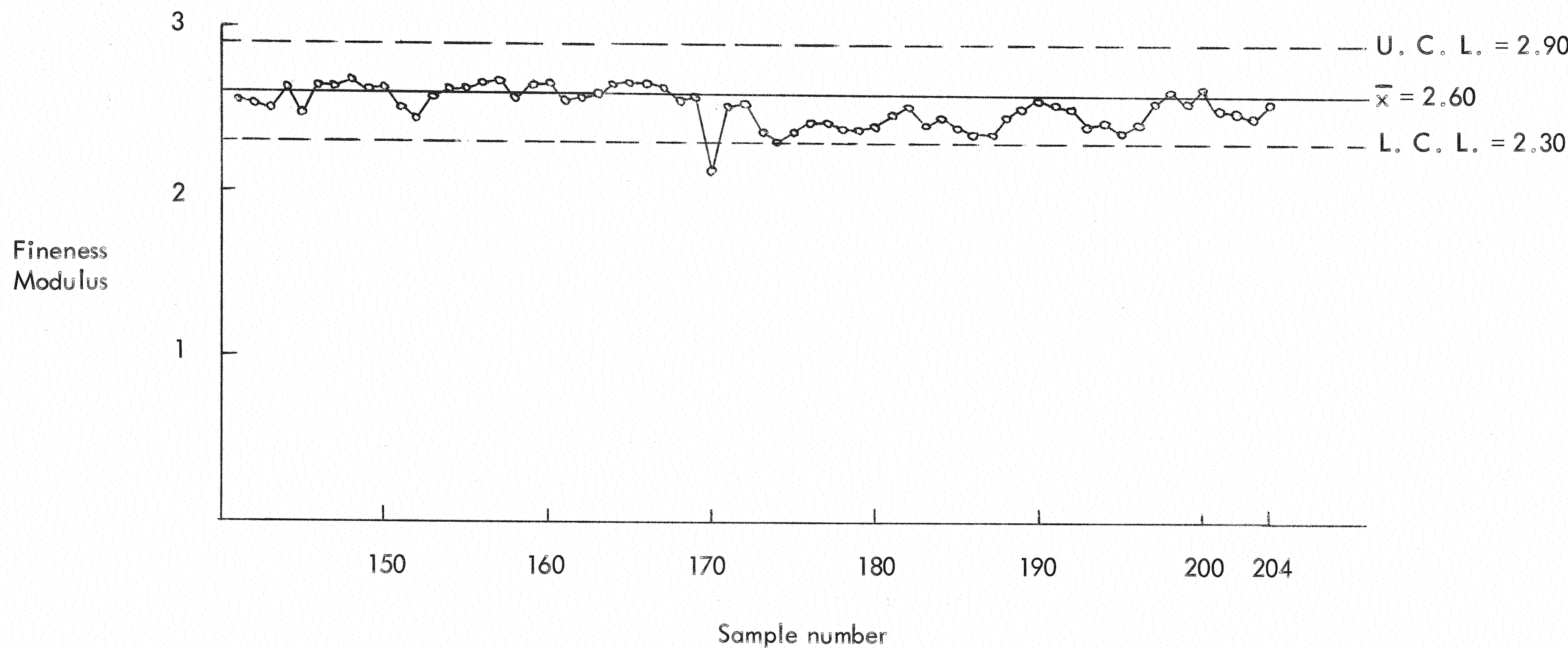


Figure II-75 (cont.). Fineness Modulus - quality control chart

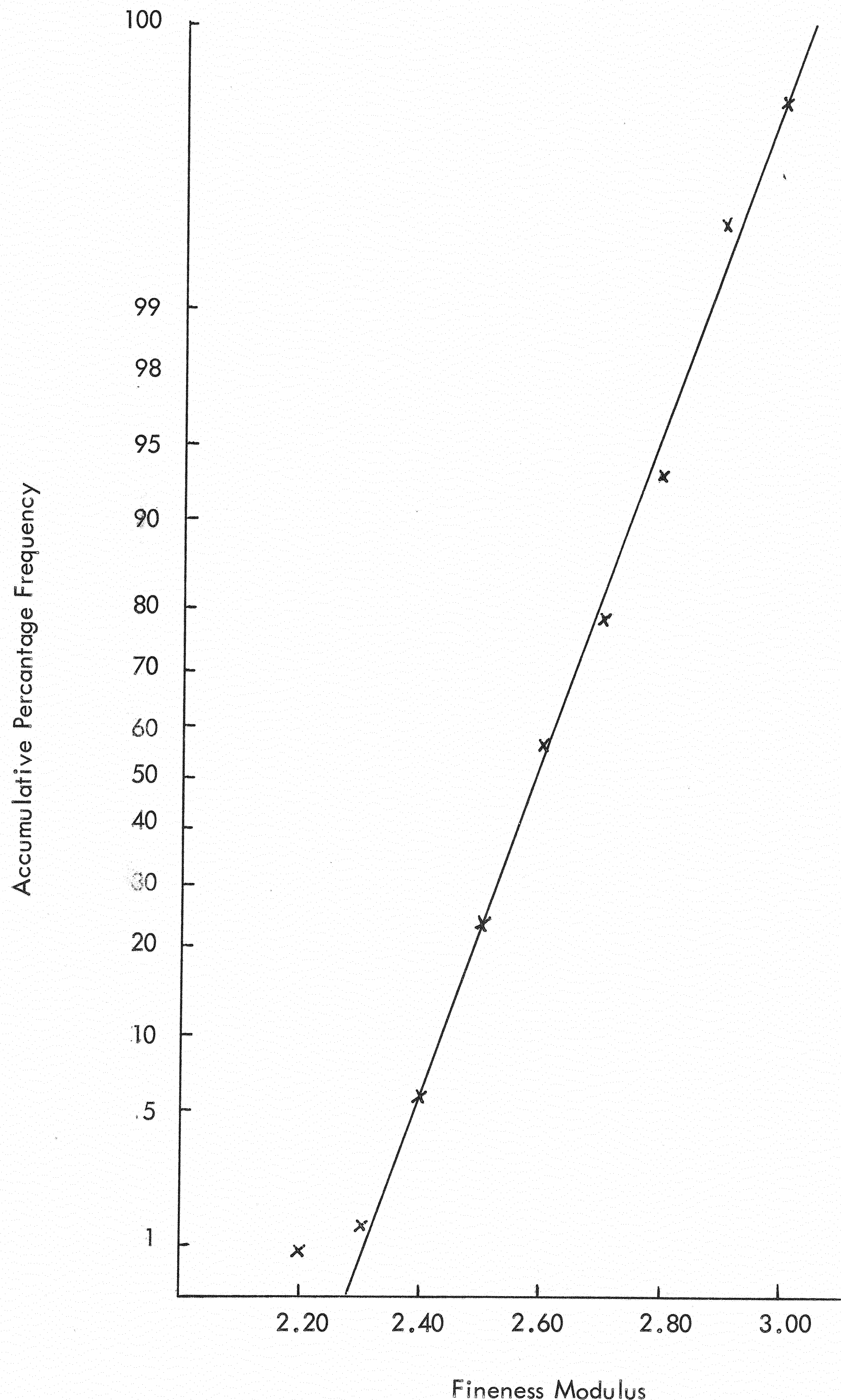


Figure II-76. Fineness Modulus - goodness of fit curve

No.	F.A. Passing No. 200 Range, %	f	%	Cum%
1	0.3 - 0.7	55	27	27
2	0.7 - 1.1	85	42	69
3	1.1 - 1.5	26	13	82
4	1.5 - 1.9	13	6	88
5	1.9 - 2.3	10	5	93
6	2.3 - 2.7	7	3	96
7	2.7 - 3.1	4	2	98
8	3.1 - 3.5	1	0.5	98.5
9	3.5 - 3.9	1	0.5	99.0
10	3.9 - 4.3	2	1	
		204	100	

n	204
specs	3.0% max
$\bar{x}$	1.09
σ_T	0.7
σ_t^2	0.18
σ_s^2	0.06
σ_a^2	0.25
V	64.2%

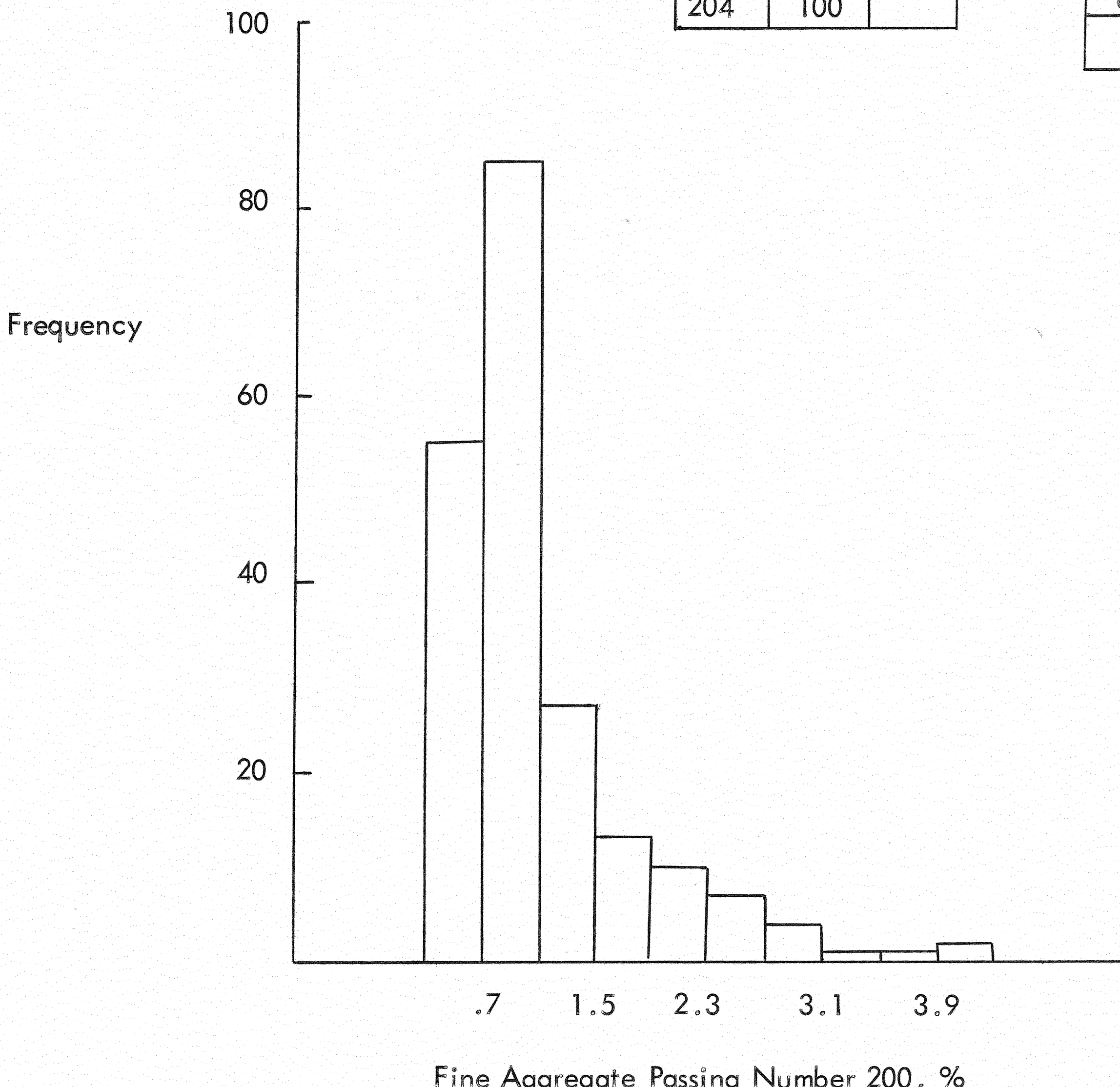


Figure II-77. % Passing No. 200 F.A. - statistical properties

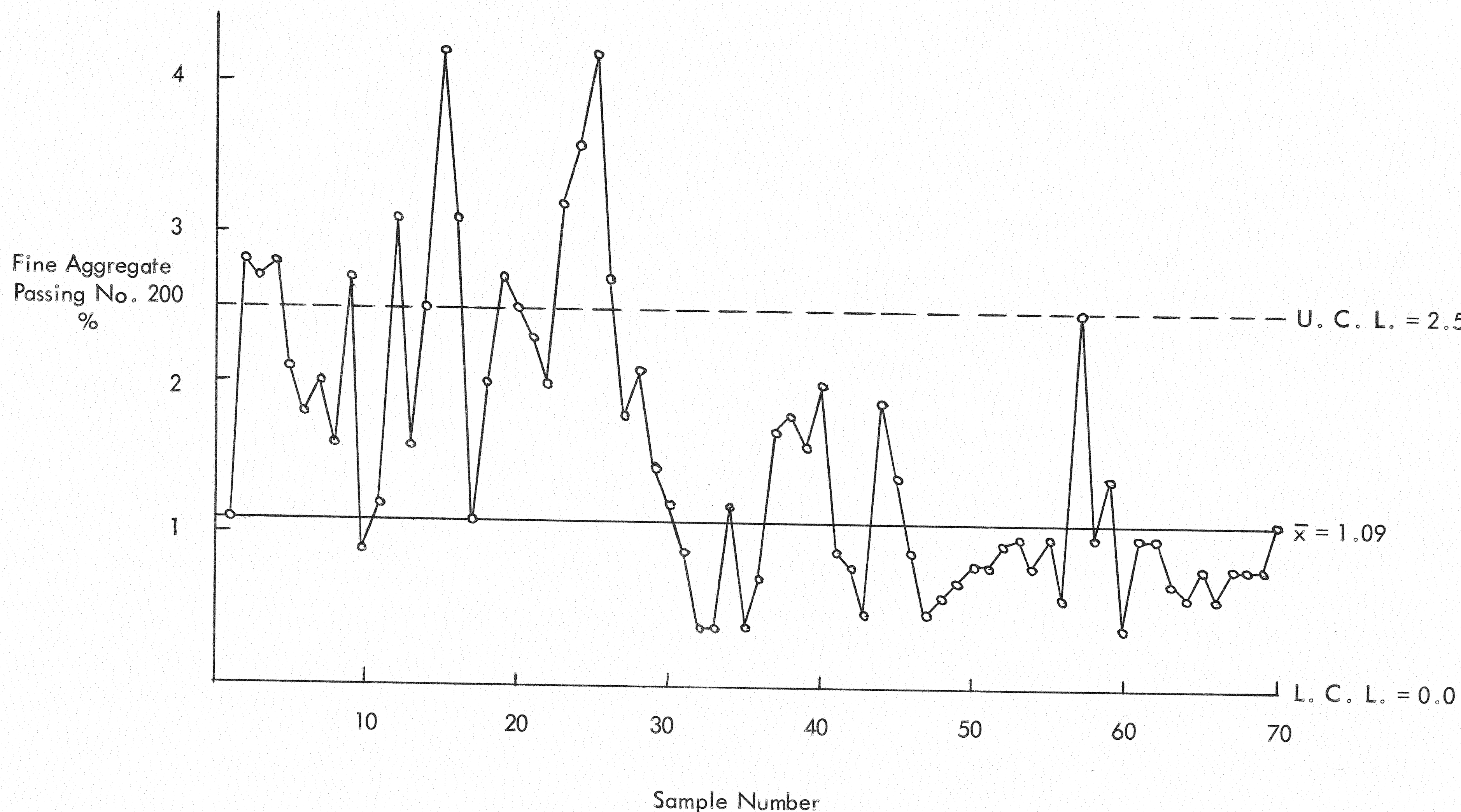


Figure II-78. % Passing No. 200 F.A. - quality control chart

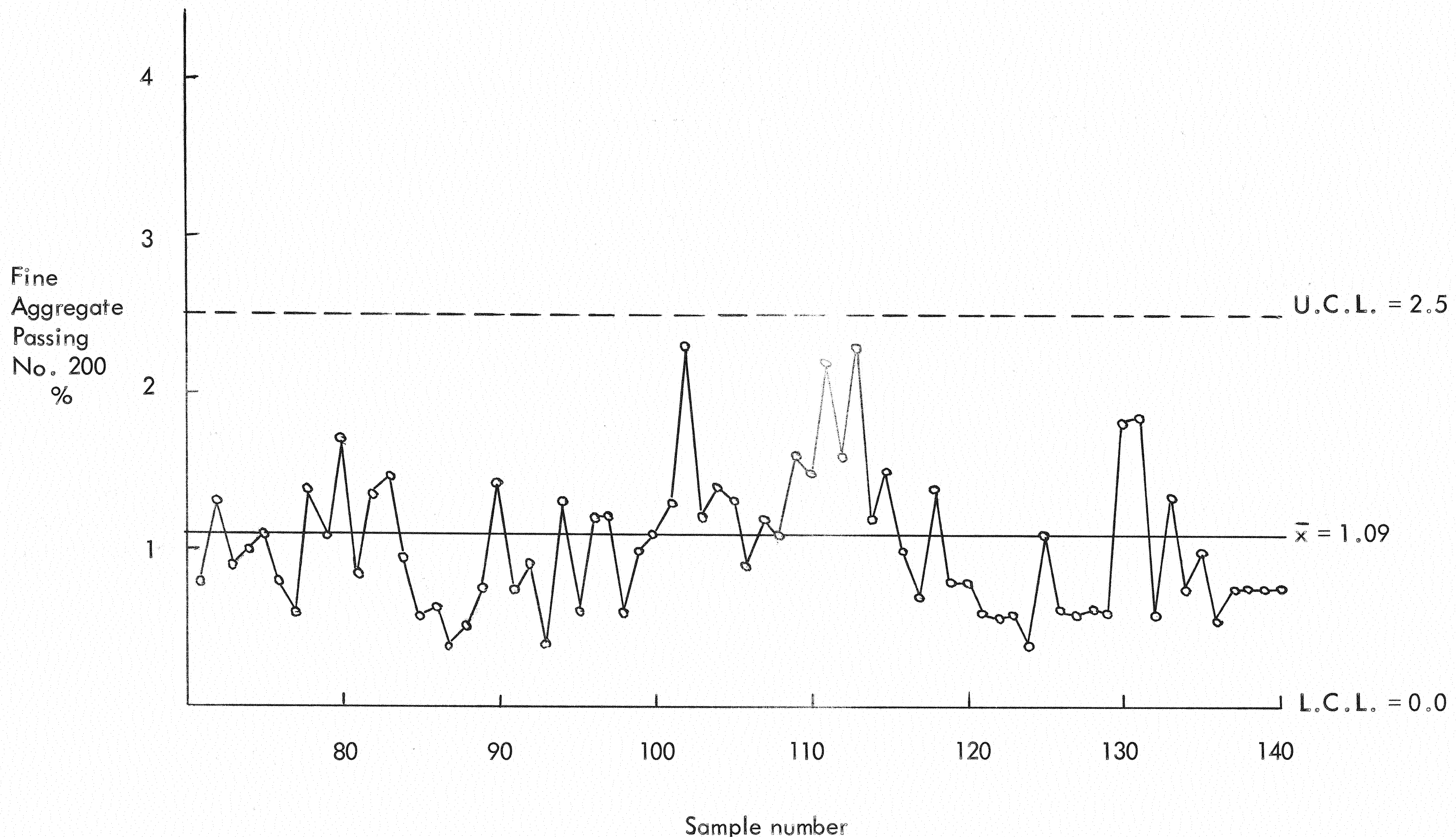


Figure II-78 (cont.). % Passing No. 200 F.A. - quality control chart

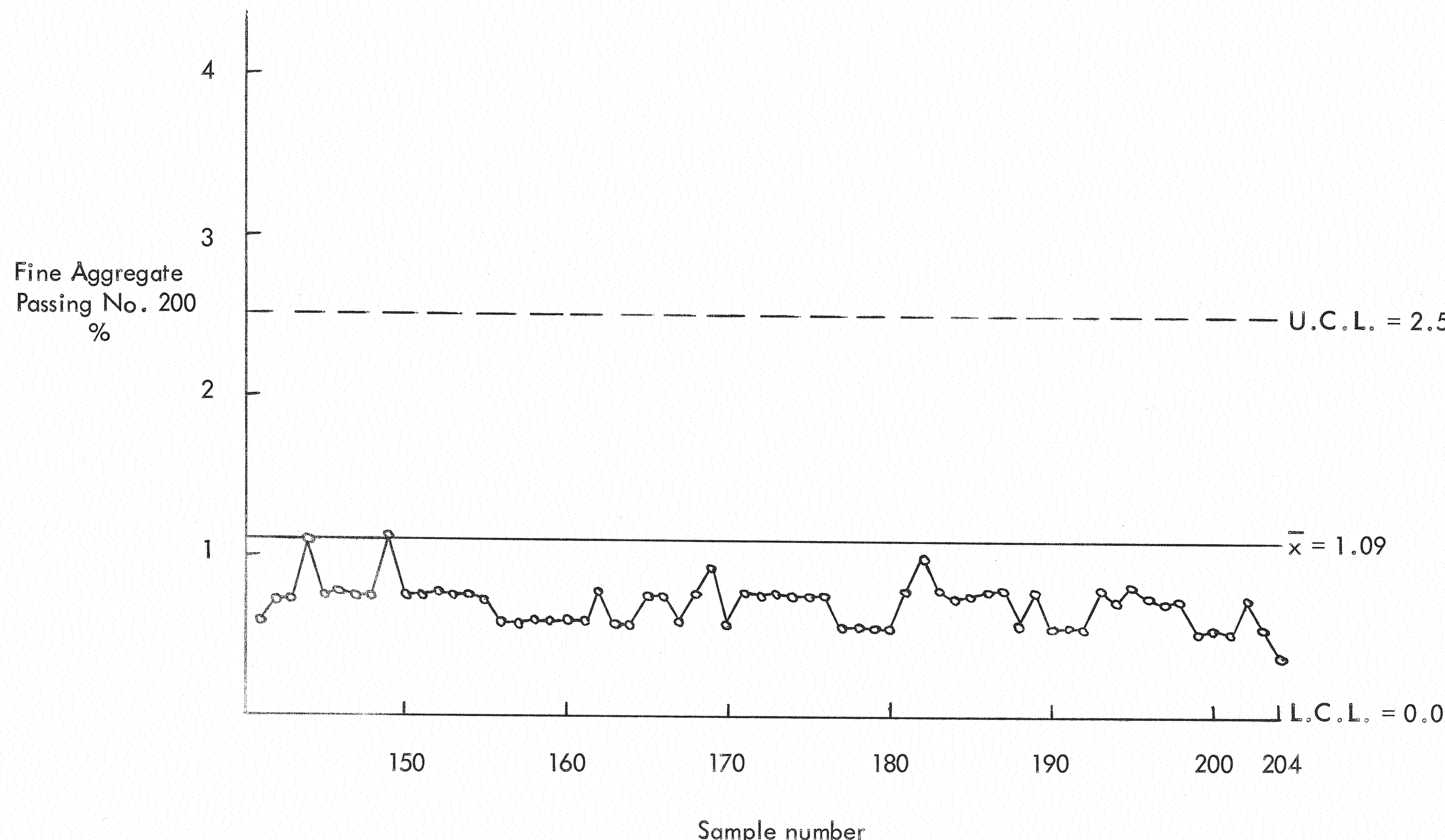


Figure II-78 (cont.). % Passing No. 200 F.A. - quality control chart

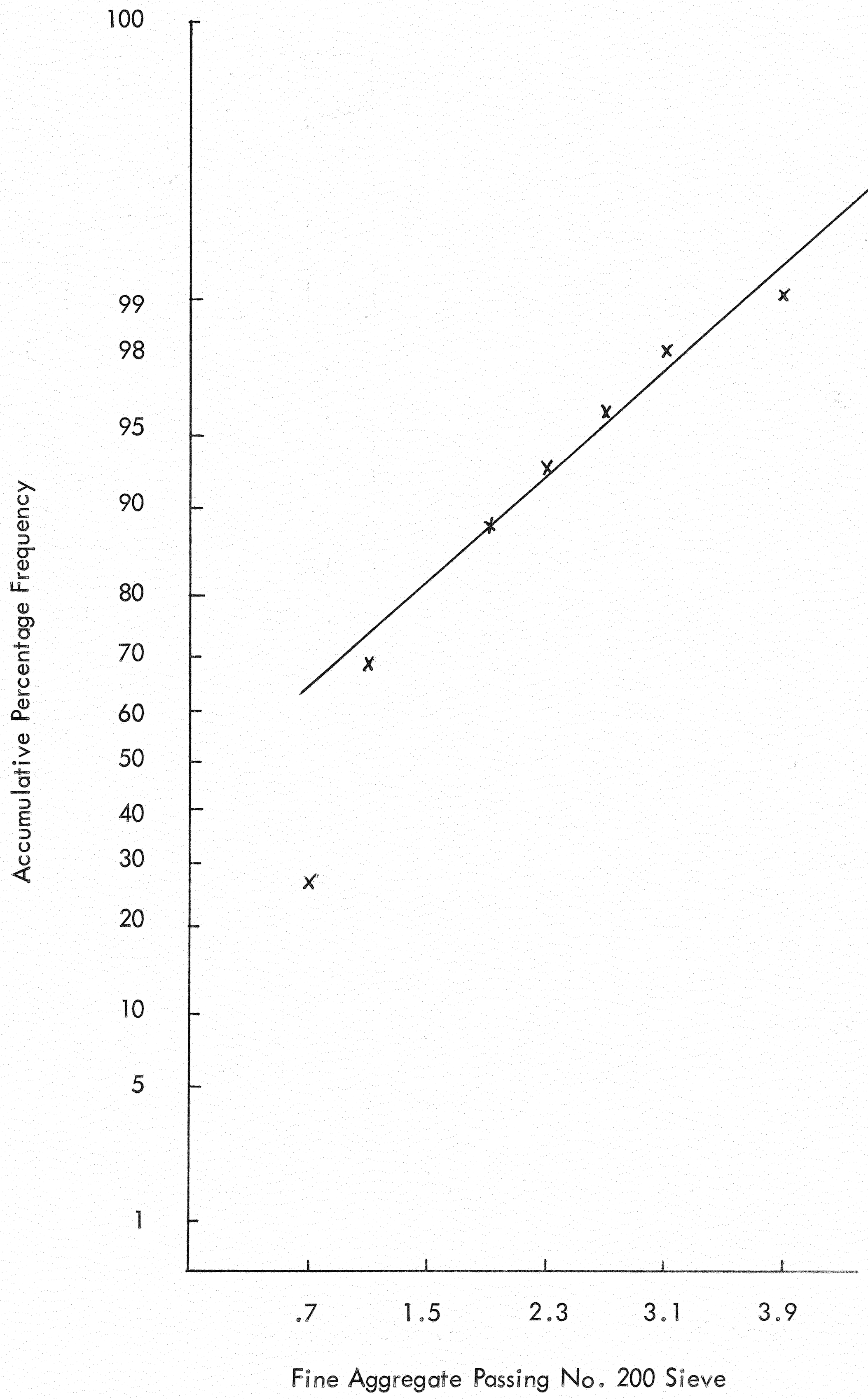
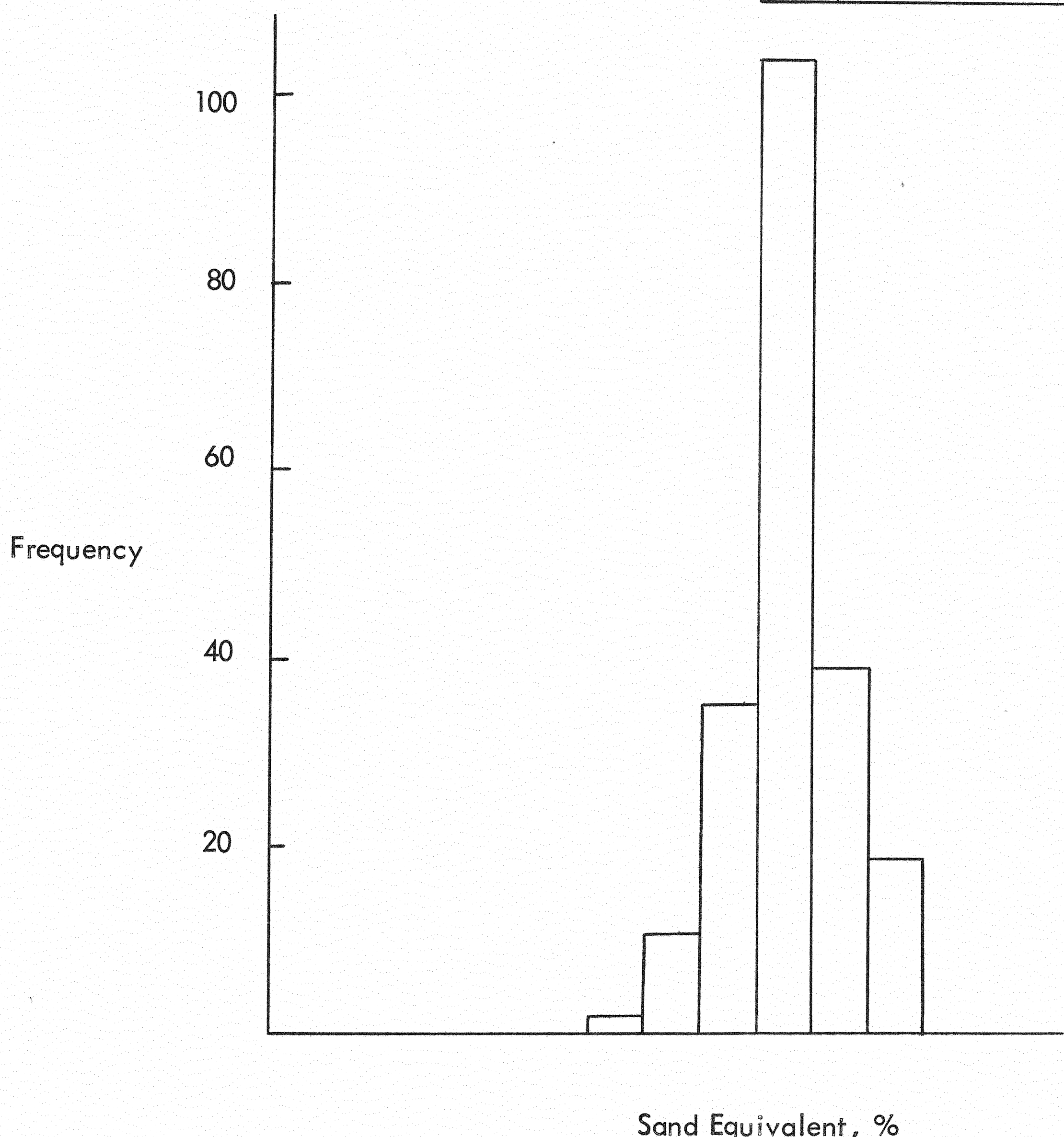


Figure II-79. % Passing No. 200 F.A. - goodness of fit curve

No.	Sand Equivalent Range, %	f	%	Cum%
1	- 95.0	2	1	1
2	95.0 - 96.0	11	5.5	6.5
3	96.0 - 97.0	35	17.5	24.0
4	97.0 - 98.0	104	52	76.0
5	98.0 - 99.0	39	19.5	95.5
6	99.0 - 100.0	9	4.5	100
		200	100	



n	200
specs	---
$\bar{x}$	97.6
σ_T	0.9
σ_t^2	0.7
σ_s^2	0
σ_a^2	0.1
V	0.9%

Figure II-80. Sand Equivalent - statistical properties

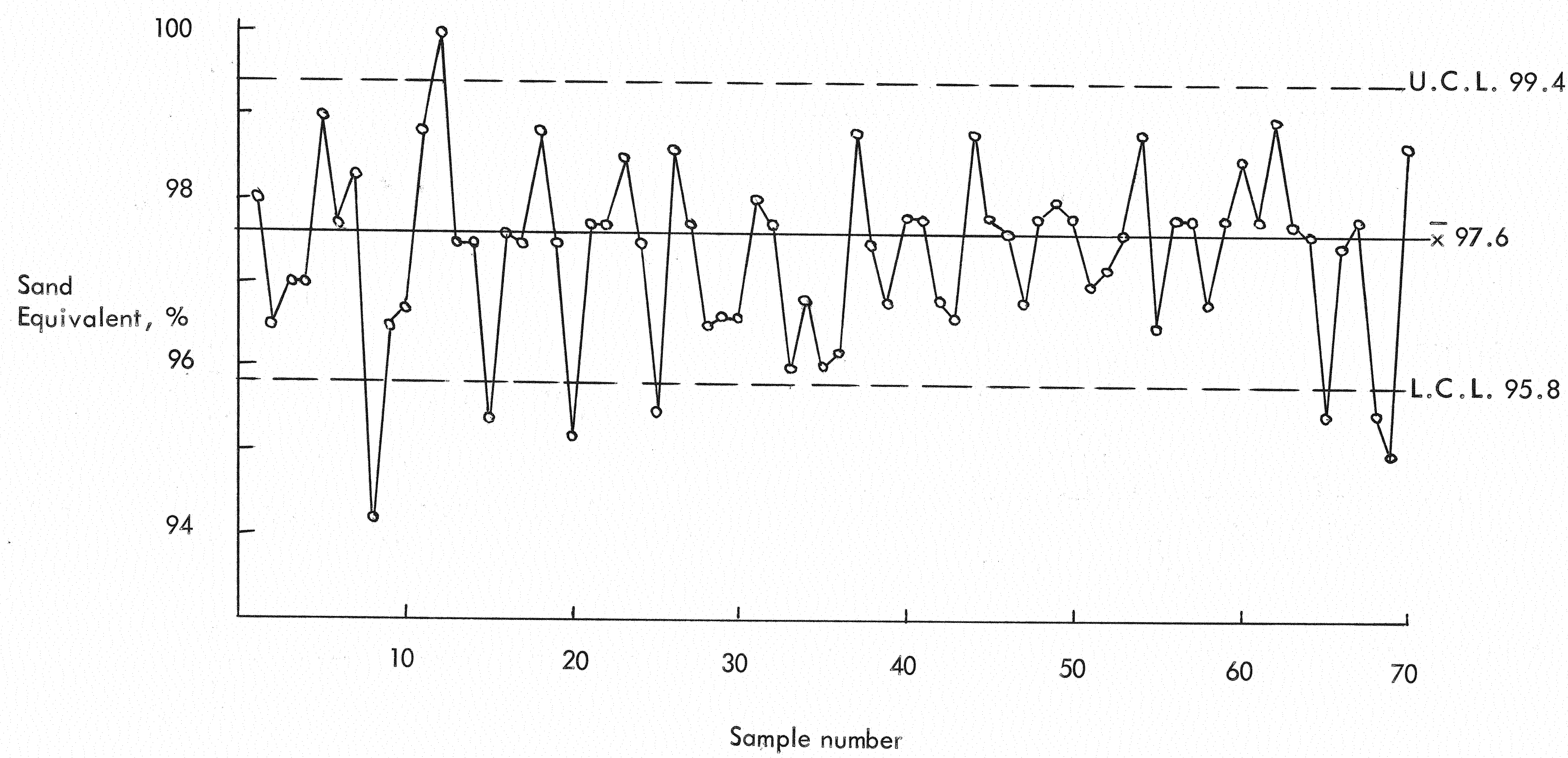


Figure II-81. Sand Equivalent - quality control chart

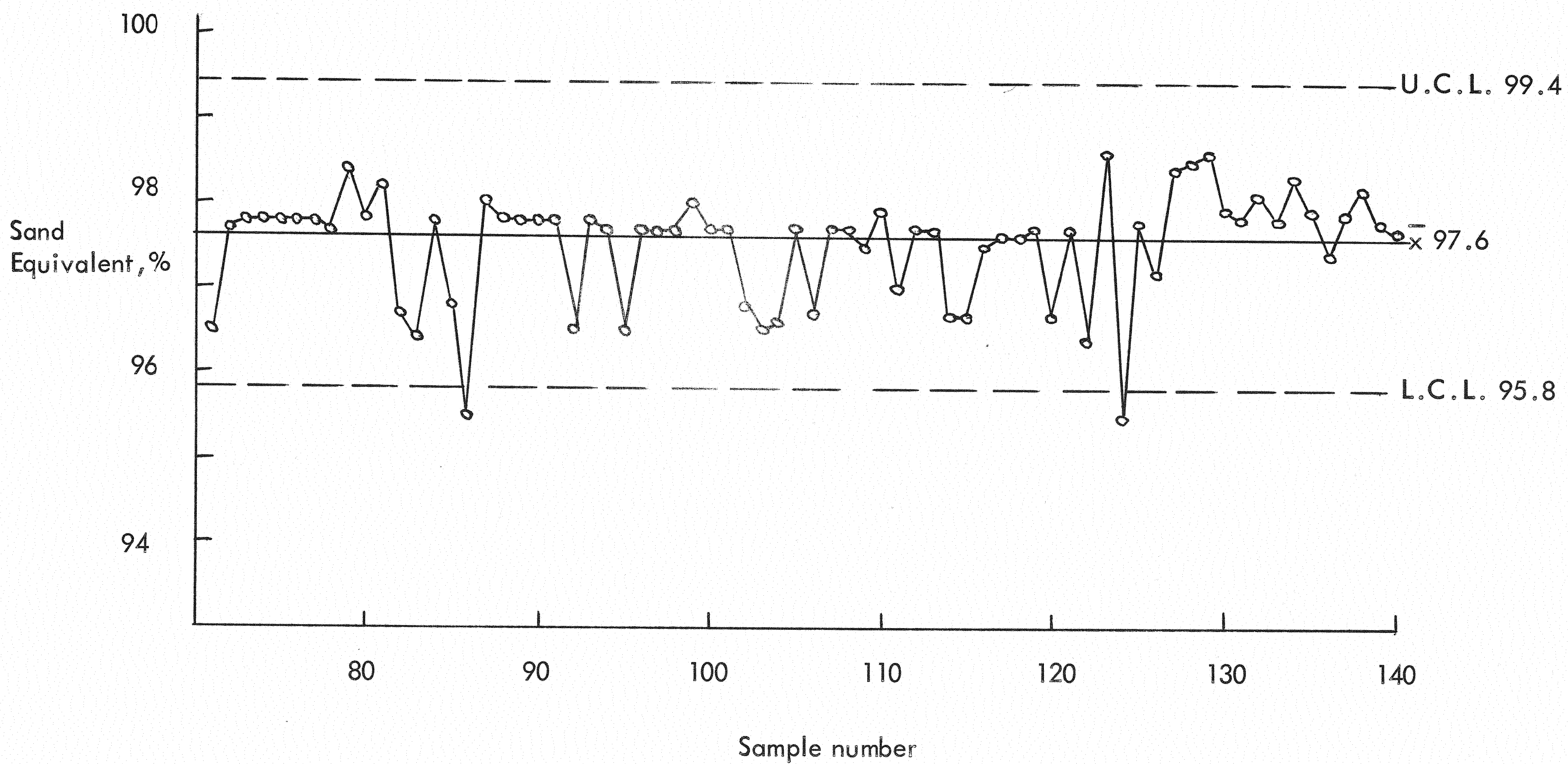


Figure II-81 (cont.). Sand Equivalent - quality control chart

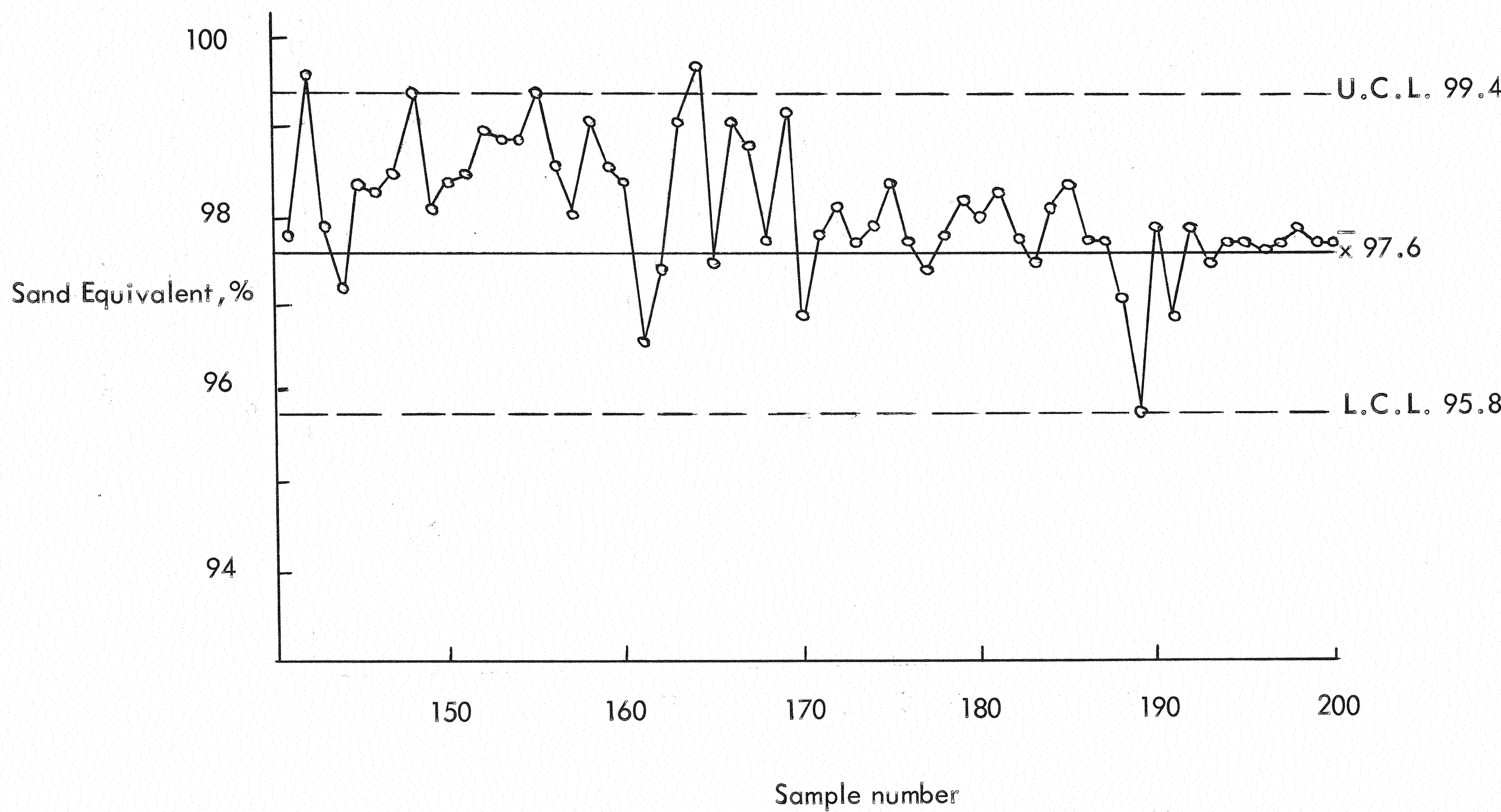


Figure II-81 (cont.). Sand Equivalent - quality control chart

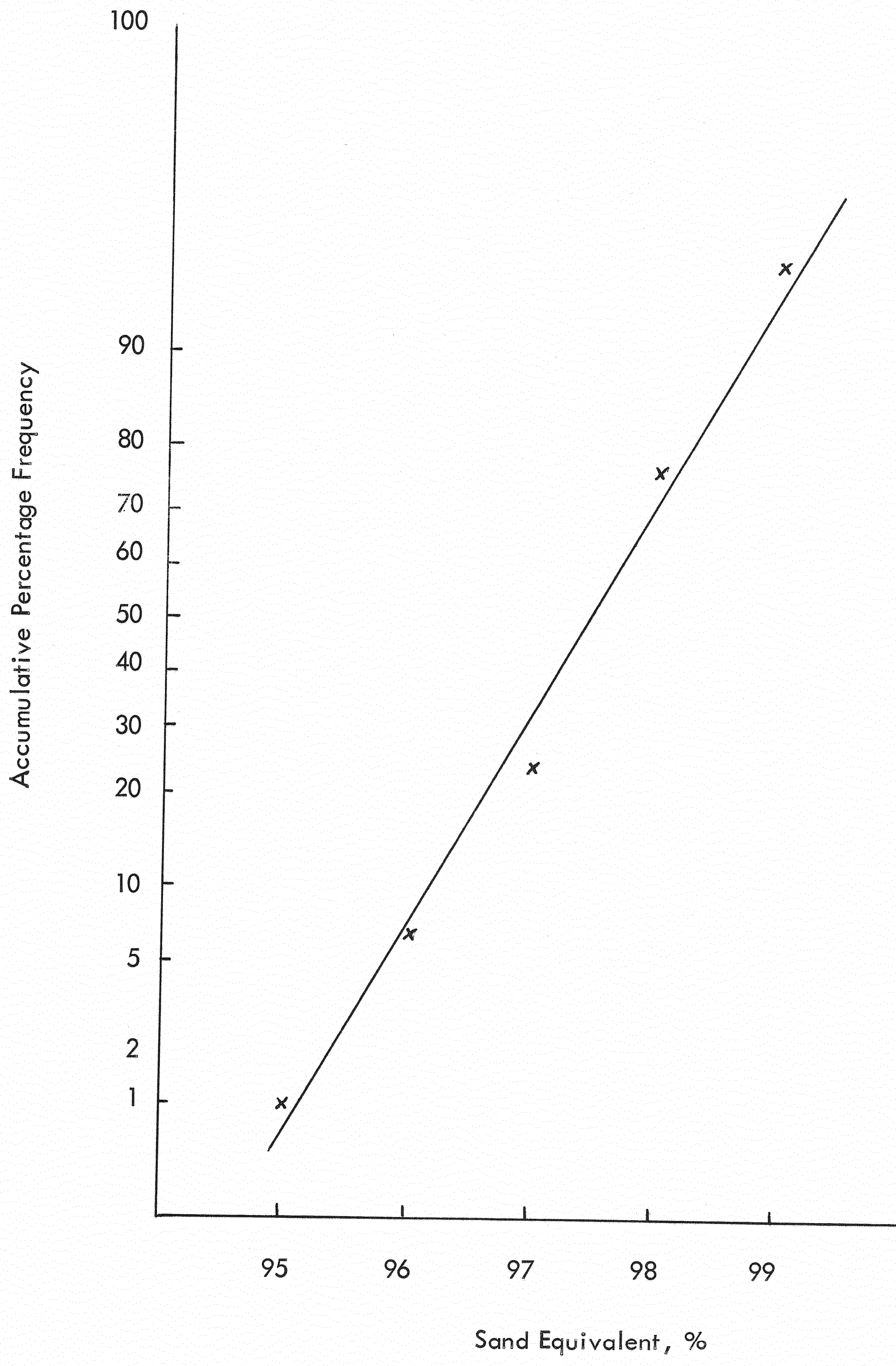
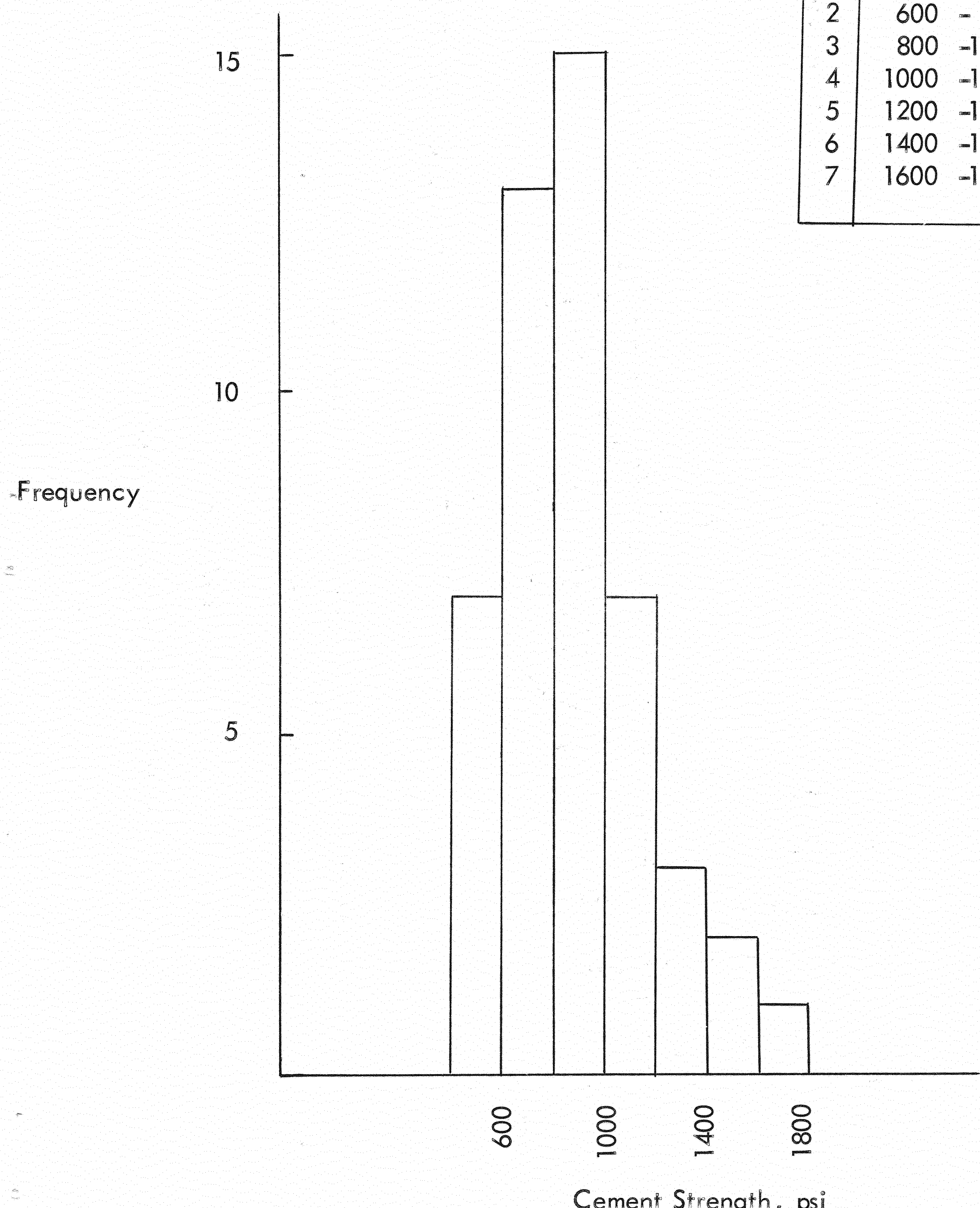


Figure II-82. Sand Equivalent - goodness of fit curve

No.	Cement Strength Range, psi	f	%	Cum%
1	400 -	7	14.6	14.6
2	600 - 800	13	27.1	41.7
3	800 -1000	15	31.2	72.9
4	1000 -1200	7	14.6	87.5
5	1200 -1400	3	6.2	93.7
6	1400 -1600	2	4.2	97.9
7	1600 -1800	1	2.1	100
		48	100	



n	48
specs	---
$\bar{x}$	883.88
σ_T	277.98
σ_t^2	56124
σ_s^2	7460
σ_a^2	13687
V	31.4%

Figure II-83. Cement Strength - statistical properties

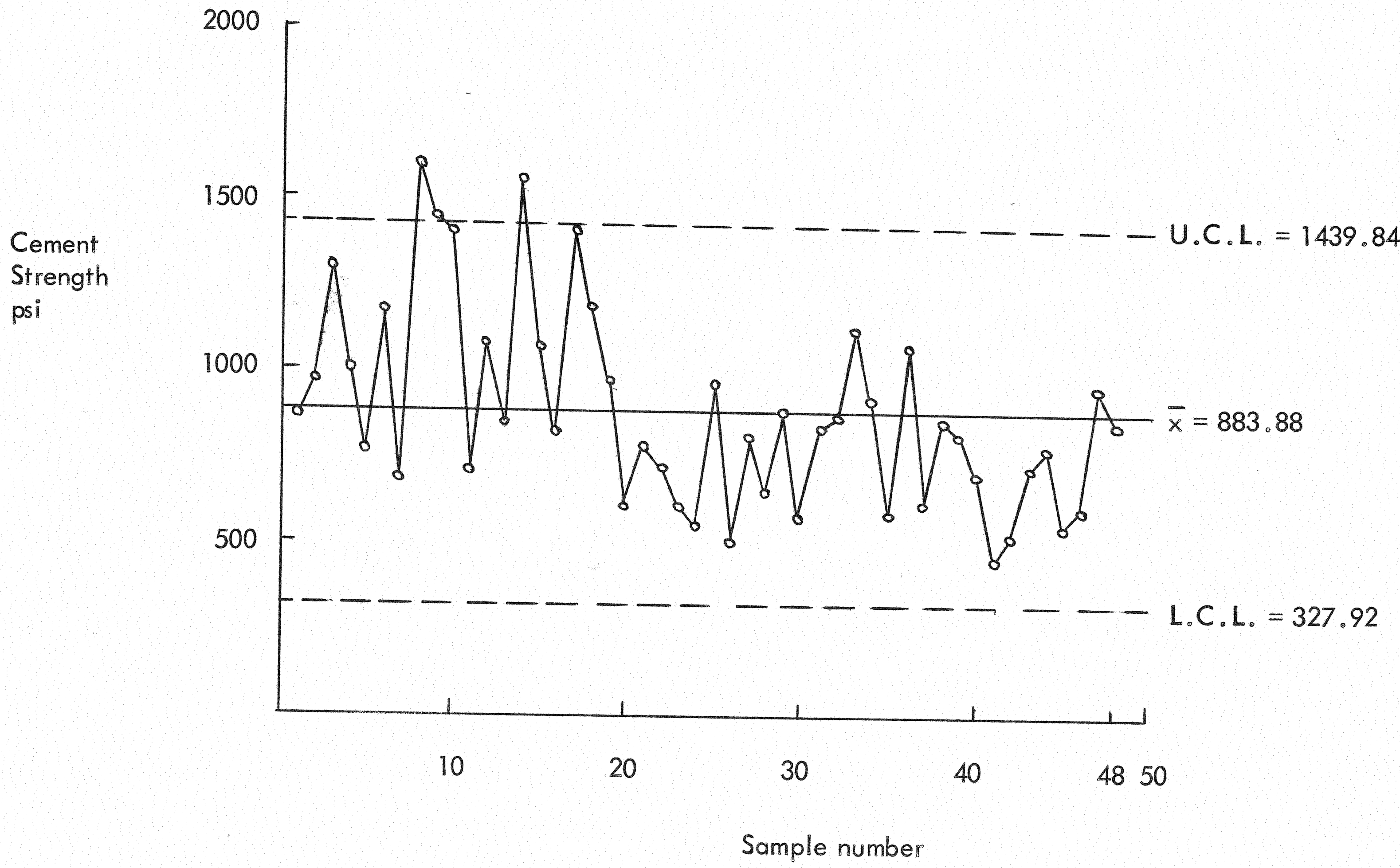


Figure II-84. Cement Strength - quality control chart

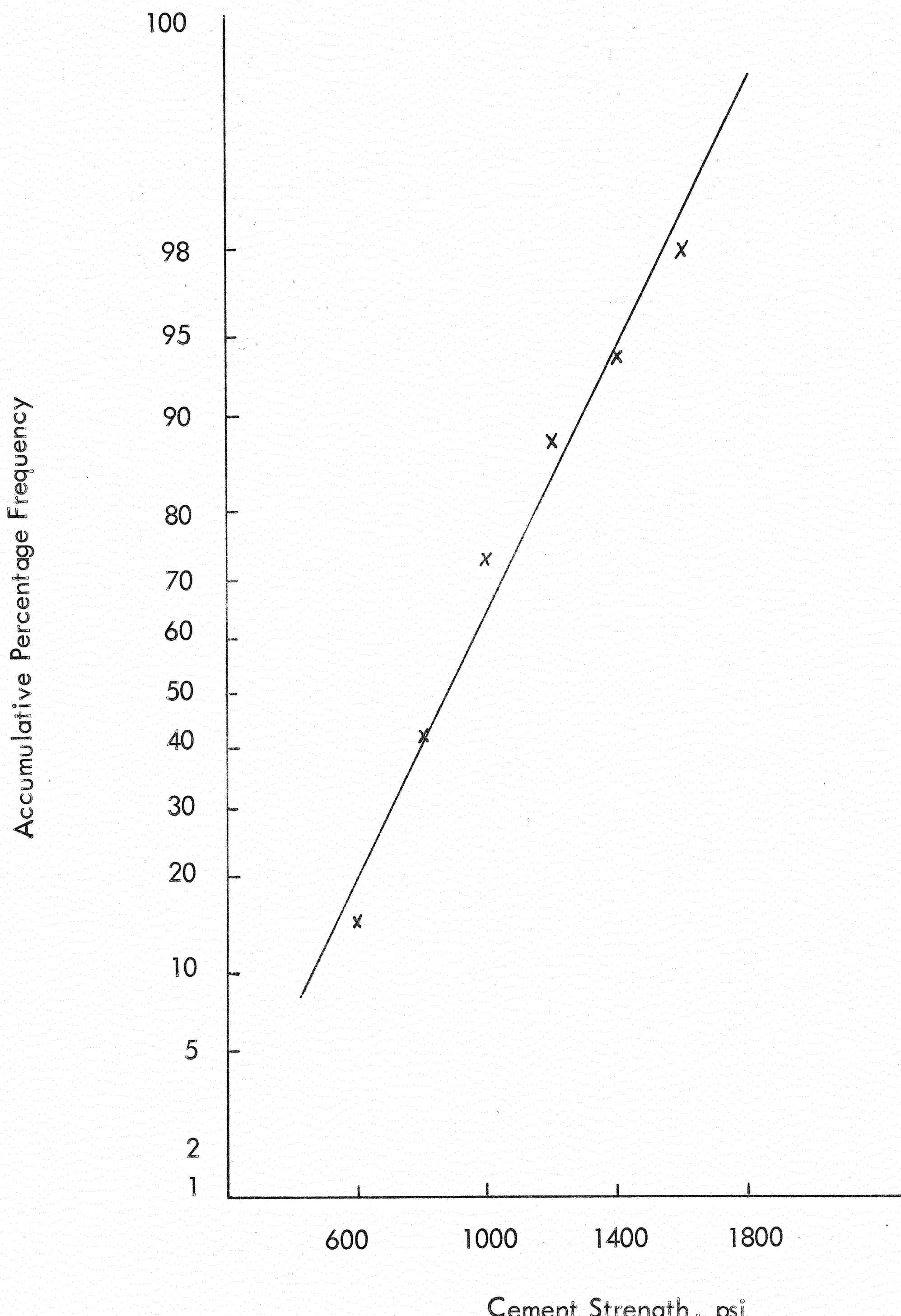


Figure II-85. Cement Strength - goodness of fit curve

No.	Cement Air Content Range, %	f	%	Cum %
1	- 3.50	2	4.4	4.4
2	3.50 - 4.00	13	30.0	34.4
3	4.00 - 4.50	10	22.6	57.0
4	4.50 - 5.00	3	6.7	63.7
5	5.00 - 5.50	4	9.1	72.8
6	5.50 - 6.00	0	0	72.8
7	6.00 - 6.50	5	11.4	84.2
8	6.50 - 7.00	6	13.5	97.7
9	7.00 -	1	2.3	100.0
		44	100	

n	44
specs	---
$\bar{x}$	4.84
σ_T	1.23
σ_t^2	---
σ_s^2	---
σ_a^2	---
V	25.4%

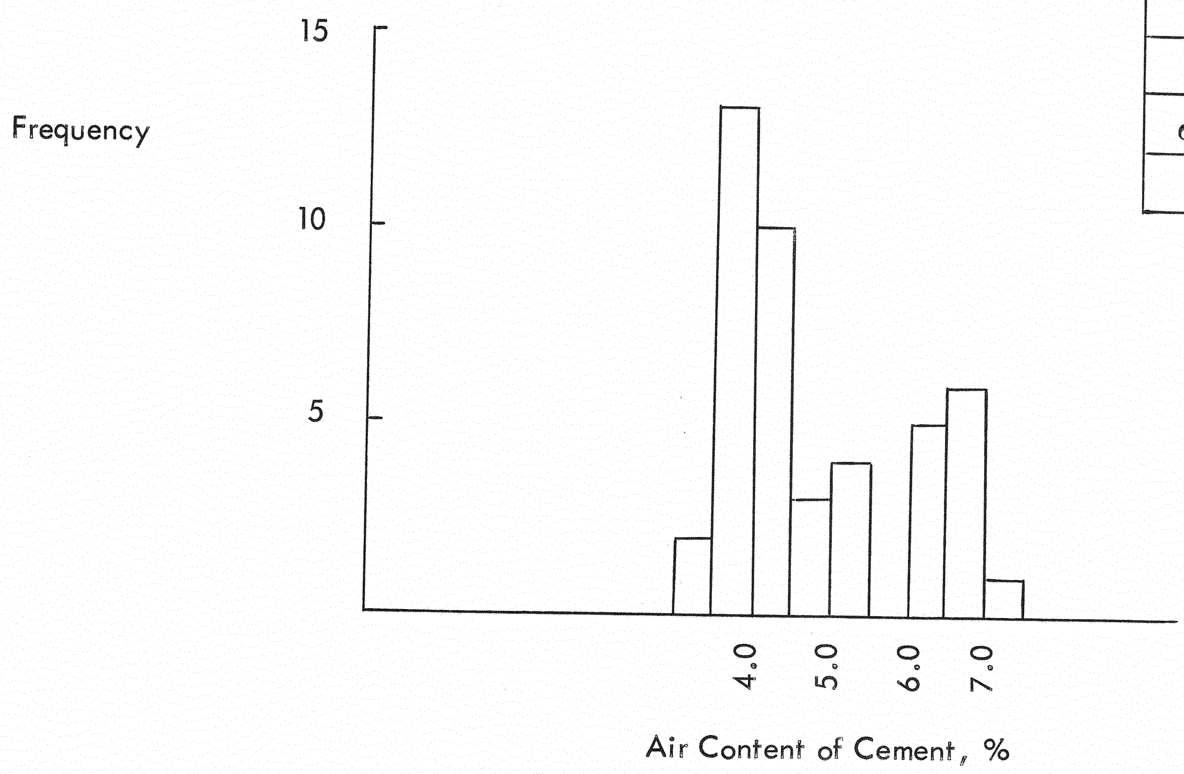


Figure II-86. Cement Air Content - statistical properties

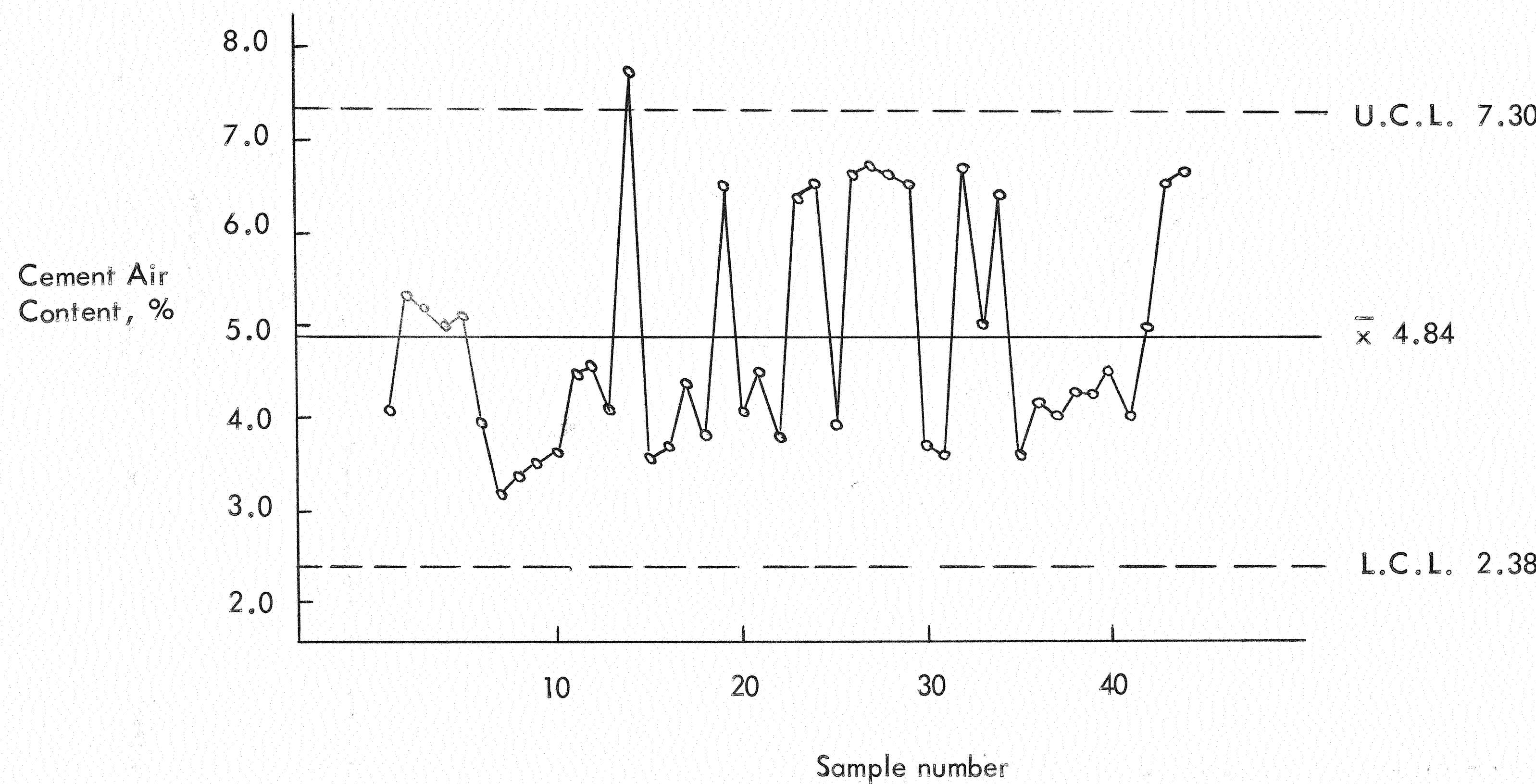


Figure II-87. Cement Air Content - quality control chart

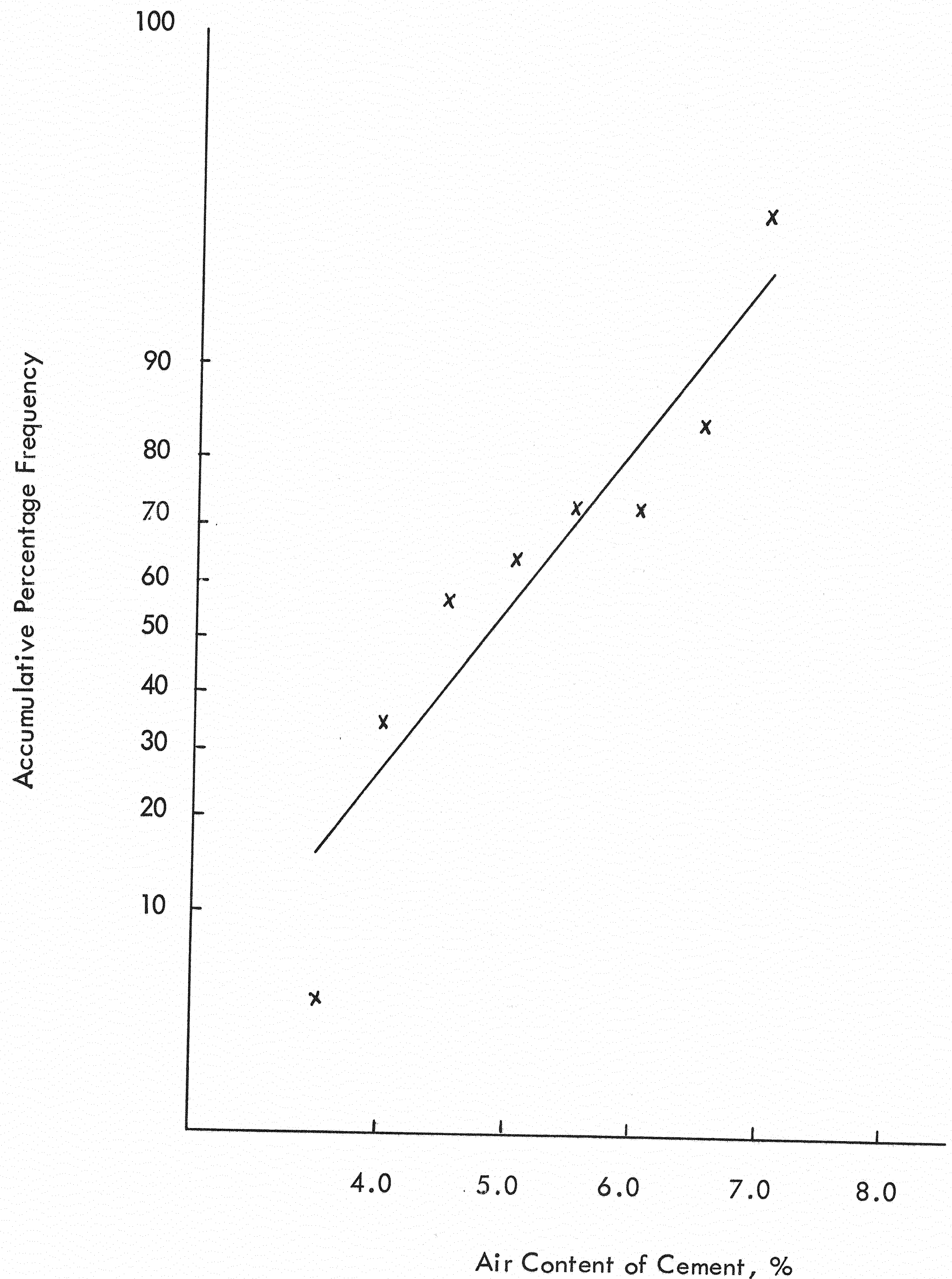
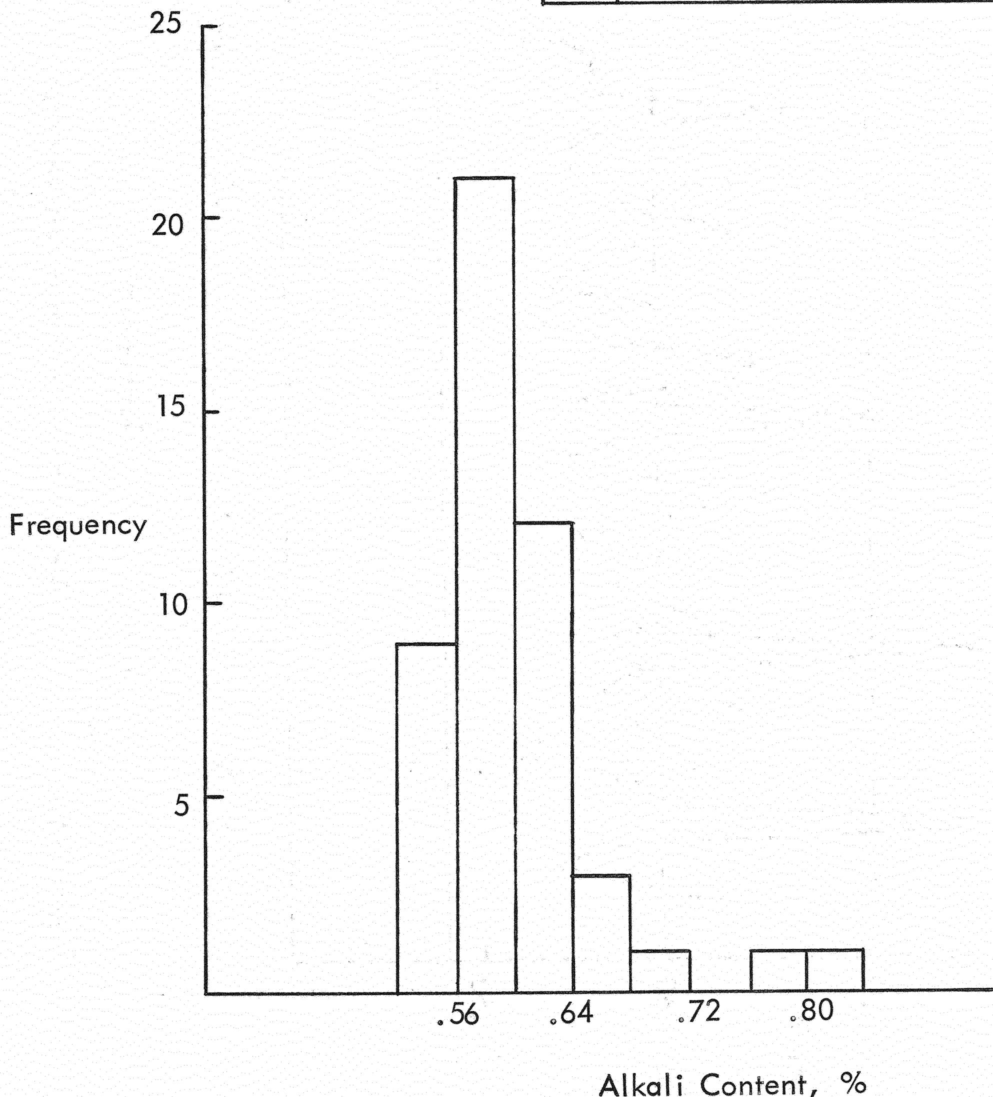


Figure II-88. Cement Air Content - goodness of fit curve

No.	Alkali Content Range, %	f	%	Cum %
1	0.52 - 0.56	9	18.7	18.7
2	0.56 - 0.60	21	43.7	62.4
3	0.60 - 0.64	12	25.0	87.4
4	0.64 - 0.68	3	6.3	93.7
5	0.68 - 0.72	1	2.1	95.8
6	0.72 - 0.76	-	0	95.8
7	0.76 - 0.80	1	2.1	97.9
8	0.80 - 0.84	1	2.1	100.0
		48	100	



n	48
specs	----
$\bar{x}$	0.59
σ_T	0.06
σ_t^2	0.0030
σ_s^2	0.0003
σ_a^2	0.0
V	10.2%

Figure II-89. Alkali Content - statistical properties

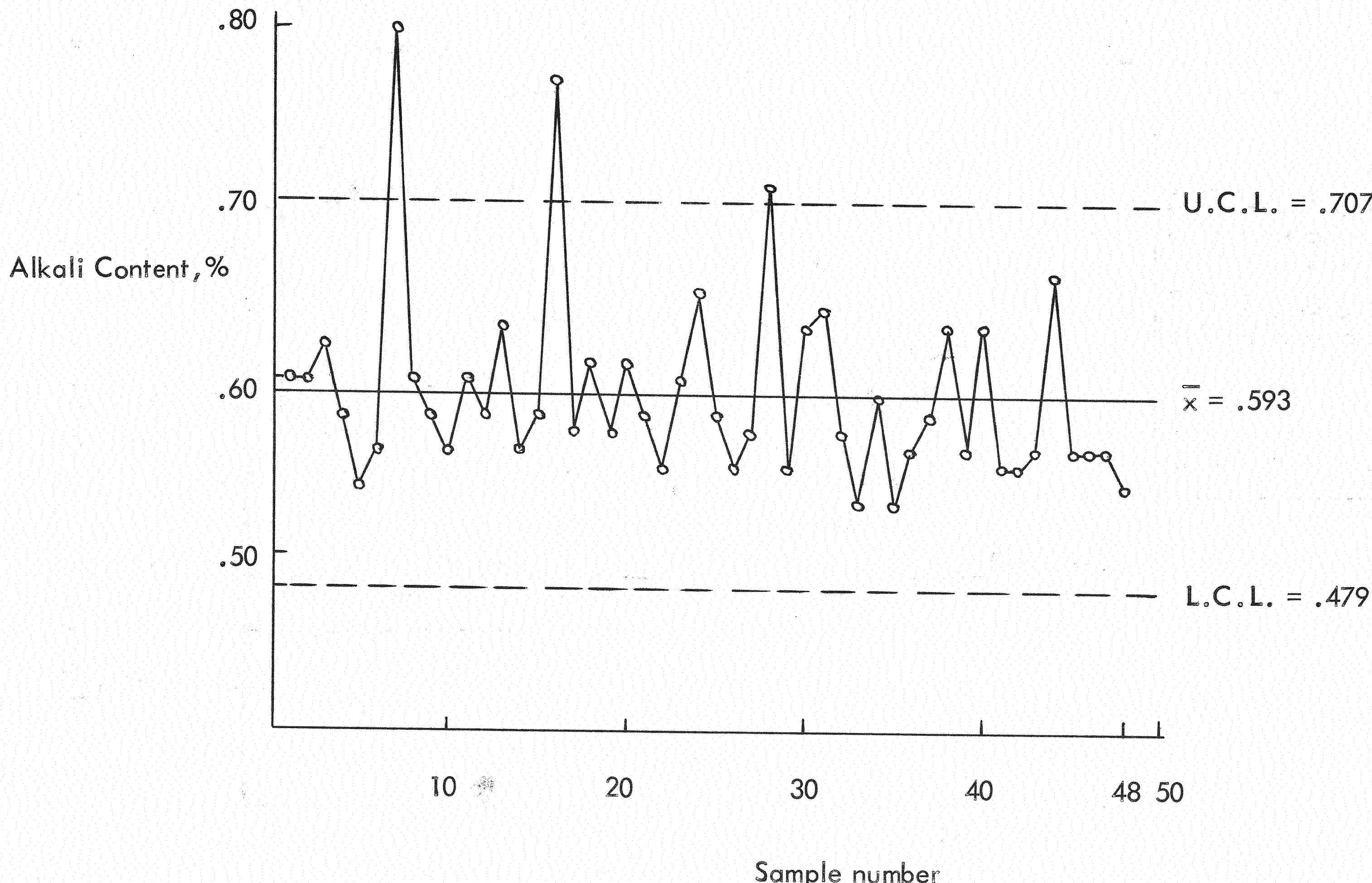


Figure II-90. Alkali Content - quality control chart

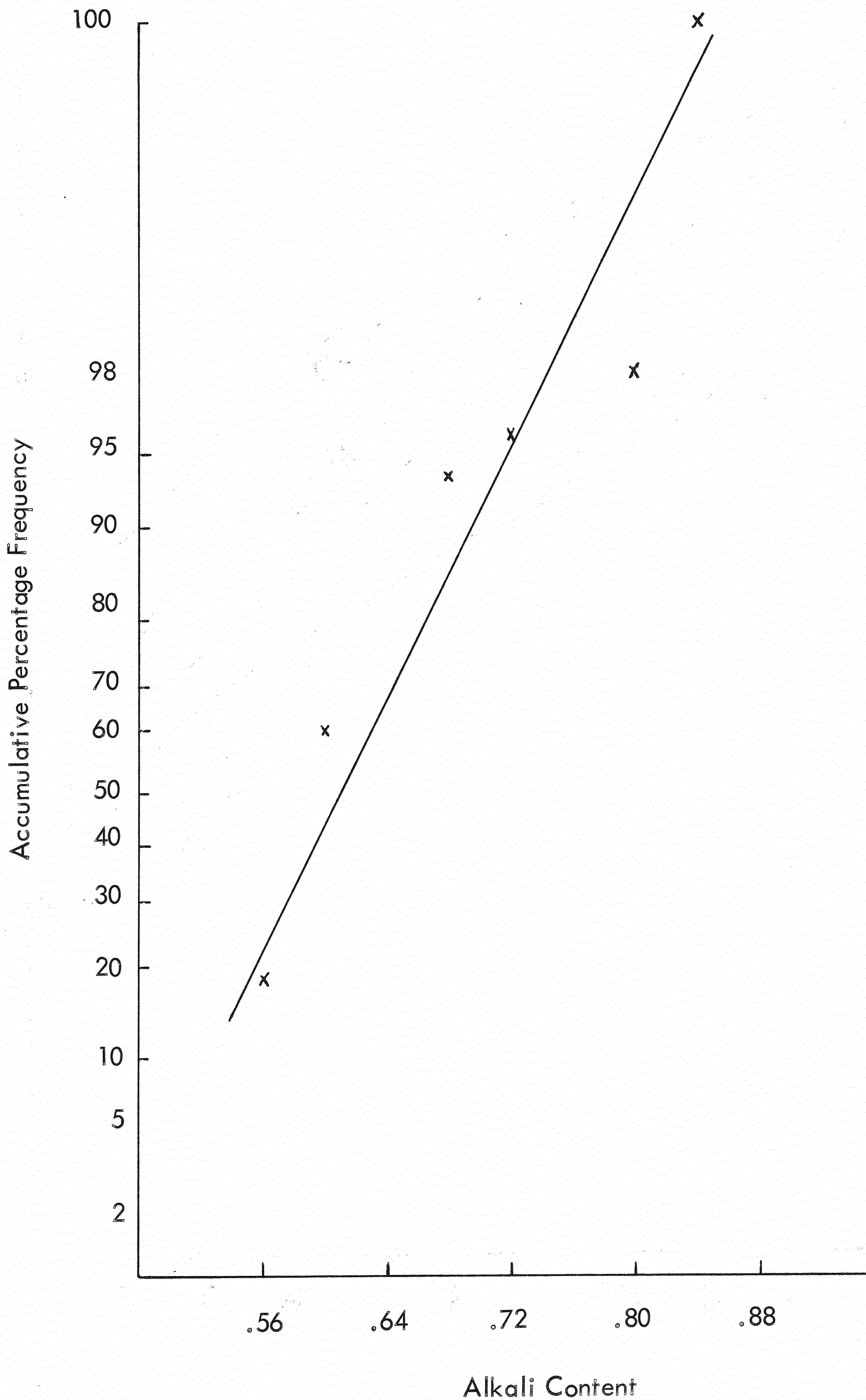


Figure II-91. Alkali Content - goodness of fit curve

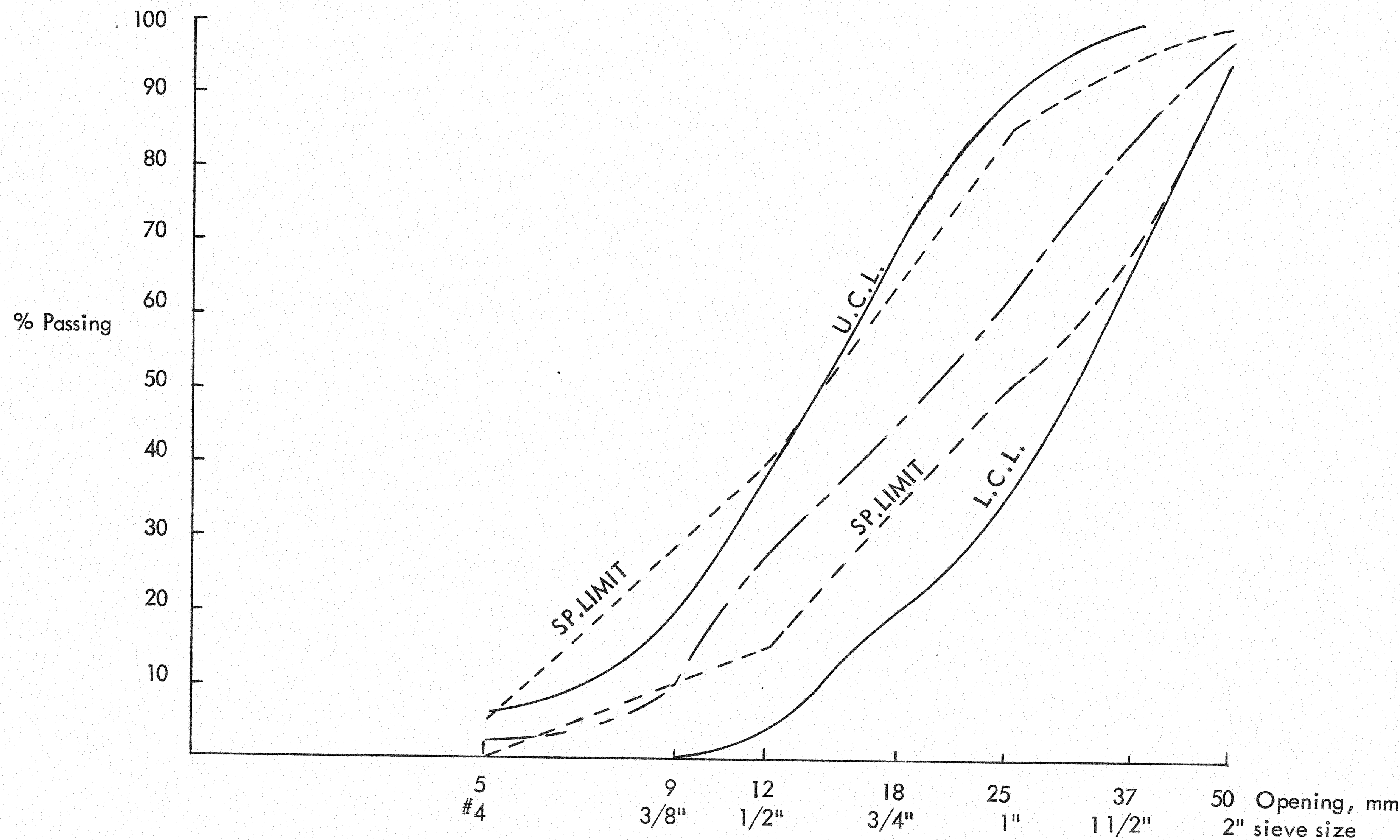


Figure II-92. Gradation analysis for coarse aggregate

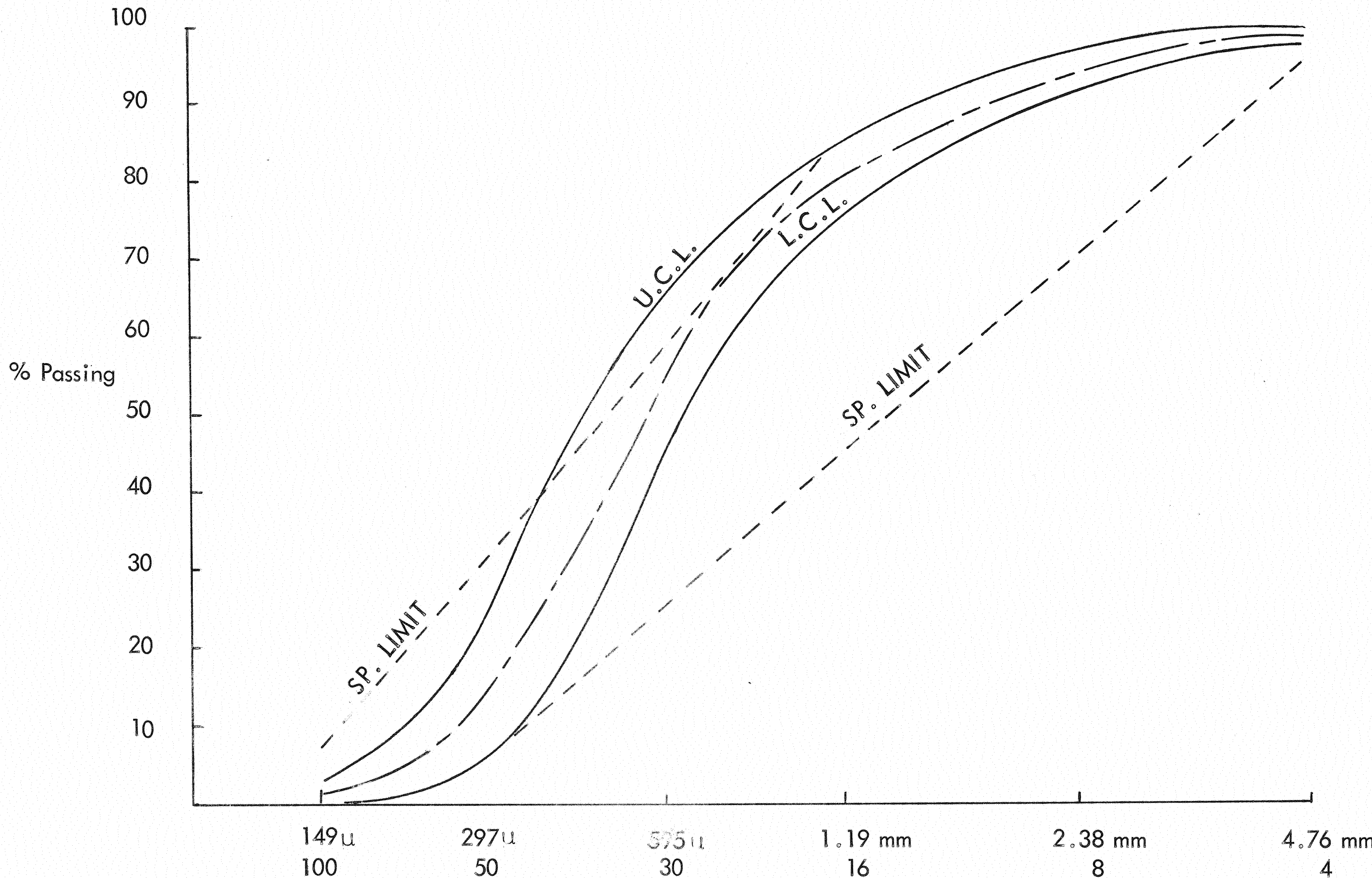


Figure II -93 - Gradation analysis for fine aggregate

APPENDIX D

Statistical Parameters for Graphs for Project III

No.	Thickness Range, inches	f	%	Cum %
1	- 8.7	1	1	1
2	- 8.8	3	3	4
3	- 8.9	26	26	30
4	- 9.0	41	41	71
5	- 9.1	12	12	83
6	- 9.2	9	9	92
7	- 9.3	6	6	98
8	- 9.4	1	1	99
9	- 9.5	1	1	100
		100	100	

n	100
specs	9
$\bar{x}$	9
σ_T	0.14
σ_t^2	---
σ_s^2	---
σ_a^2	---
V	1.6%

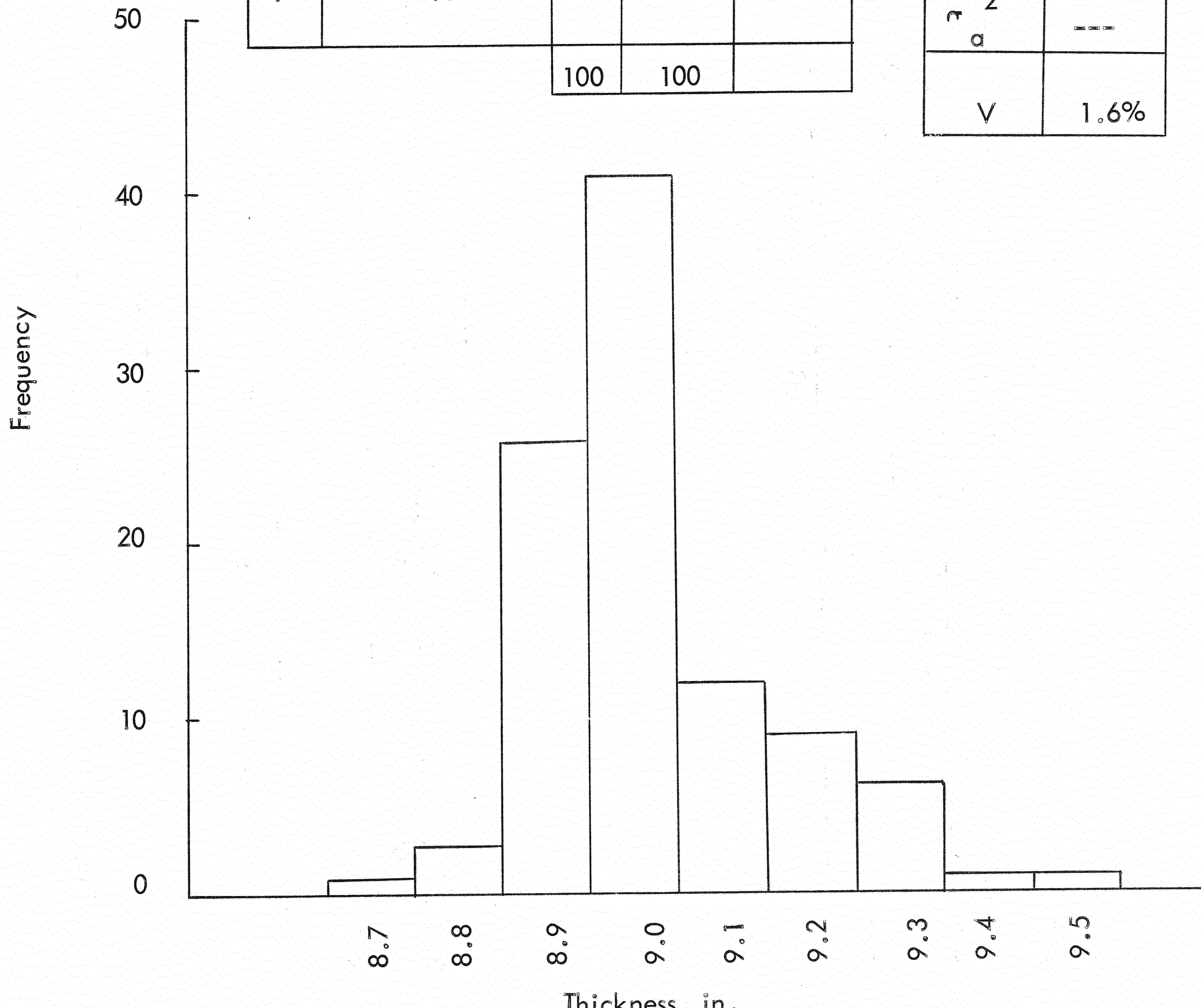
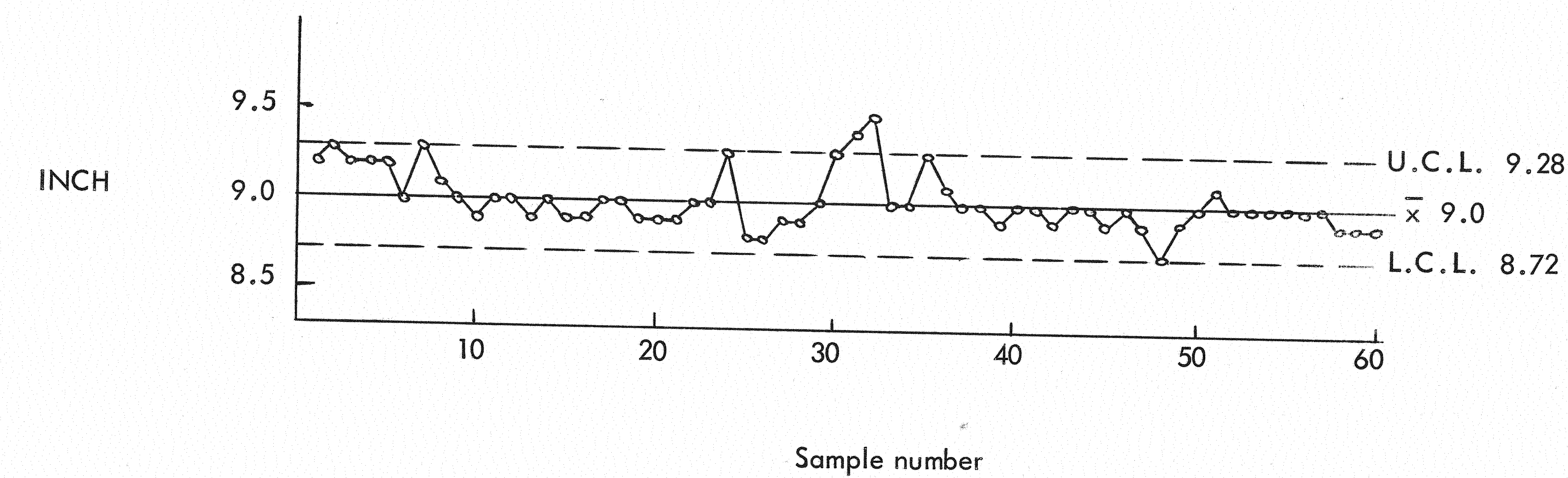


Figure III-94. Thickness - statistical properties



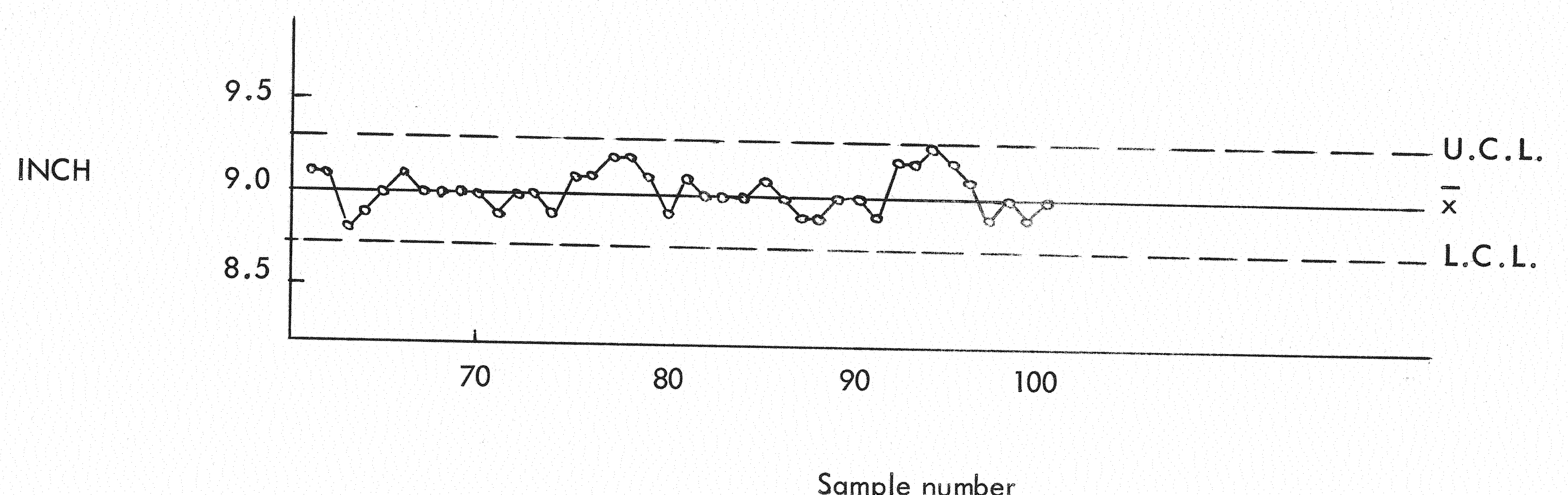


Figure III-95. Thickness - quality control chart

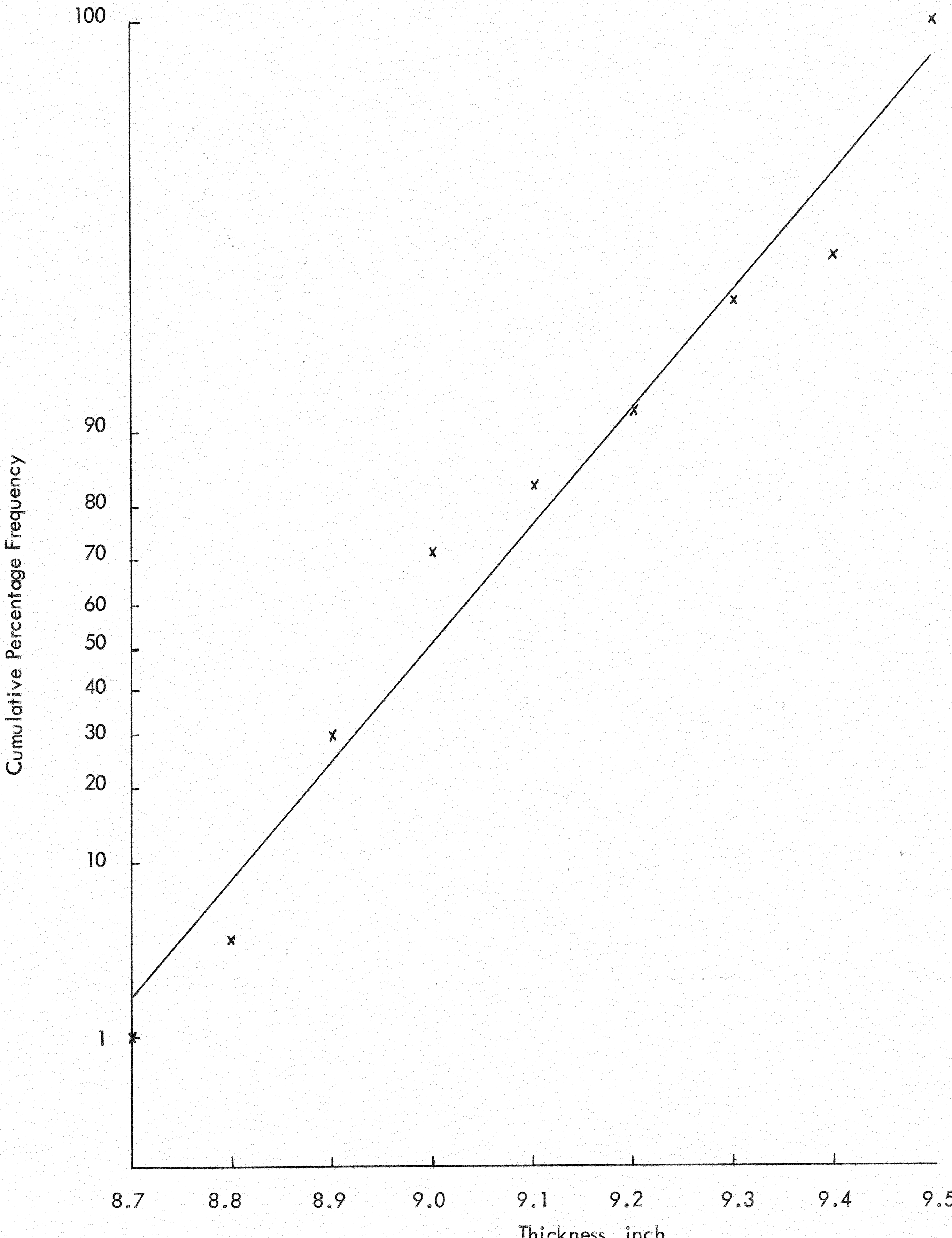


Figure III-96. Thickness - goodness of fit curve

No.	Slump Range, inches	f	%	Cum %
1	- 1.0	3	1.5	1.5
2	1.0 - 1.5	11	5.5	7.0
3	1.5 - 2.0	29	14.5	21.5
4	2.0 - 2.5	49	24.5	46.0
5	2.5 - 3.0	44	22.0	68.0
6	3.0 - 3.5	37	18.5	86.5
7	3.5 - 4.0	12	6.0	92.5
8	4.0 - 4.5	8	4.0	96.5
9	4.5 - 5.0	3	1.5	98.0
10	5.0 - 5.5	3	1.5	99.5
11	5.5 -	1	.5	100.0
		200	100	

n	200
specs	0.5"-3.5"
$\bar{x}$	2.76
σ_T	0.89
σ_t^2	.25
σ_s^2	.09
σ_a^2	.46
V	32.2%

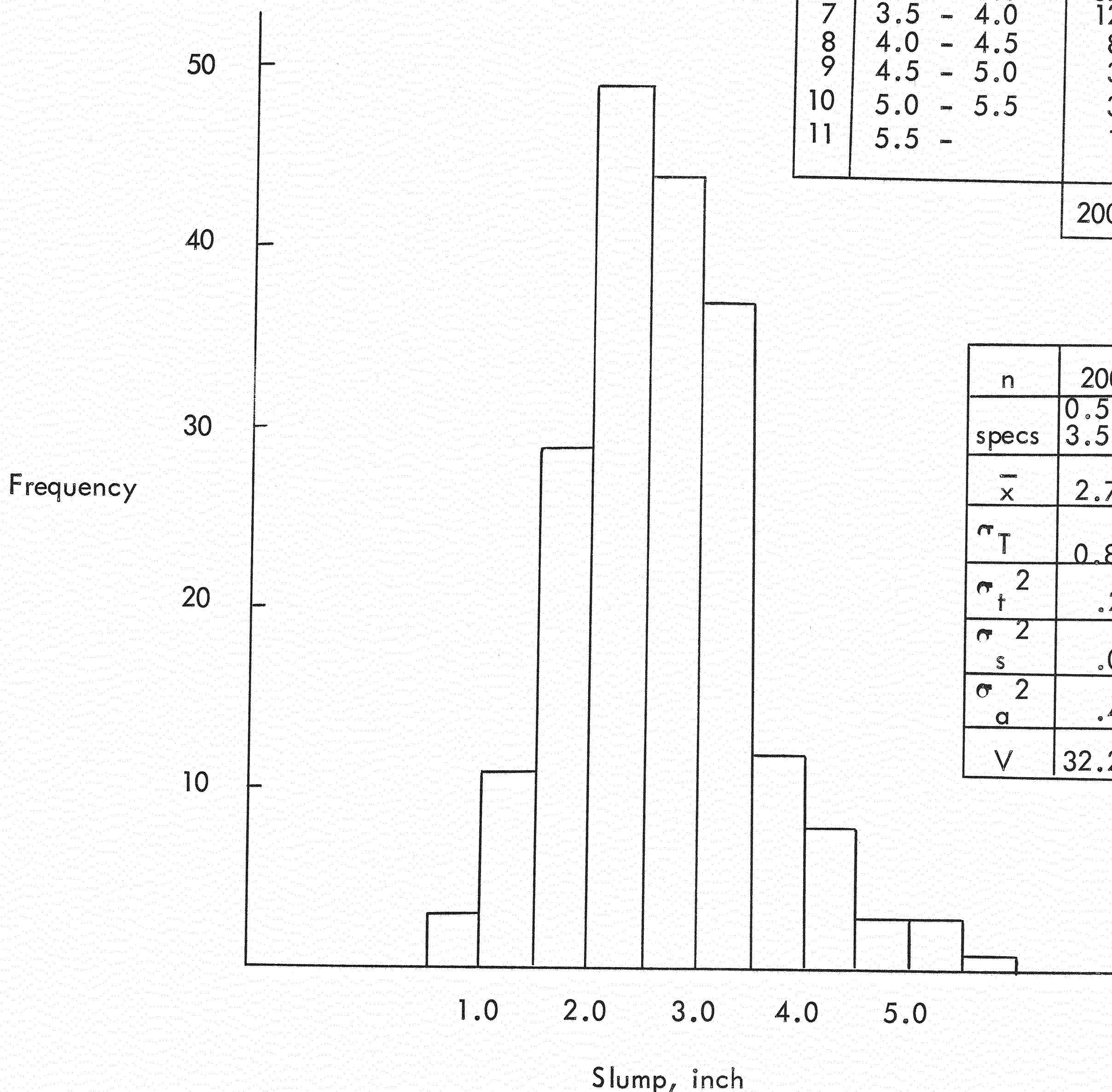


Figure III-97. Slump - statistical properties

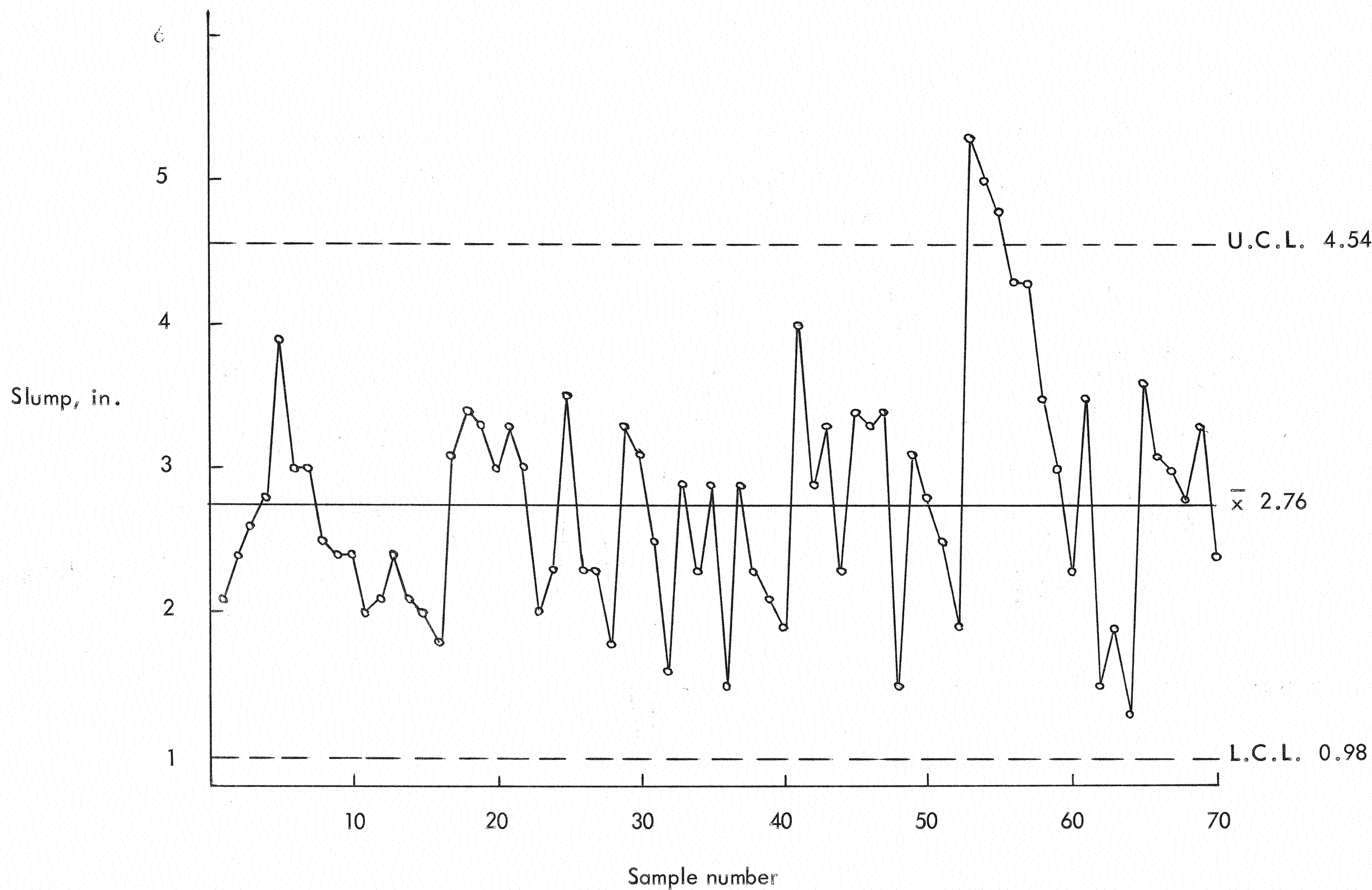


Figure III-98. Slump - quality control chart

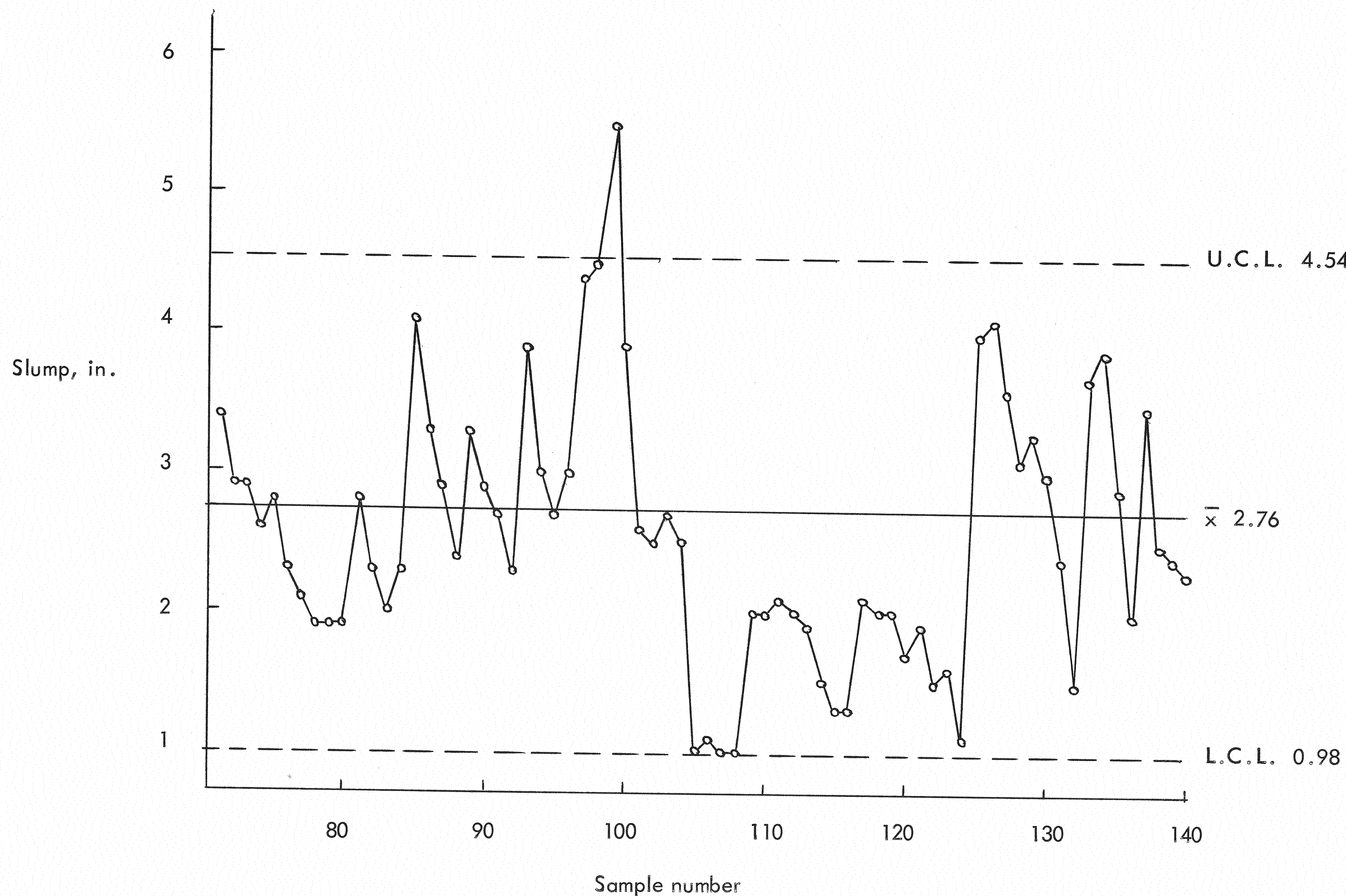


Figure III-98 (cont.). Slump - quality control chart

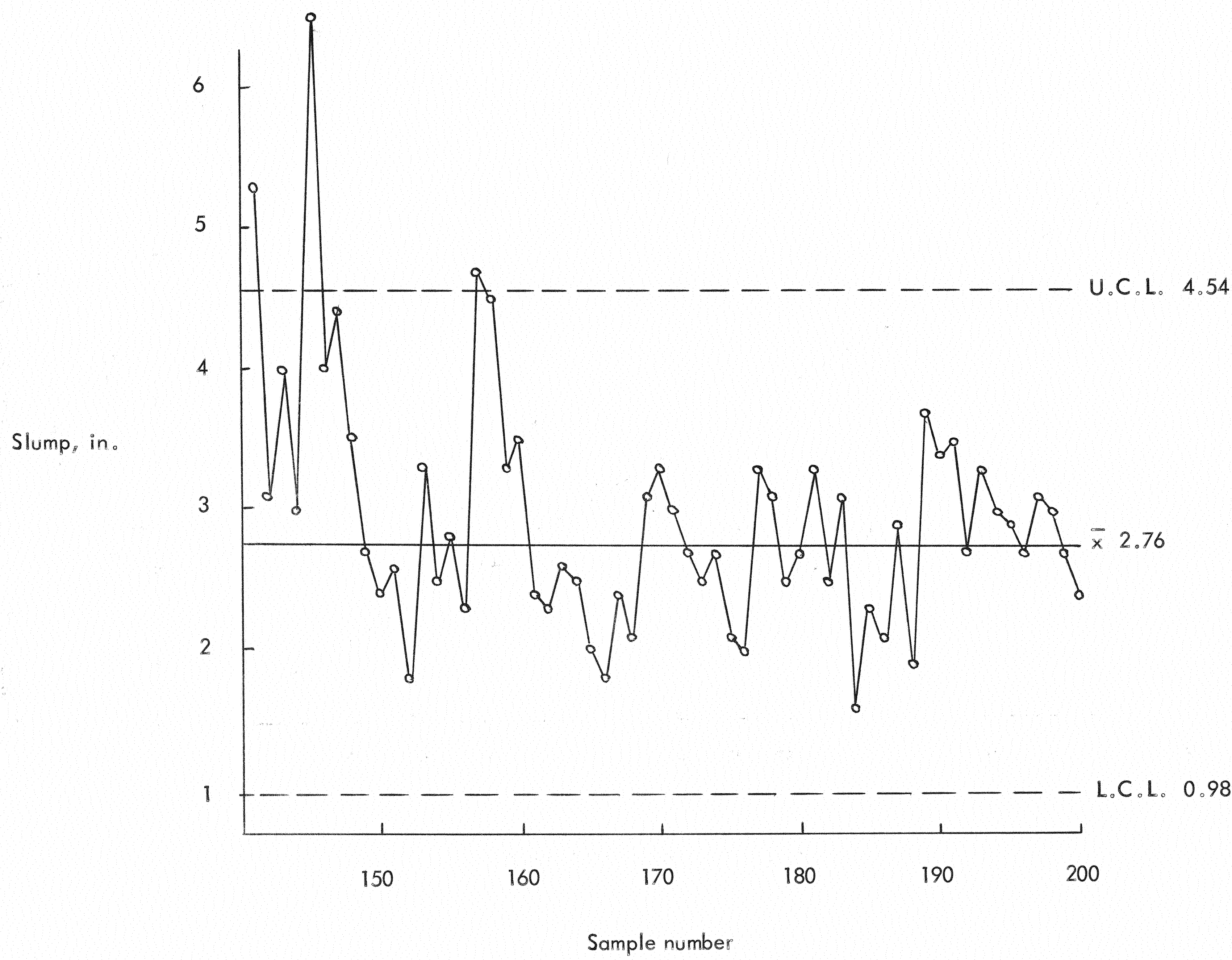


Figure III-98 (cont.). Slump - quality control chart

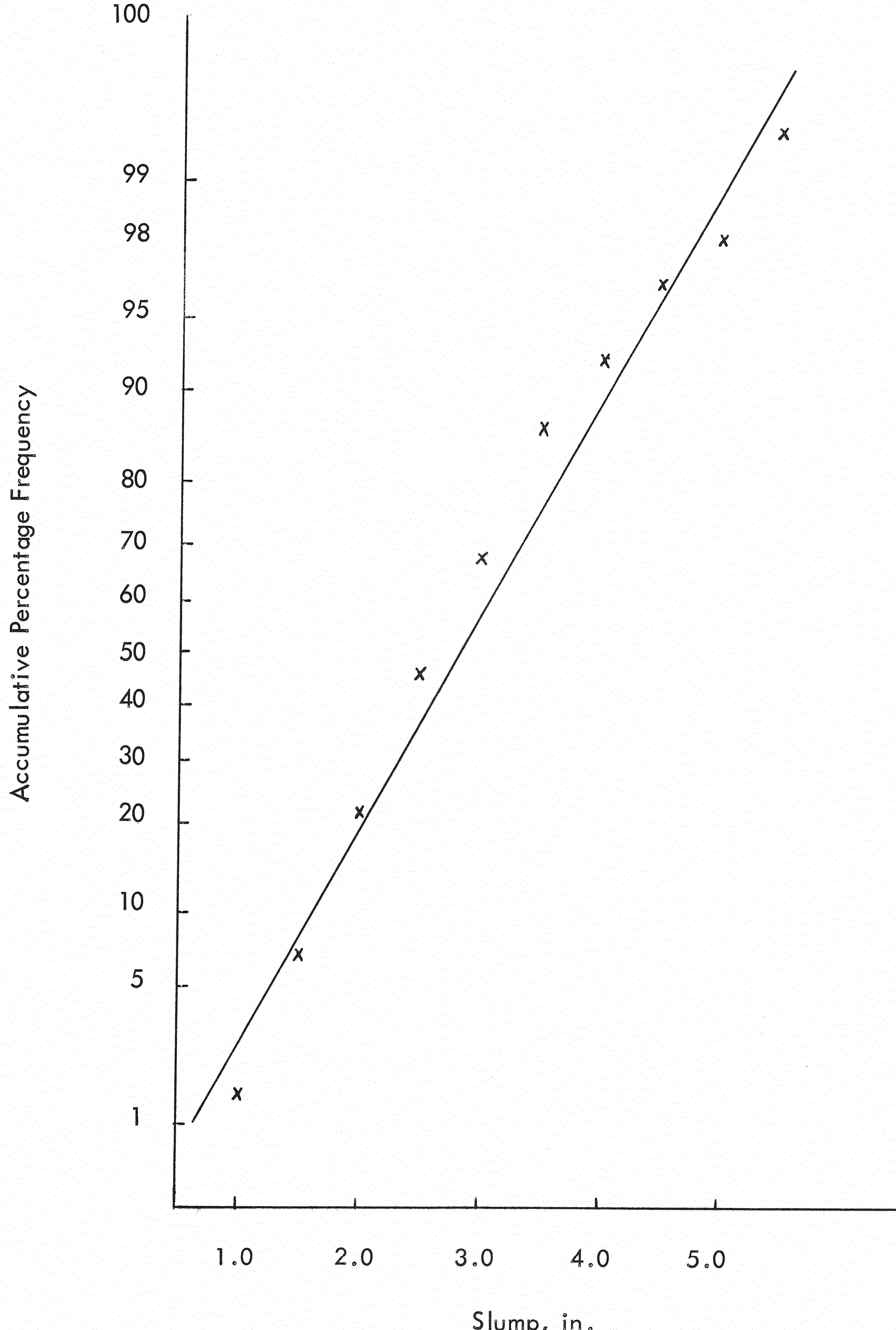


Figure III-99. Slump - goodness of fit curve

No.	Concrete Air Content Range, %	f	%	Cum %
1	- 3.5	2	1.0	1.0
2	3.5 - 4.0	14	7.0	8.0
3	4.0 - 4.5	62	31.0	39.0
4	4.5 - 5.0	90	45.0	84.0
5	5.0 - 5.5	21	10.5	94.5
6	5.5 - 6.0	9	4.5	99.0
7	6.0 -	2	1.0	100.0
		200	100	

n	200
specs	3-6%
$\bar{x}$	4.7
σ_T	0.5
σ_t^2	0.08
σ_s^2	0.04
σ_a^2	0.14
V	10.6%

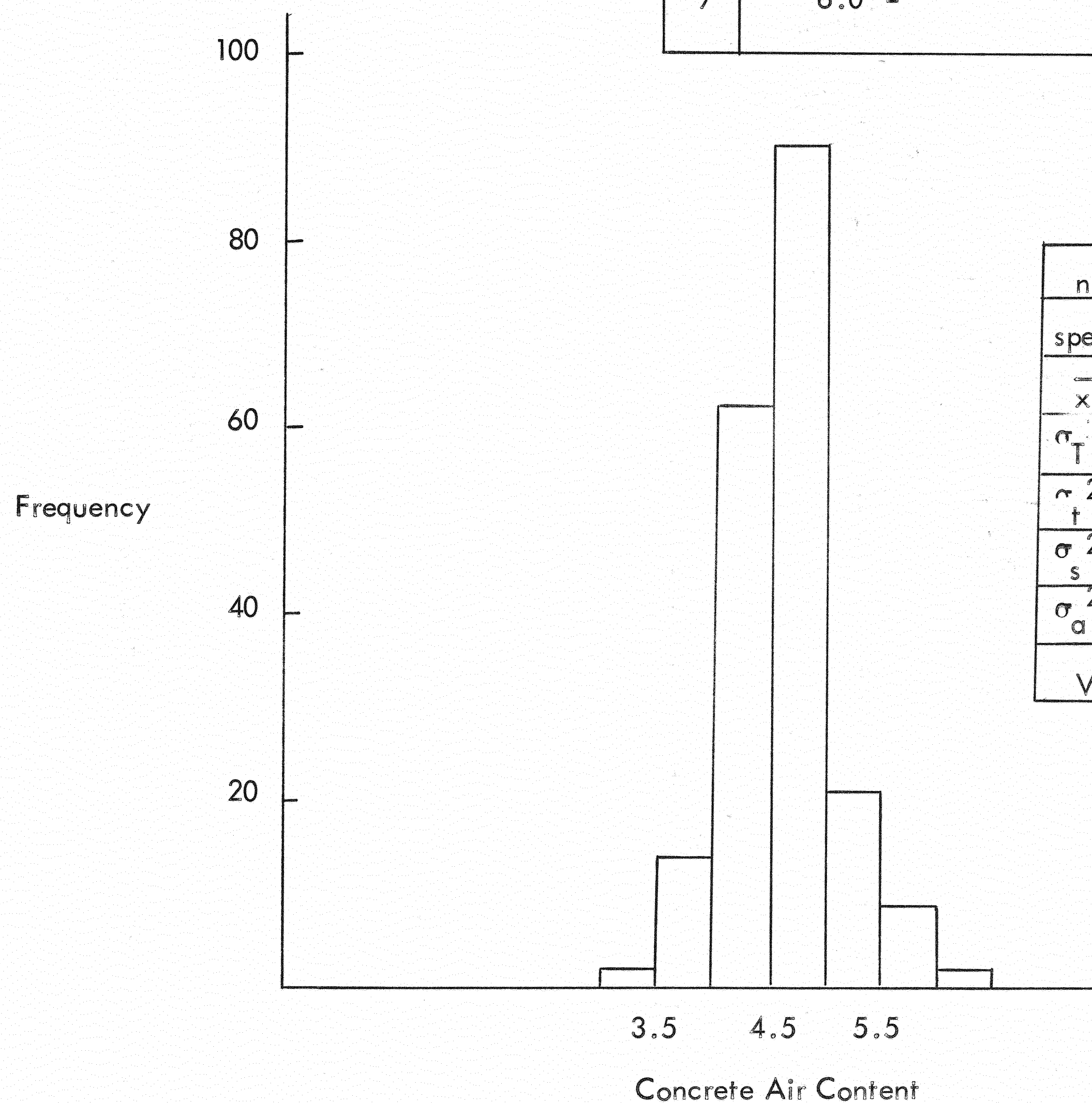


Figure III-100. Concrete Air Content - statistical properties

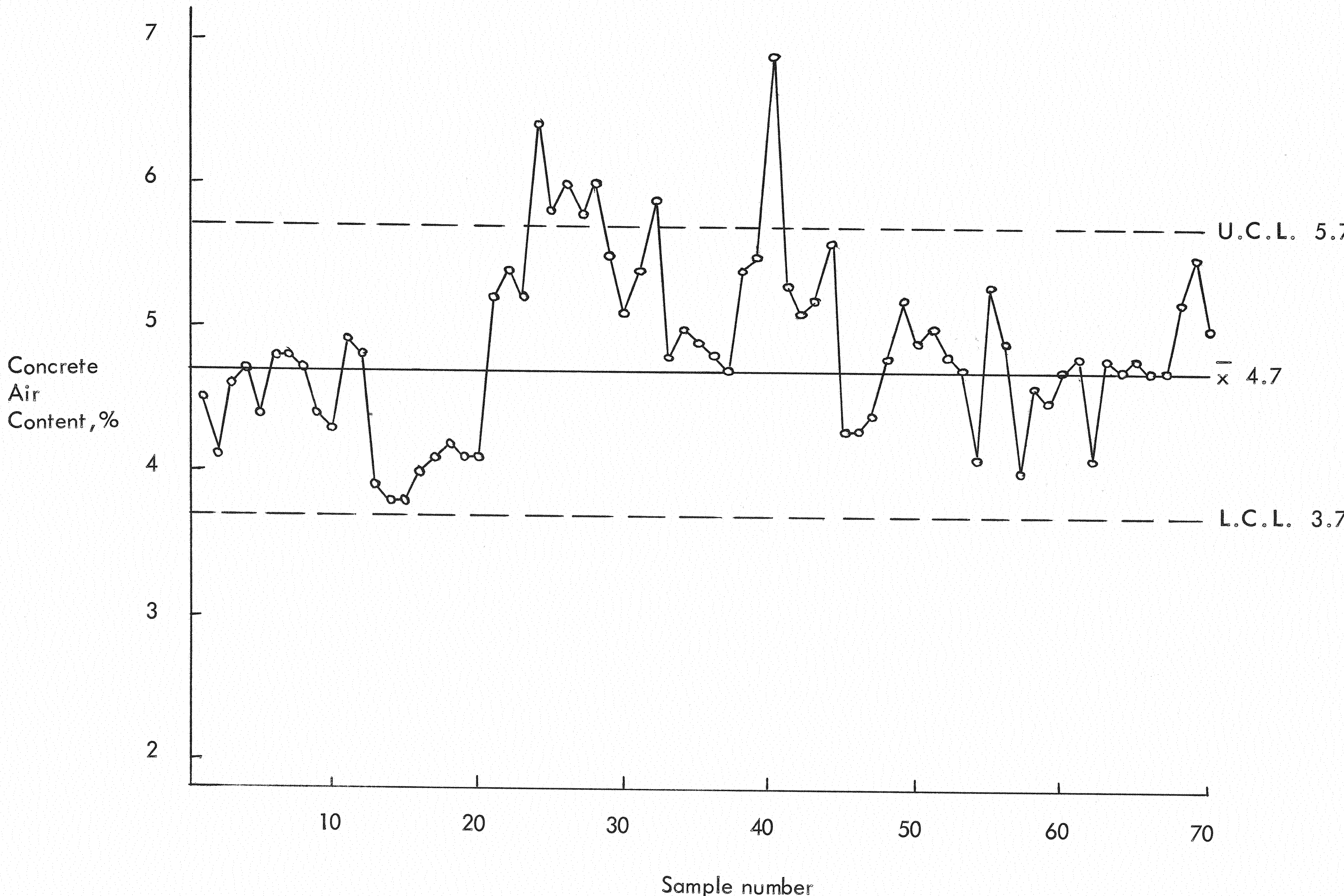


Figure III-101. Concrete Air Content - quality control chart

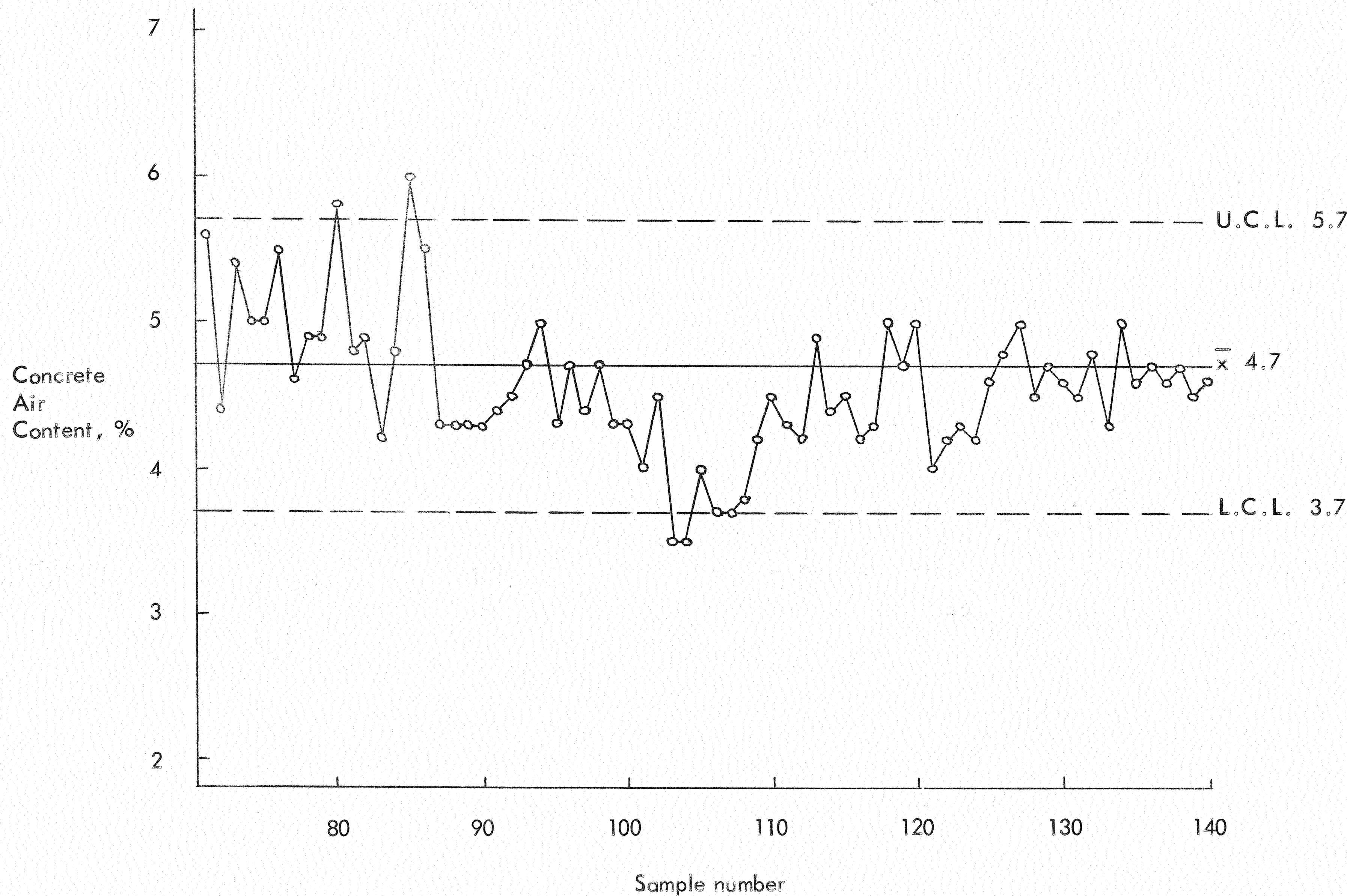


Figure III-101(cont.). Concrete Air Content - quality control chart

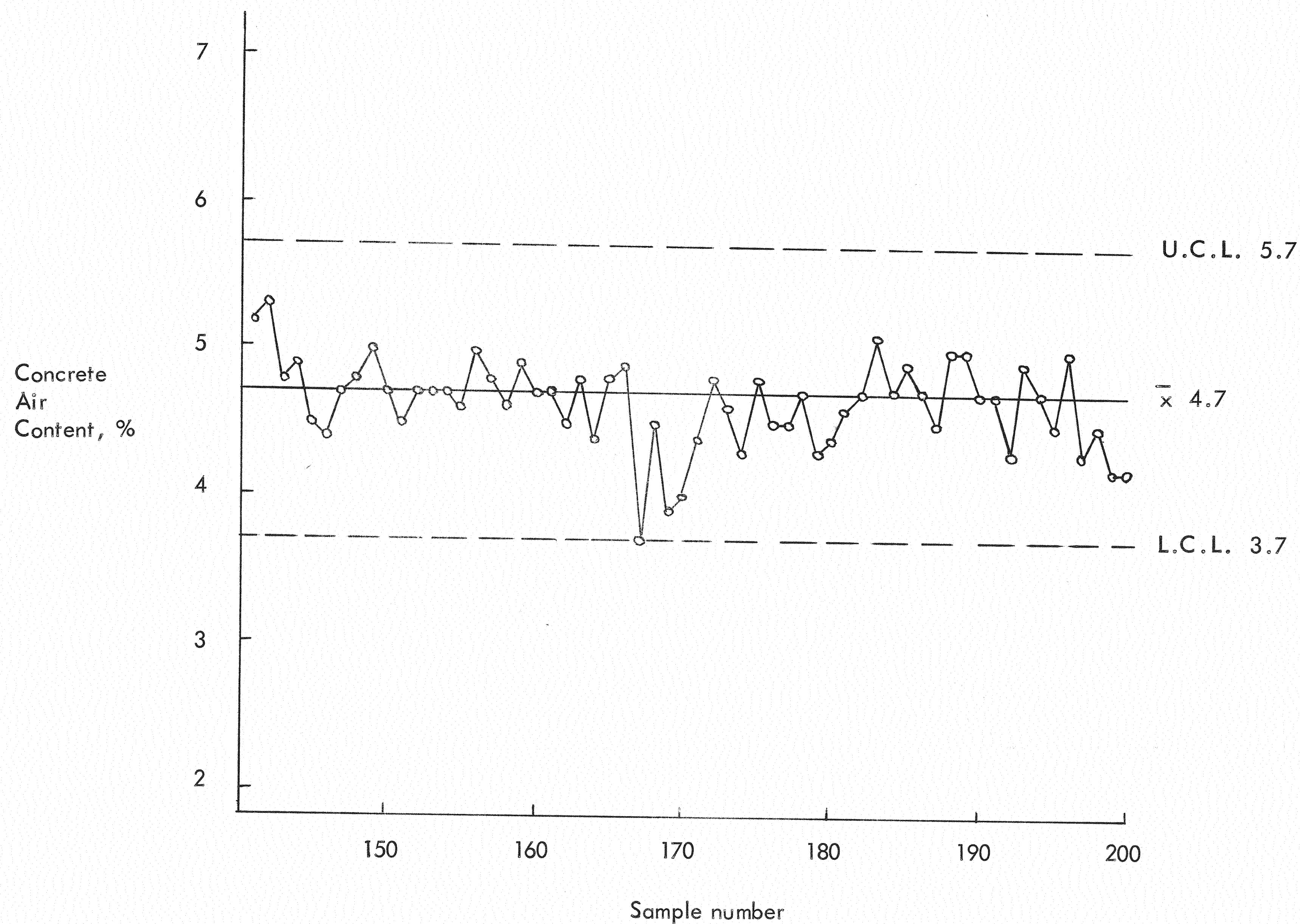


Figure III-101(cont.). Concrete Air Content - quality control chart

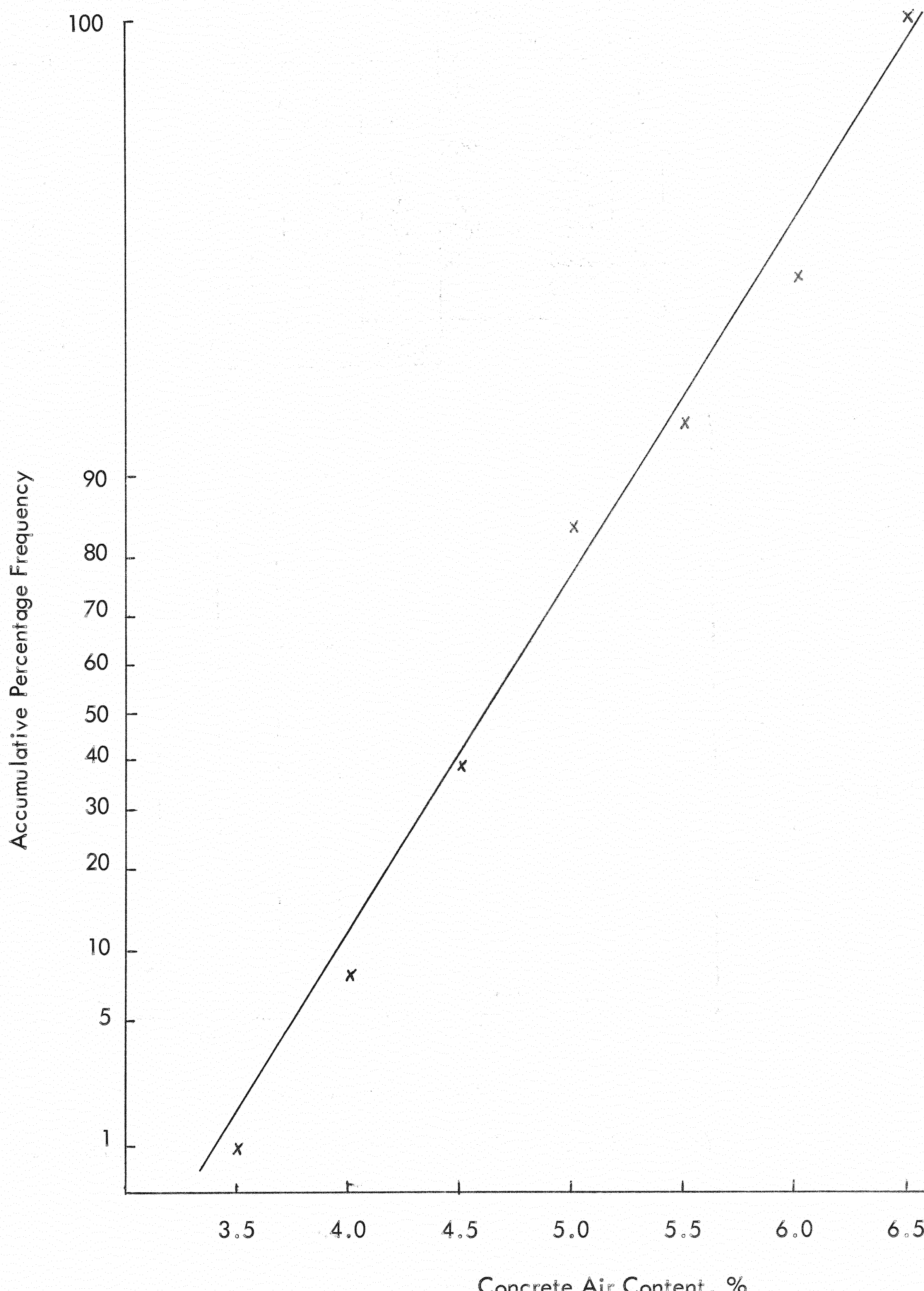


Figure III-102. Concrete Air Content - goodness of fit curve

No.	Concrete Compr. Strength Range psi	f	%	Cum%
1	- 3000	3	1.5	1.5
2	3000 - 3400	6	3.0	4.5
3	3400 - 3800	16	8.0	12.5
4	3800 - 4200	50	25.0	37.5
5	4200 - 4600	68	34.0	71.5
6	4600 - 5000	47	23.5	95.0
7	5000 - 5400	7	3.5	98.5
8	5400 -	3	1.5	100.0
		200	100	

n	200
specs	---
$\bar{x}$	4238
σ_T	771
σ_t^2	153486
σ_s^2	1868
σ_a^2	439308
V	18.2%

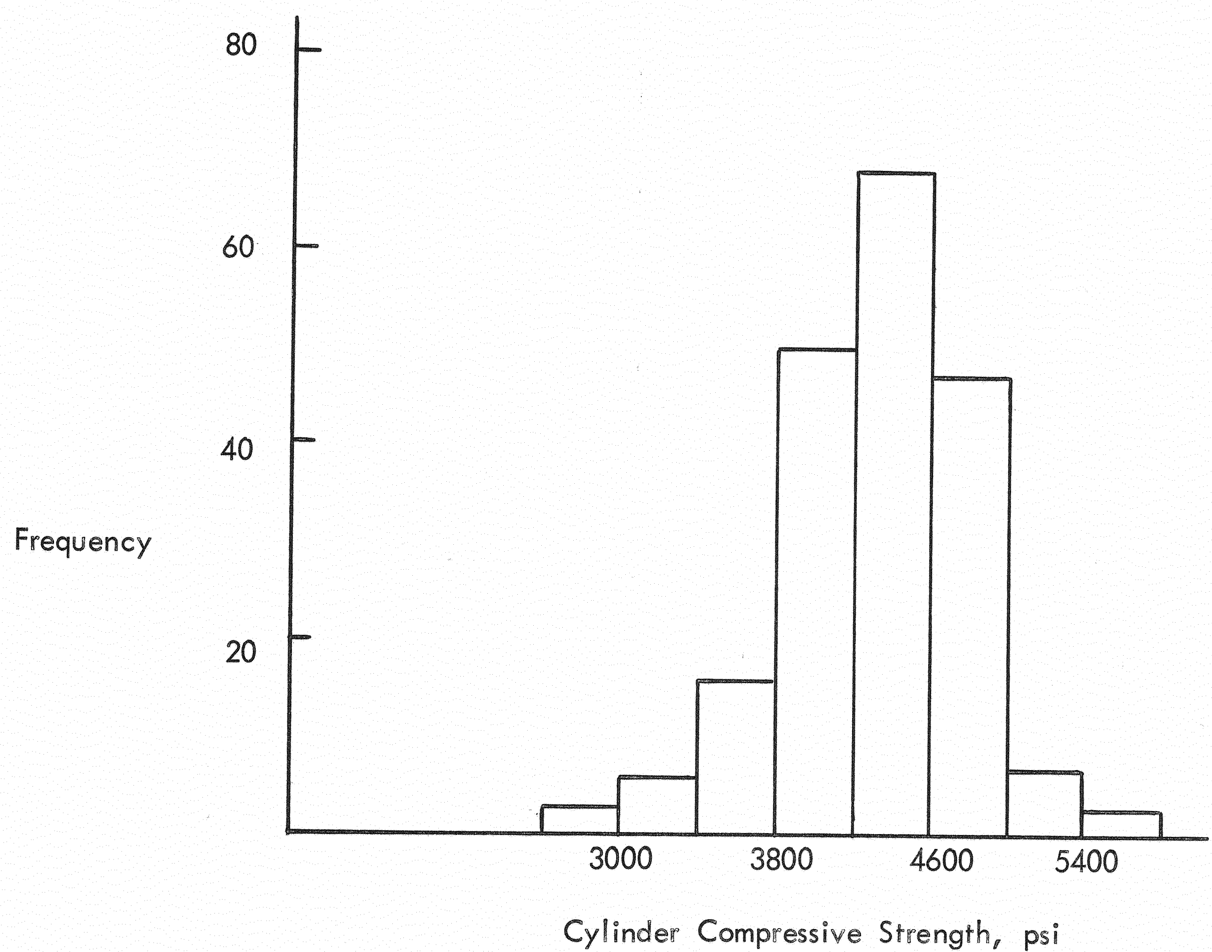


Figure III-103. Cylinder Compressive Strength - statistical properties

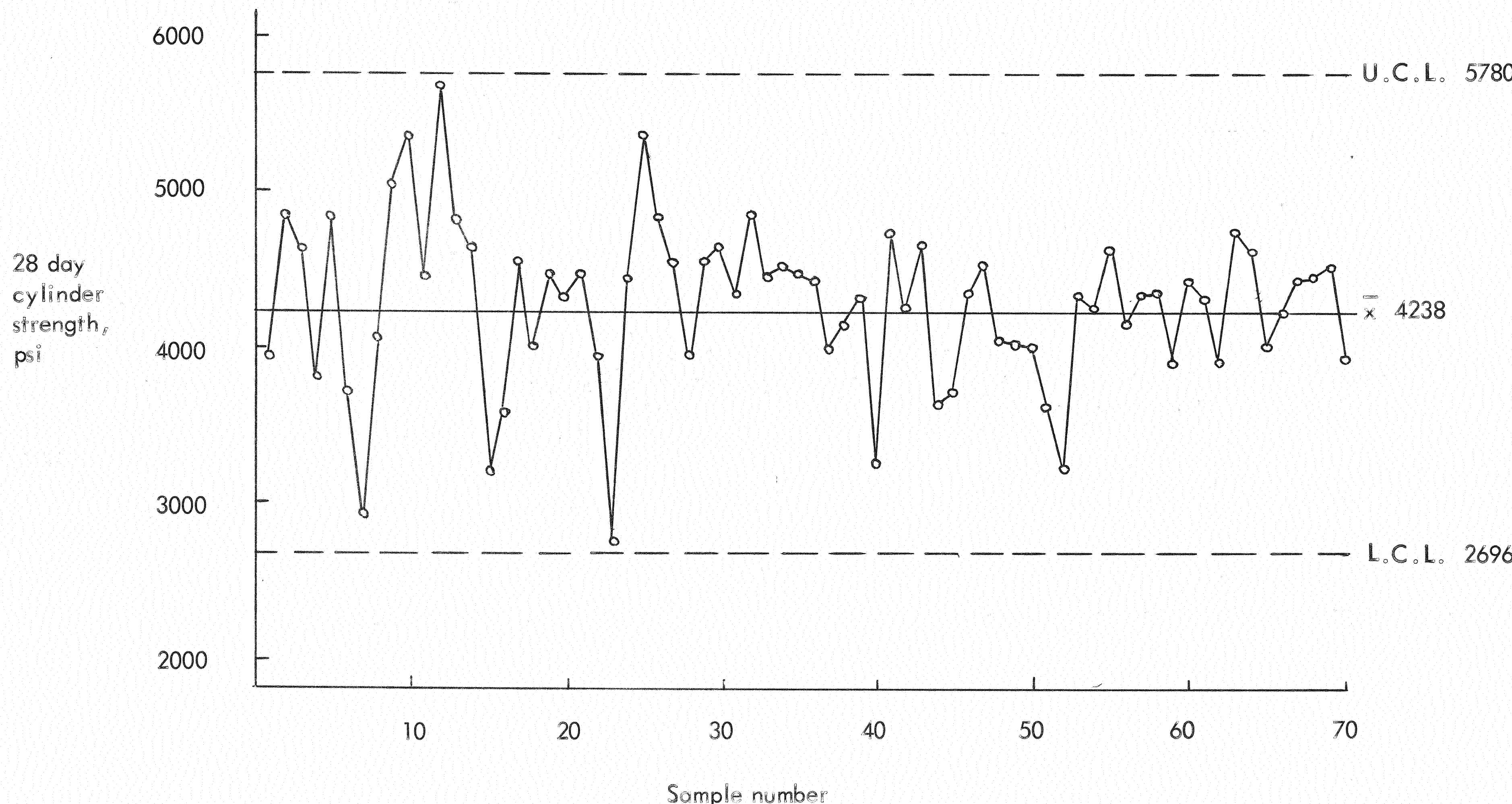


Figure III-104. Cylinder Compressive Strength - quality control chart

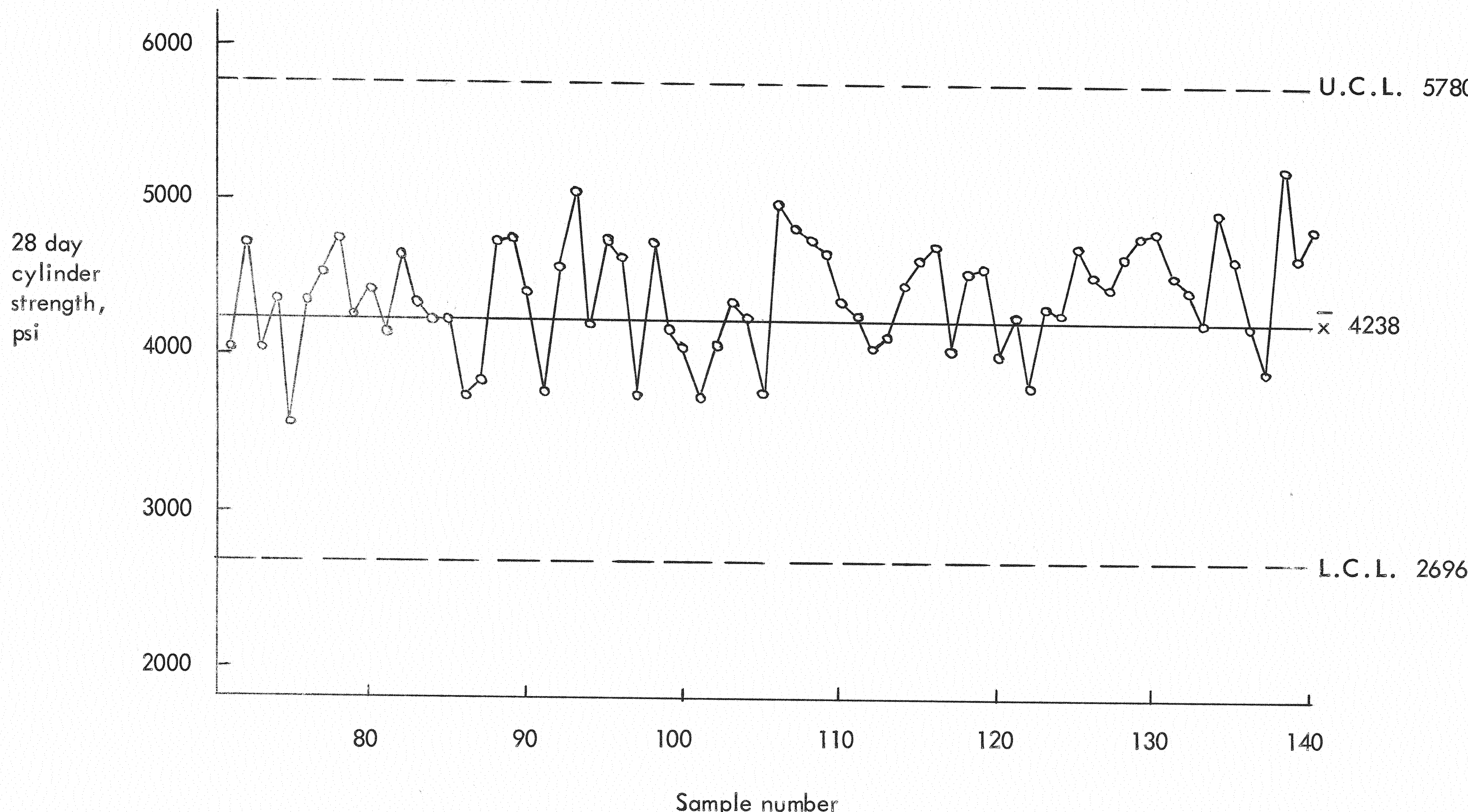


Figure III-104 (cont.). Cylinder Compressive Strength - quality control chart

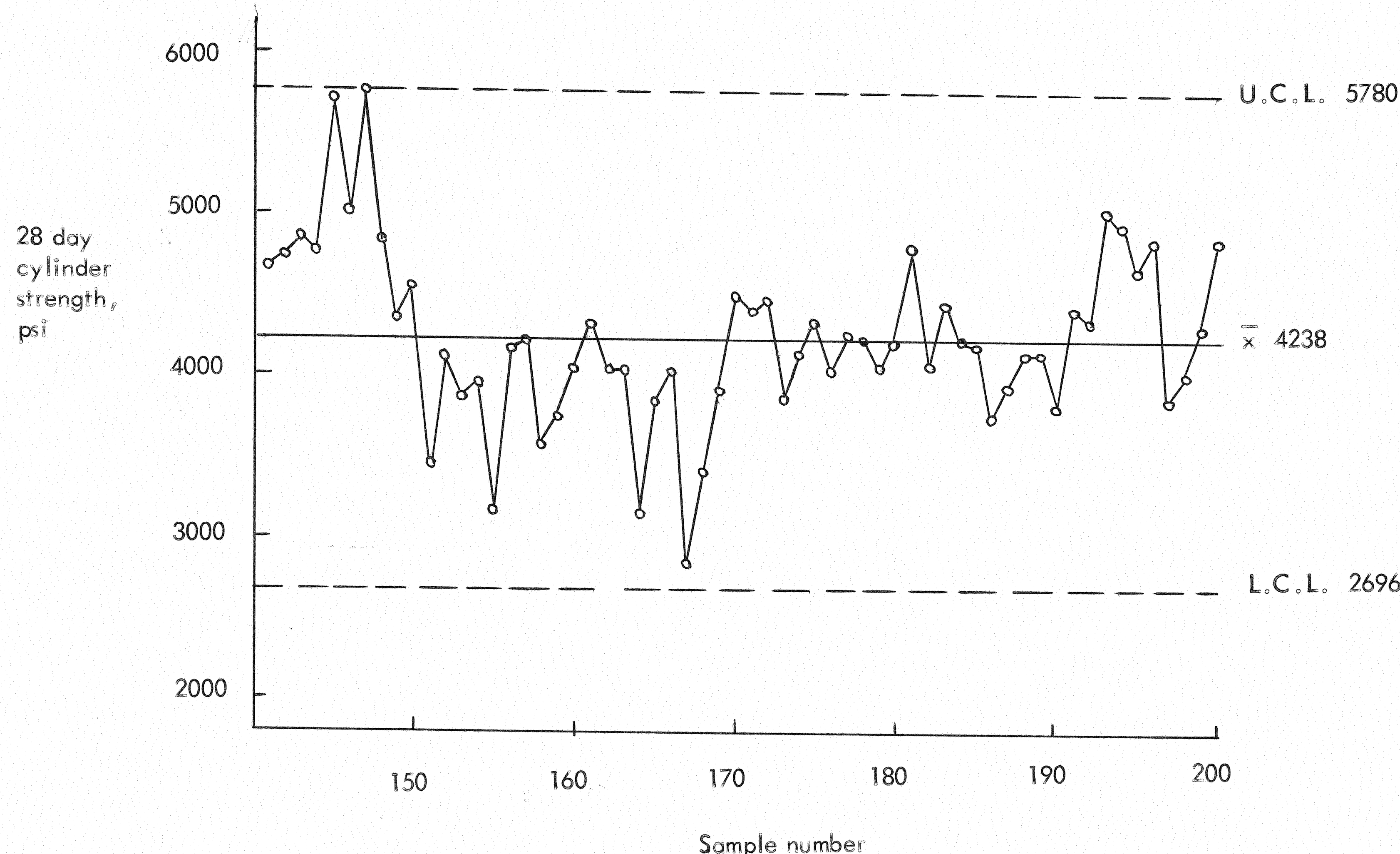


Figure III-104 (cont.). Cylinder Compressive Strength - quality control chart

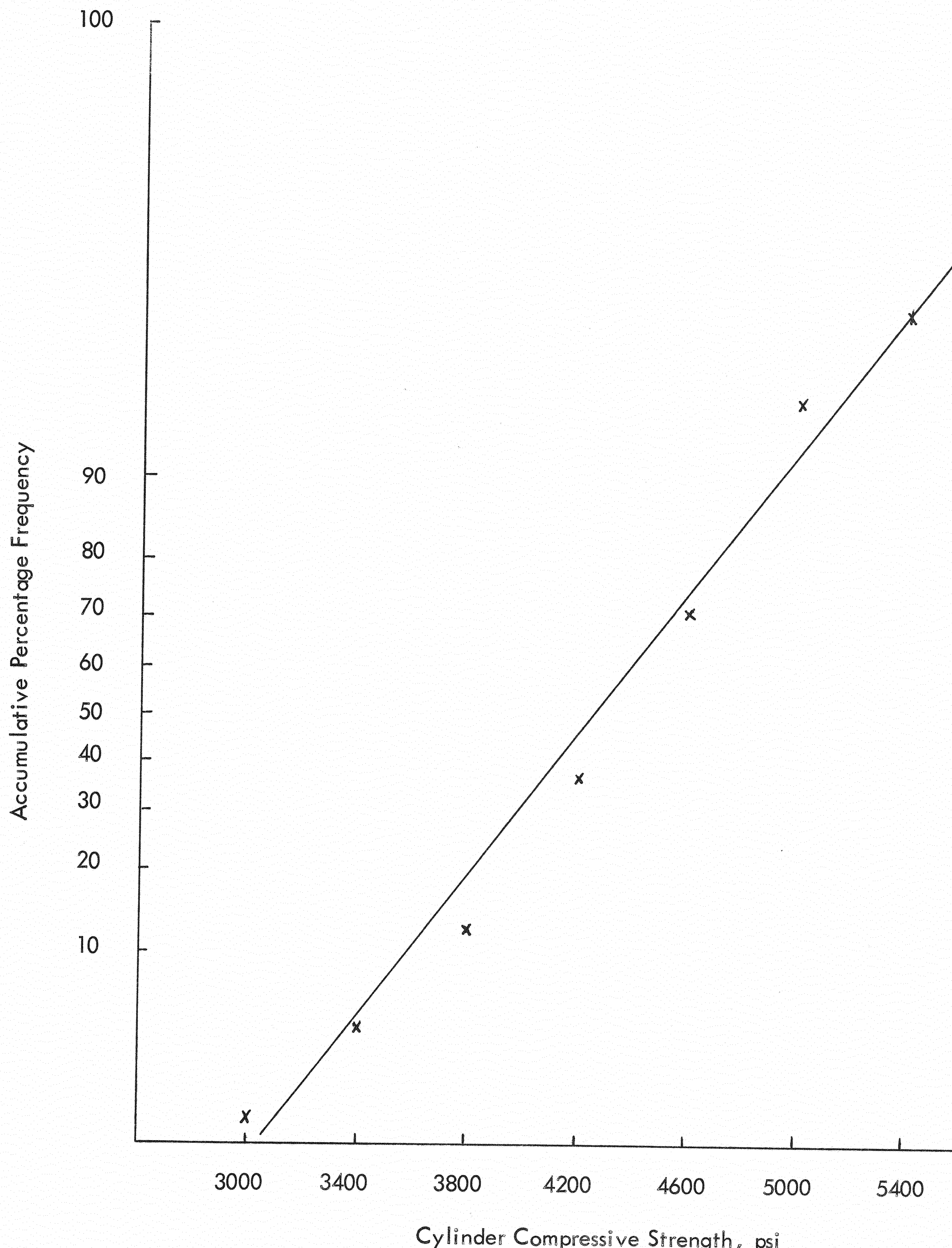
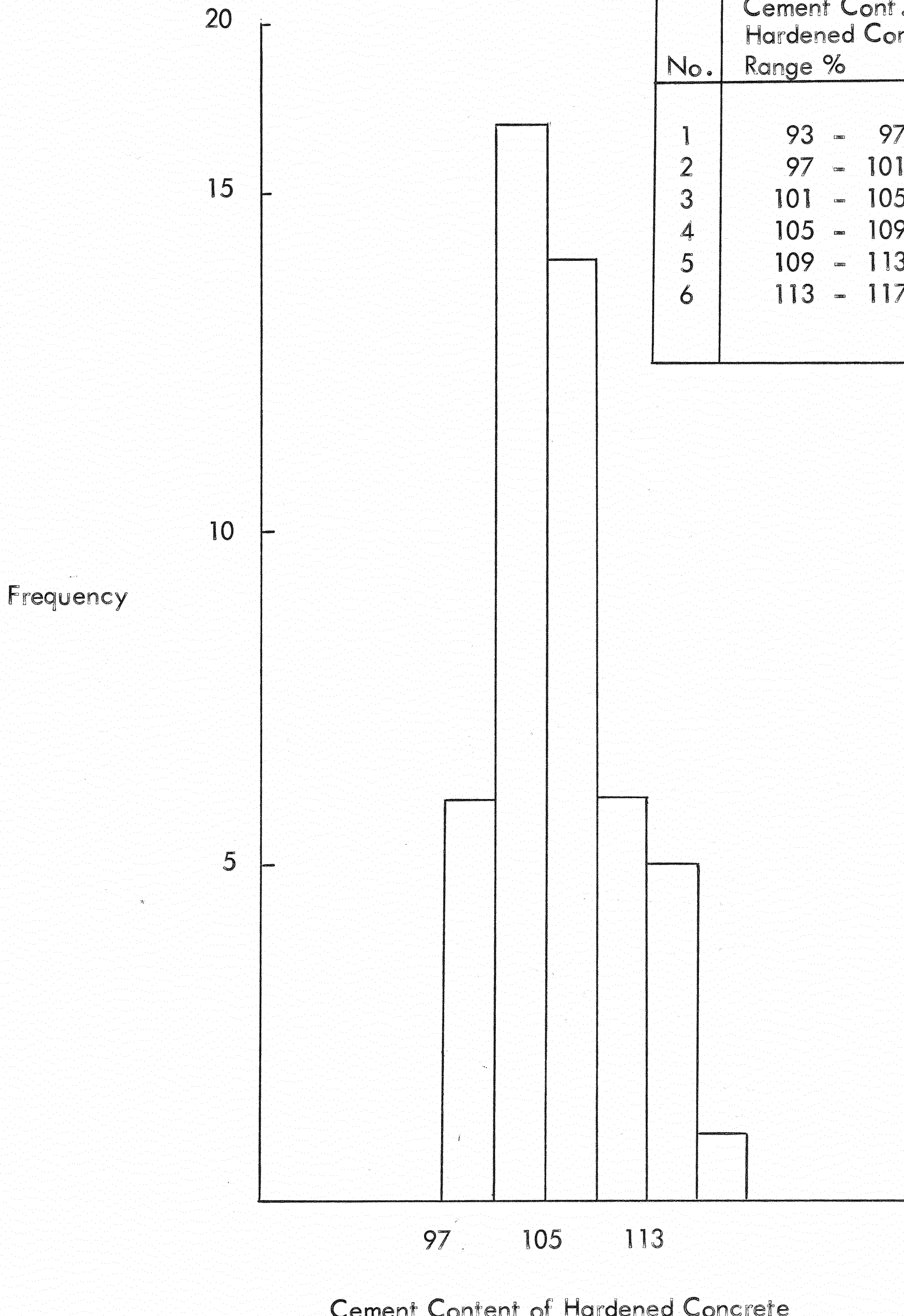


Figure III-105. Cylinder Compressive Strength - goodness of fit curve



No.	Cement Cont. of Hardened Concrete Range %	f	%	Cum%
1	93 - 97	6	12.5	12.5
2	97 - 101	16	33.3	45.8
3	101 - 105	14	29.2	75.0
4	105 - 109	6	12.5	87.5
5	109 - 113	5	10.4	97.9
6	113 - 117	1	2.1	100.0
		48	100	

n	48
specs	---
$\bar{x}$	101.75
σ_T	5.38
σ_t^2	22.0
σ_s^2	0.63
σ_a^2	6.30
V	5.3%

Figure III-106. Cement Content of Hardened Concrete - statistical properties

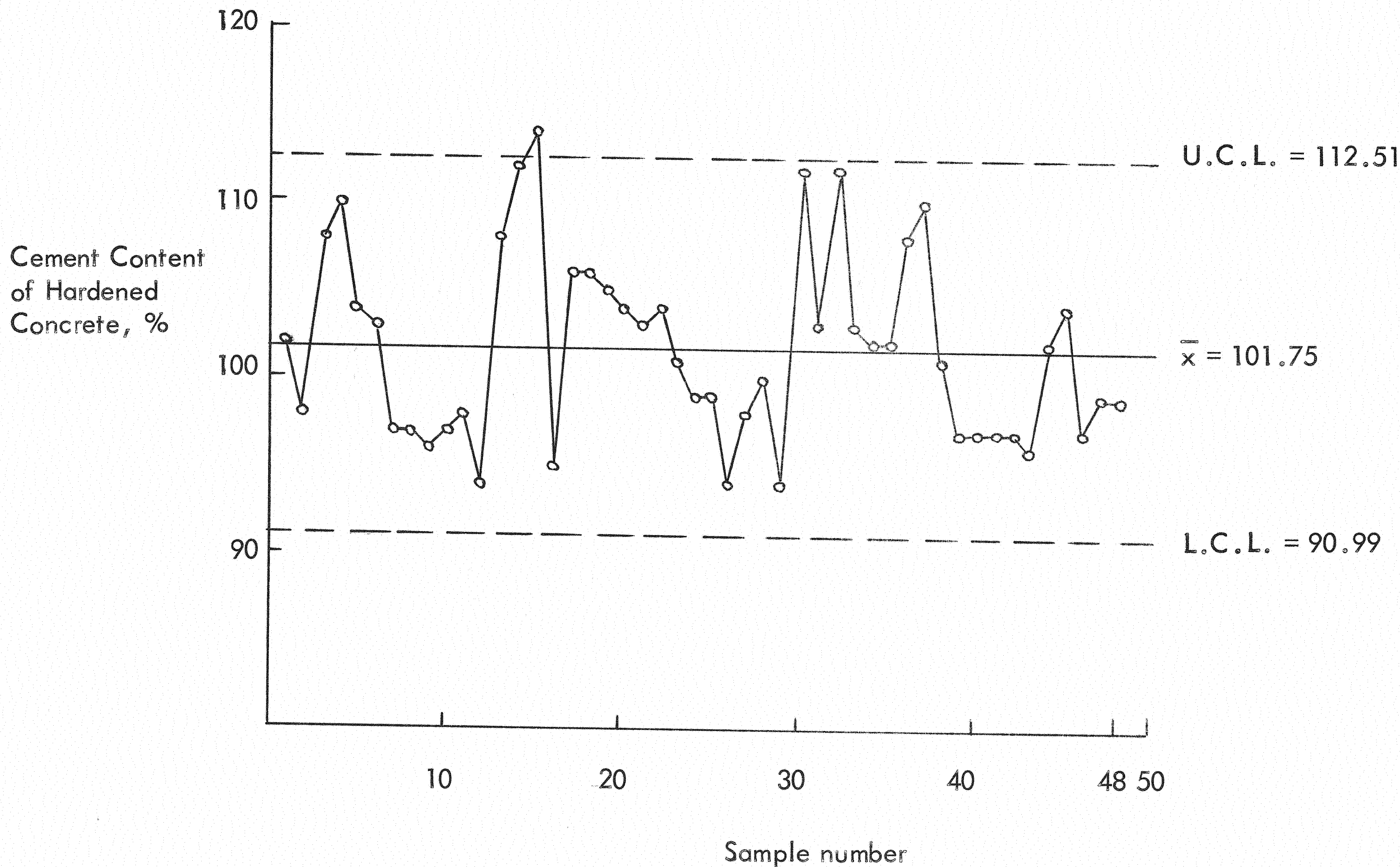


Figure III-107. Cement Content of Hardened Concrete - quality control chart

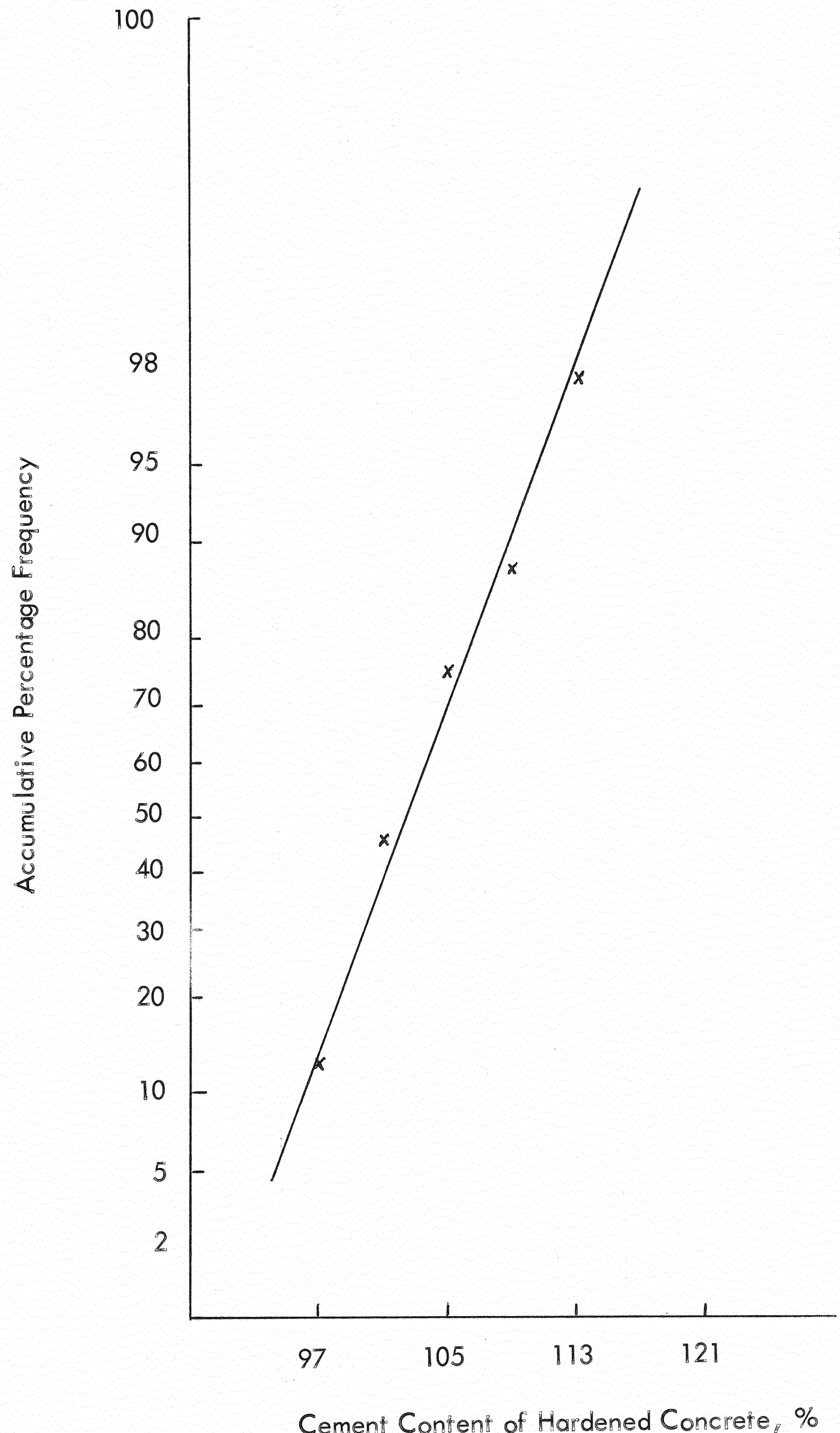


Figure III-108. Cement Content of Hardened Concrete - goodness of fit curve

No.	Durability Range, %	f	%	Cum%
1	76 - 78	11	5.5	5.5
2	79 - 81	21	10.5	16.0
3	82 - 84	41	20.5	36.5
4	85 - 87	66	33.0	69.5
5	88 - 90	54	27.0	96.5
6	91 -	7	3.5	100.0
		200	100	

n	200
specs	--
$\bar{x}$	83.6
σ_T	12.6
σ_t^2	16.0
σ_s^2	0.0
σ_a^2	141.5
V	15.1%

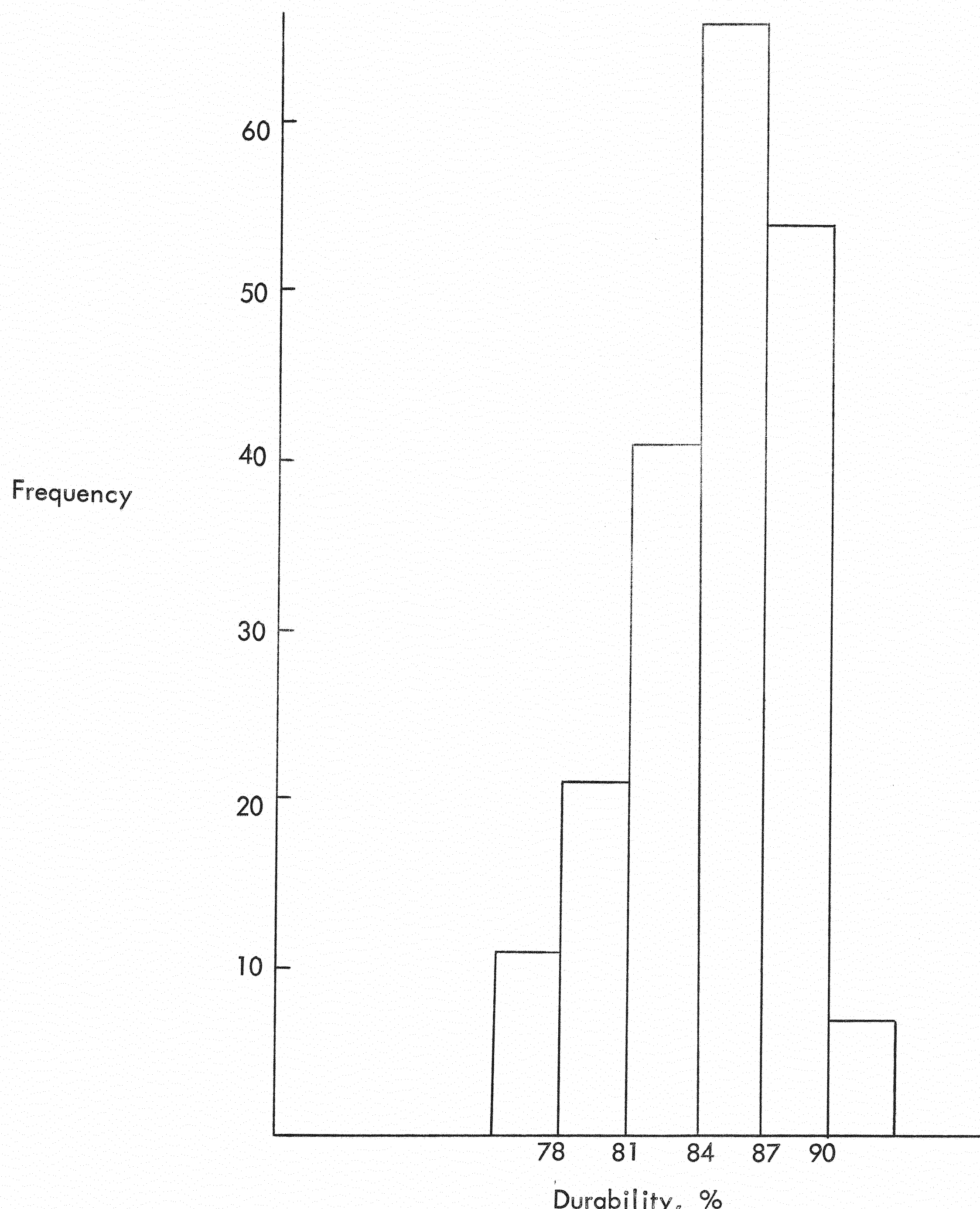


Figure III-109. Durability - statistical properties

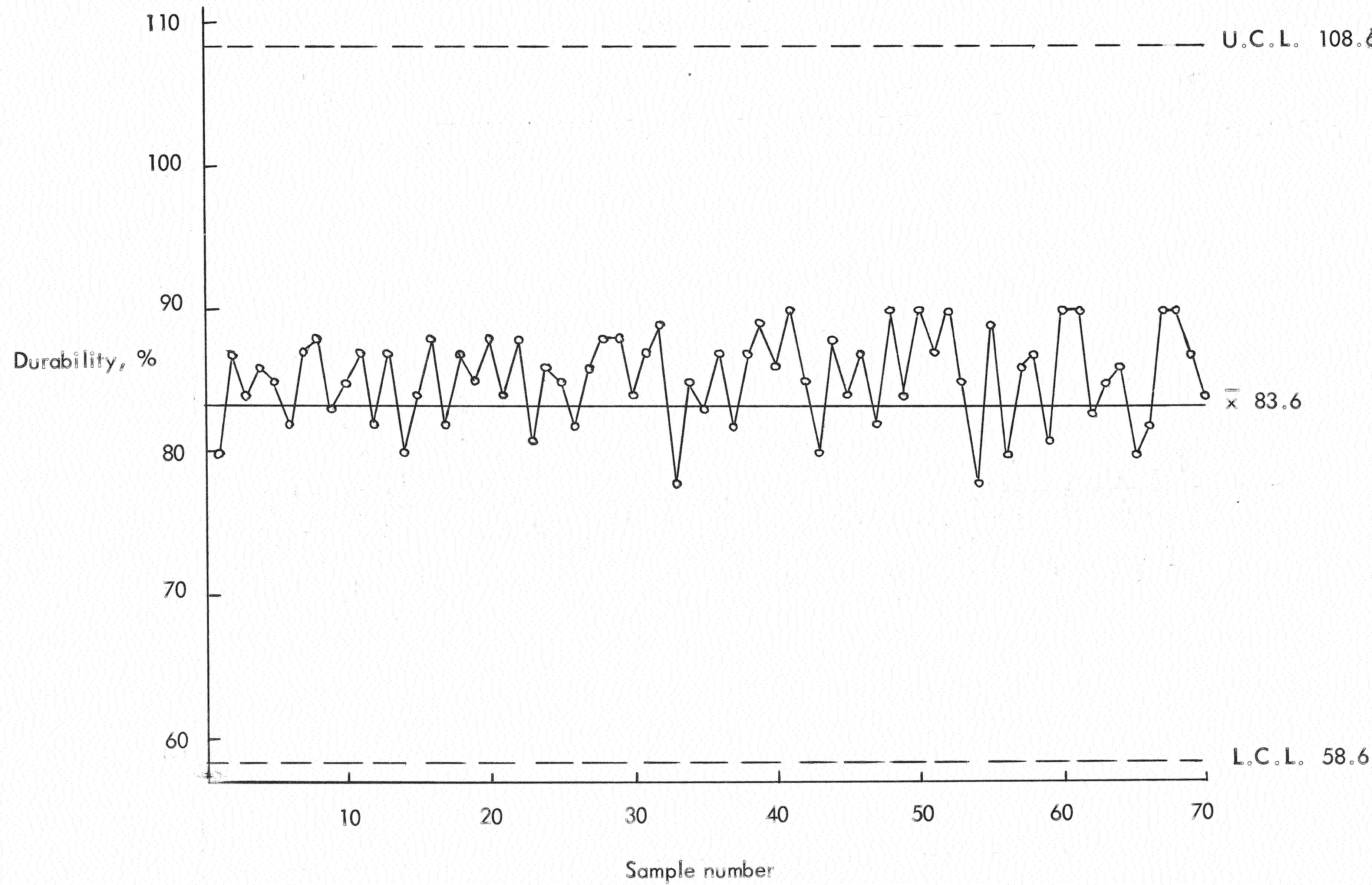


Figure III-110. Durability - quality control chart

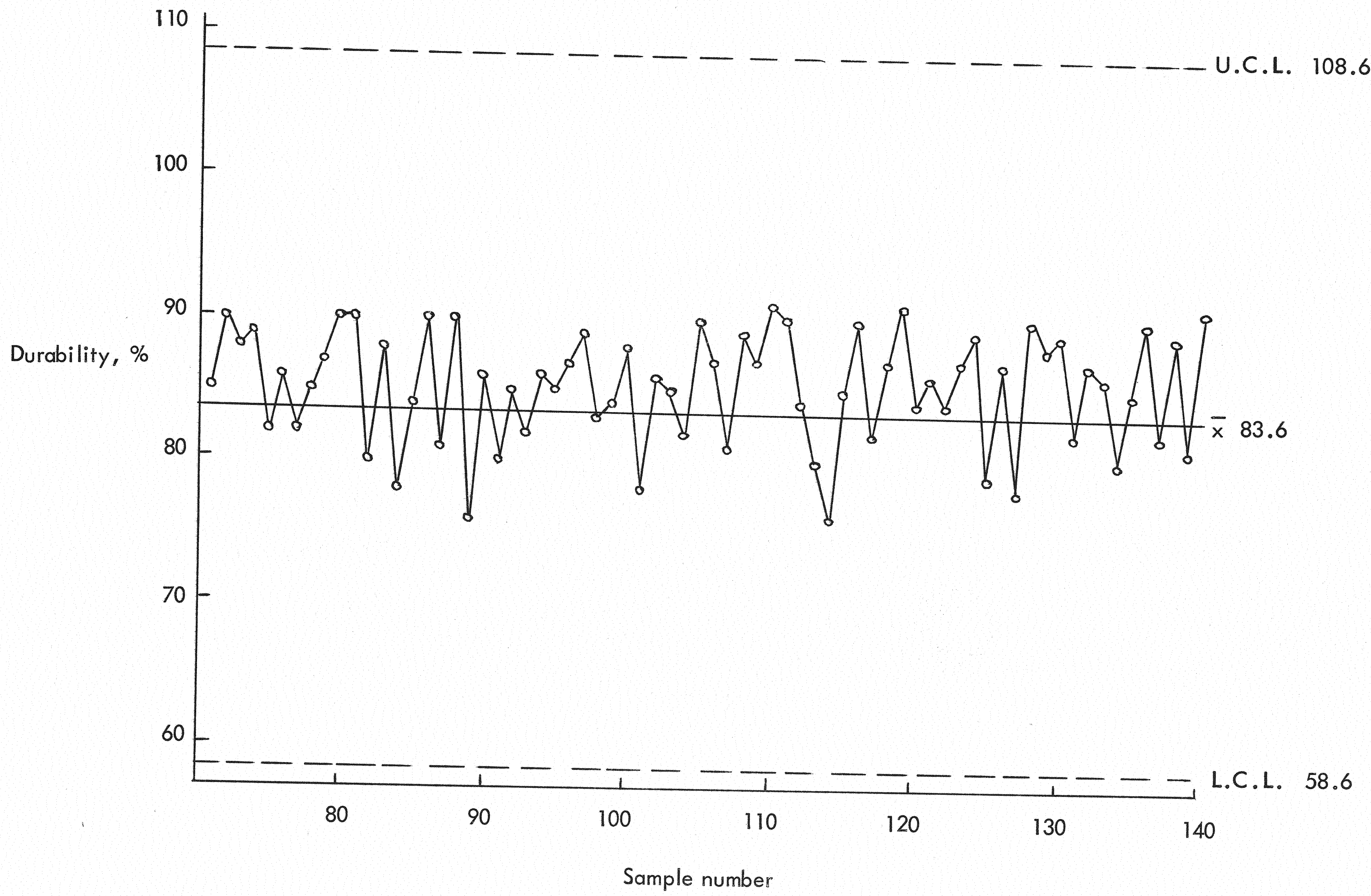


Figure III-110 (cont.). Durability - quality control chart

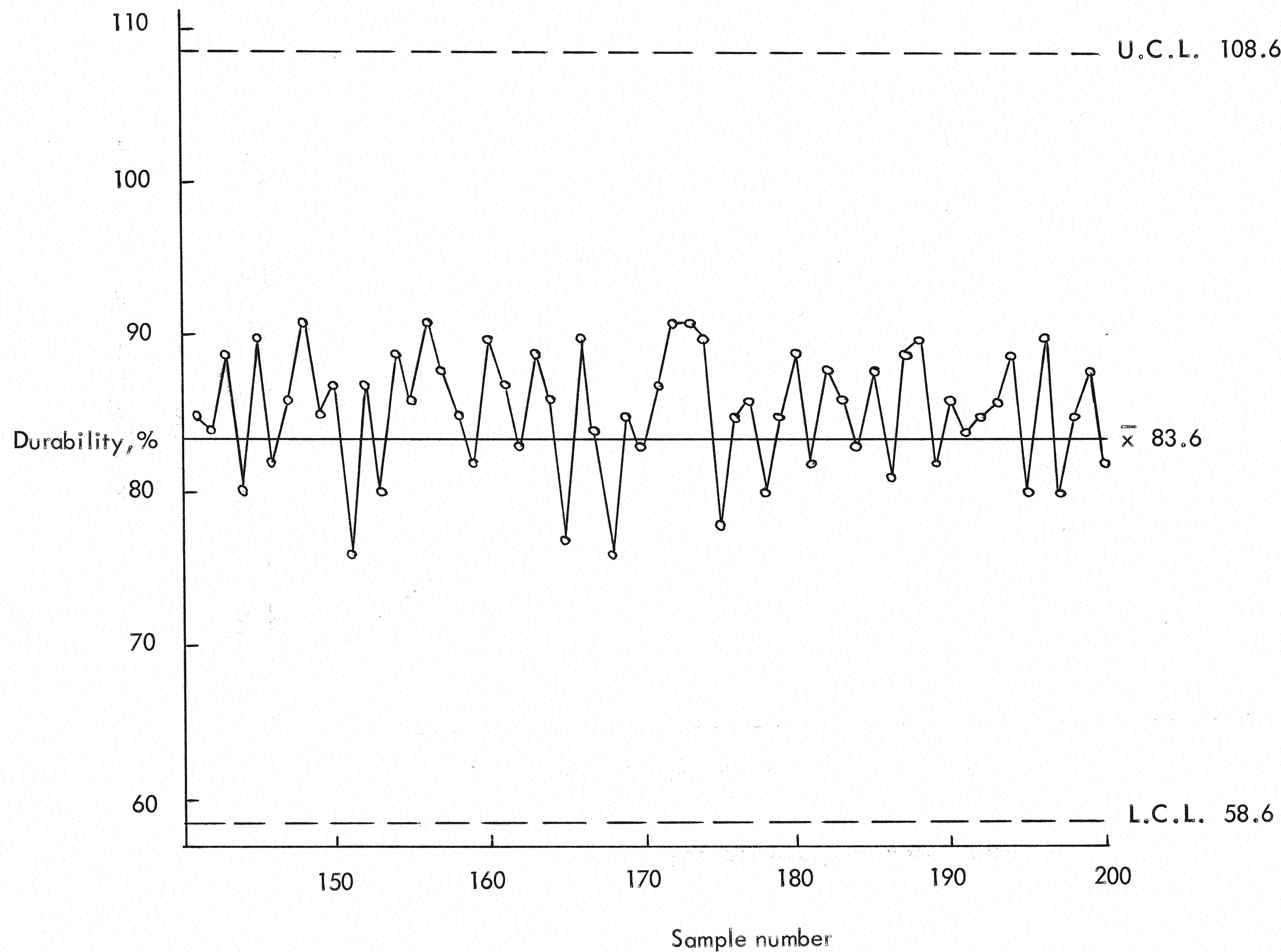


Figure III-110 (cont.). Durability - quality control chart

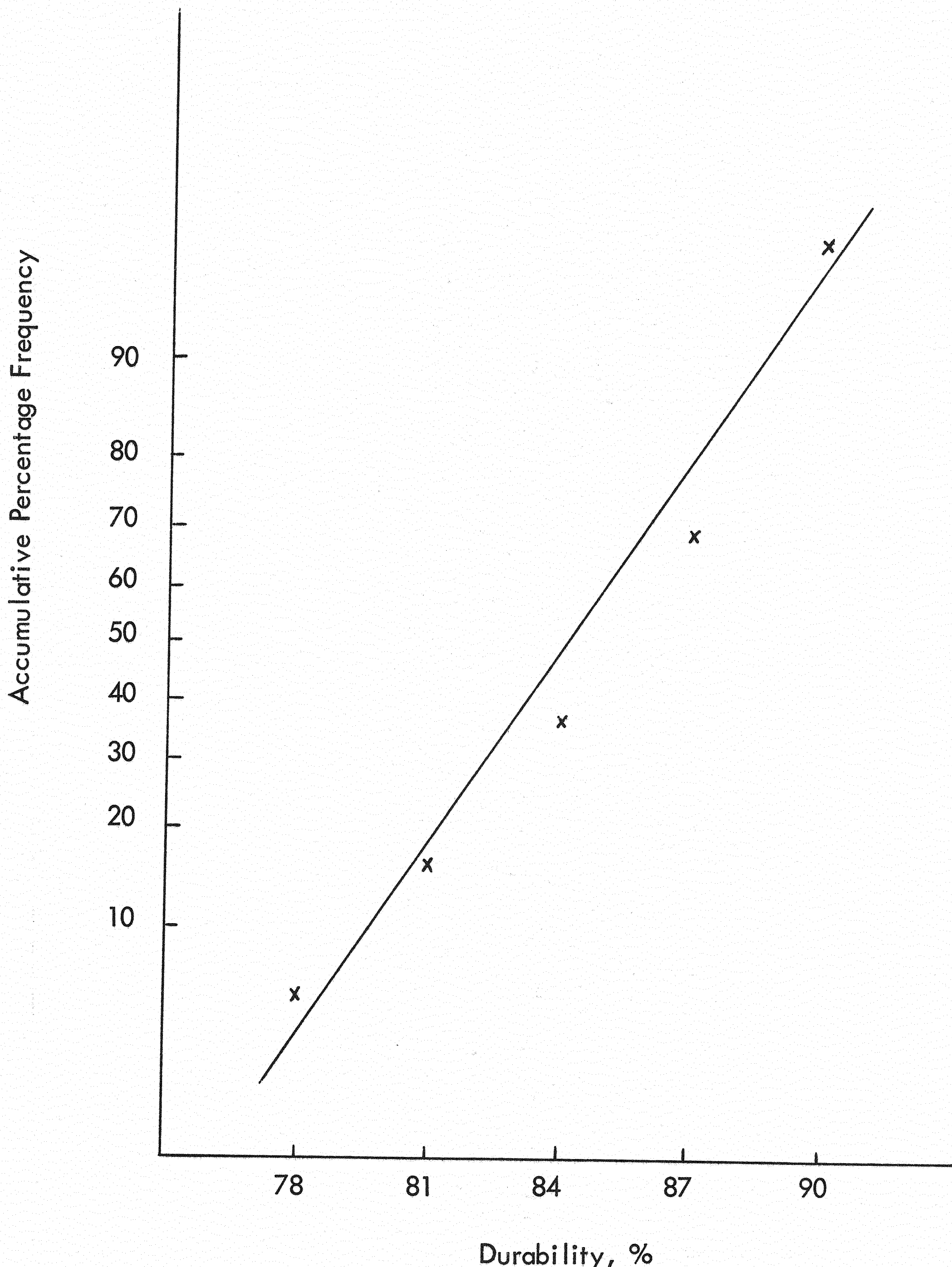


Figure III-111. Durability - goodness of fit curve

No.	C.A. Passing #200 Range %	f	%	Cum %
1	0.0 - 0.50	49	24.5	24.5
2	0.51 - 1.00	67	33.5	58.0
3	1.01 - 1.50	47	23.5	81.5
4	1.51 - 2.00	26	13.0	94.5
5	2.01 - 2.51	11	5.5	100.0
		200	100	

n	200
specs	2% max
$\bar{x}$	0.945
σ_T	0.58
σ_t^2	0.11
σ_s^2	0.06
σ_a^2	0.17
V	61.4%

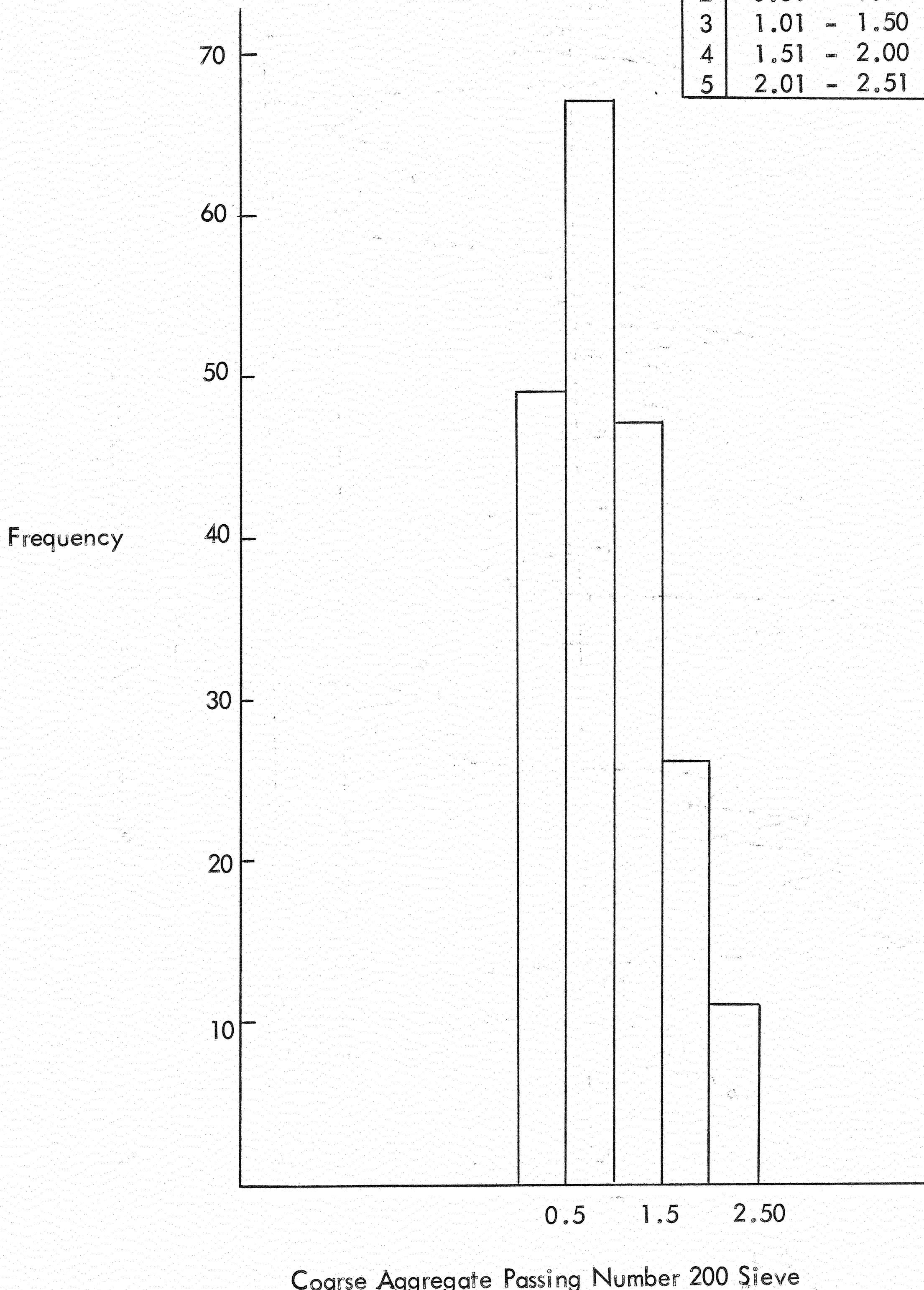


Figure III-112. % Passing No. 200 C.A. - statistical properties

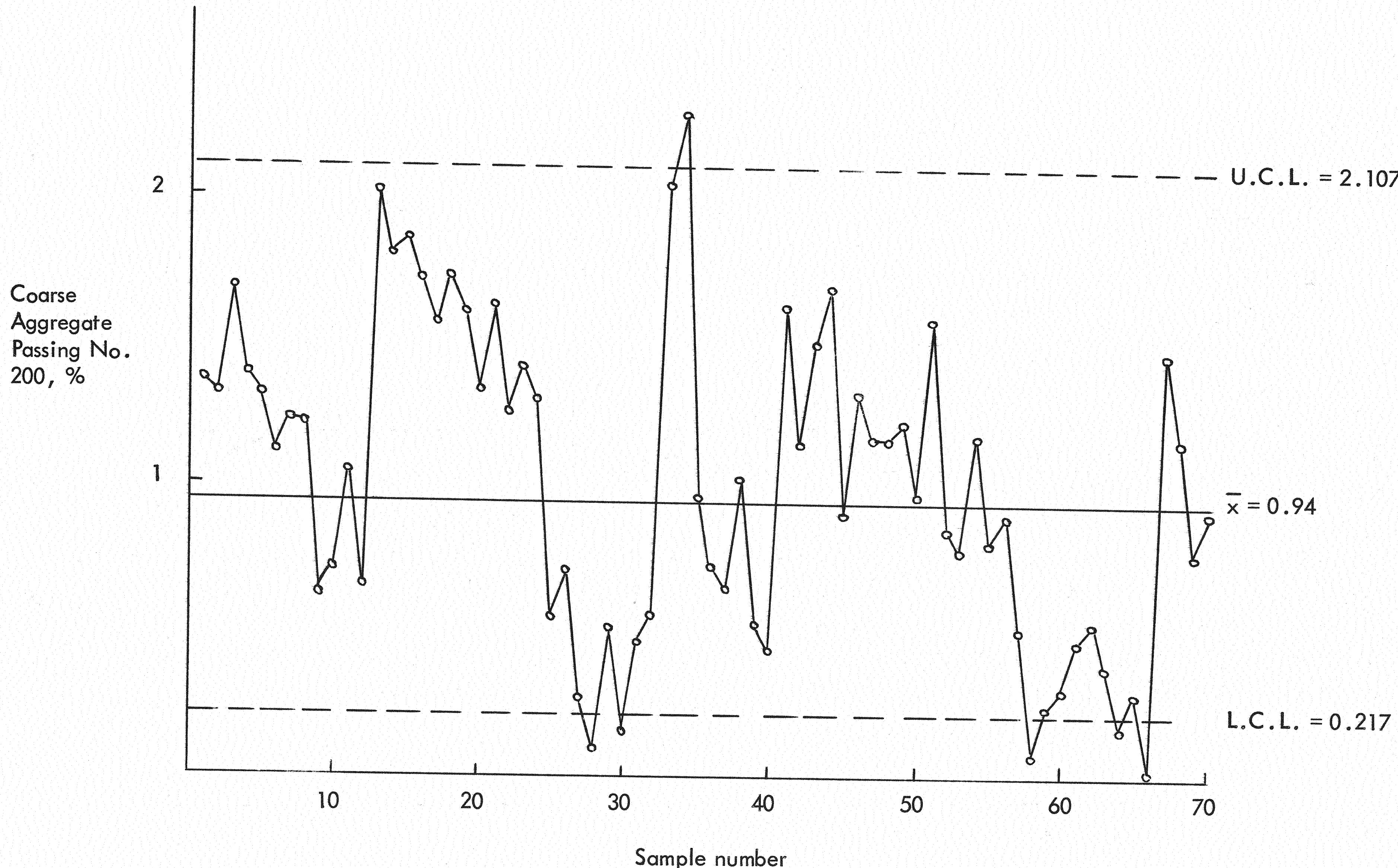


Figure III-113. % Passing No. 200 C.A. - quality control chart

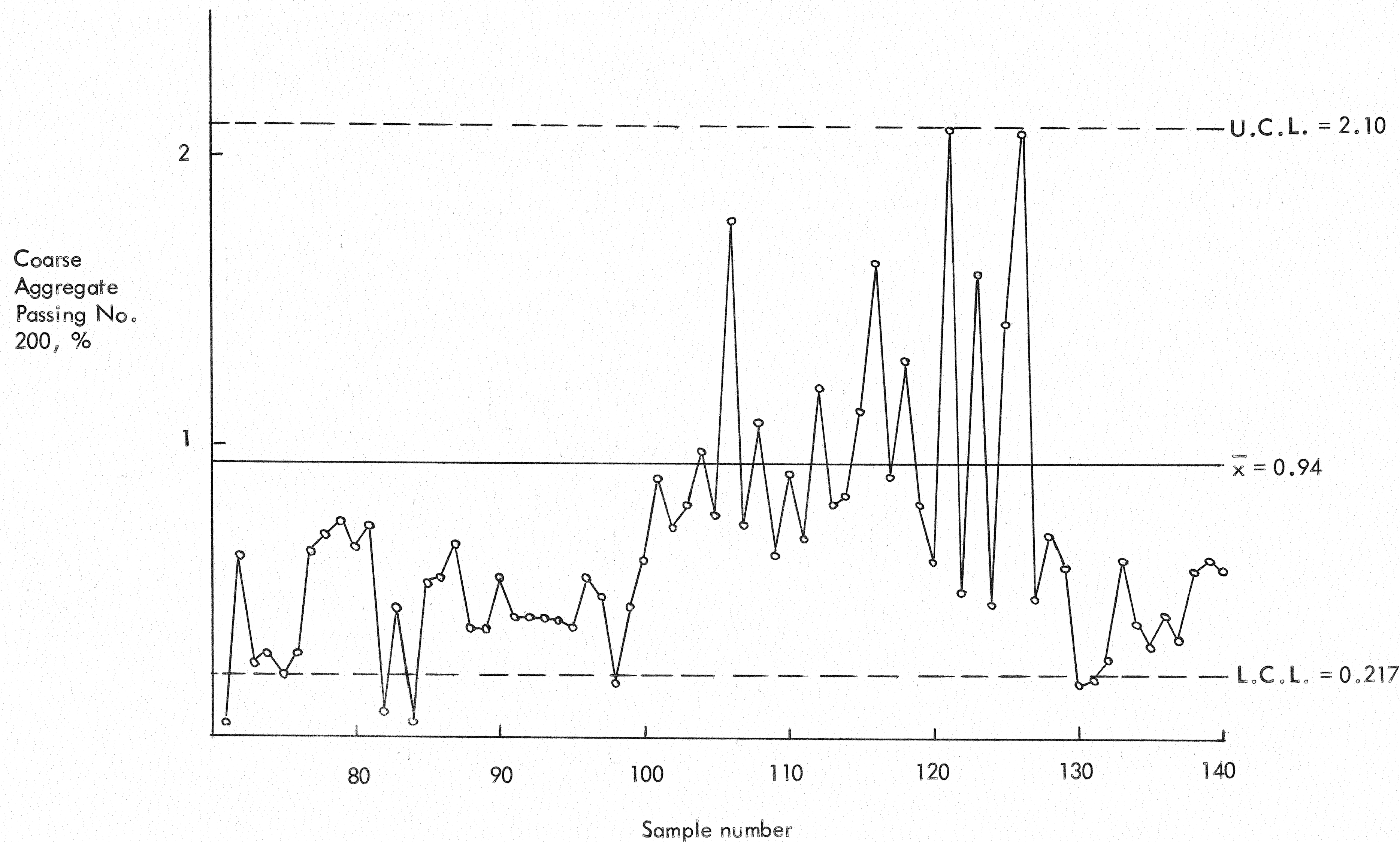


Figure III-113 (cont.). % Passing No. 200 C.A. – quality control chart

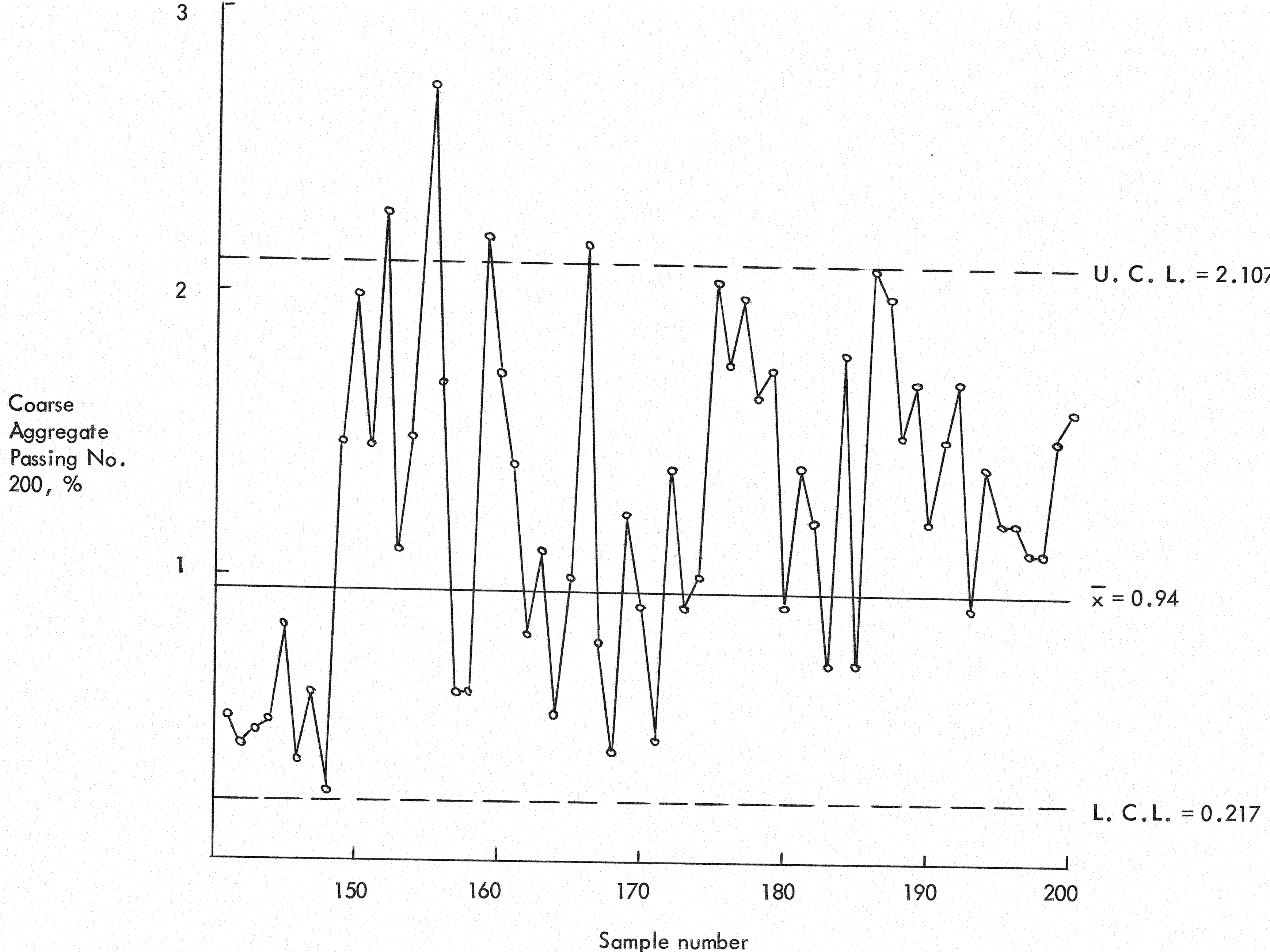


Figure III-113 (cont.). % Passing No. 200 C.A. - quality control chart

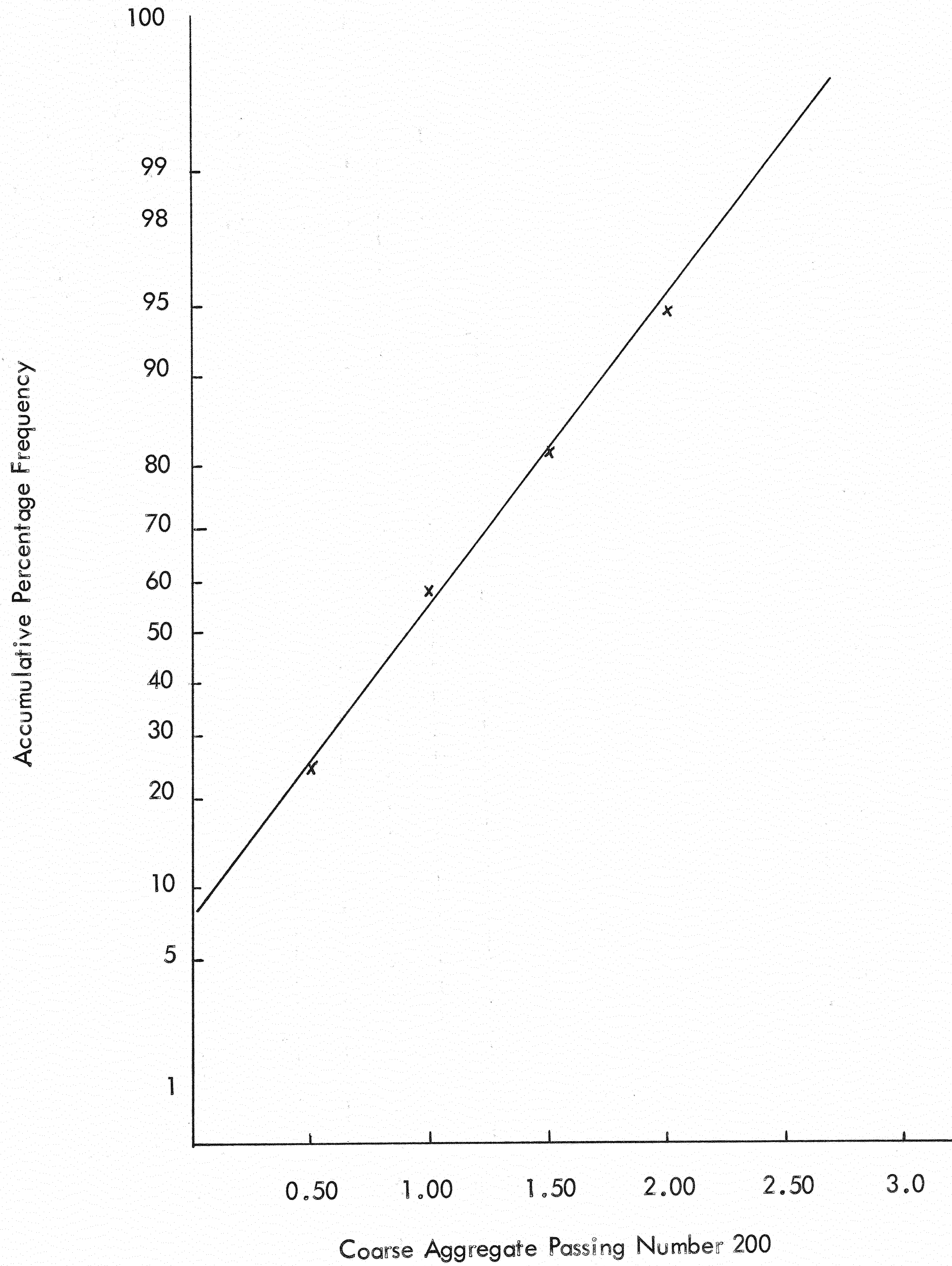


Figure III-114. % Passing No. 200 C.A. - goodness of fit curve

No.	Los Angles Range, %	f	%	Cum %
1	- 21.5	3	1.5	1.5
2	21.5 - 22.5	6	3.0	4.5
3	22.5 - 23.5	8	4.0	8.5
4	23.5 - 24.5	51	25.5	34.0
5	24.5 - 25.5	64	32.0	66.0
6	25.5 - 26.5	31	15.5	81.5
7	26.5 - 27.5	18	9	90.5
8	27.5 - 28.5	7	3.5	94.0
9	28.5 - 29.5	9	4.5	98.5
10	29.5 -	3	1.5	100.0
		200	100	

n	200
specs	40%max
$\bar{x}$	24.7
σ_T	3.9
σ_t^2	2.32
σ_s^2	0.31
σ_a^2	12.9
V	15.8%

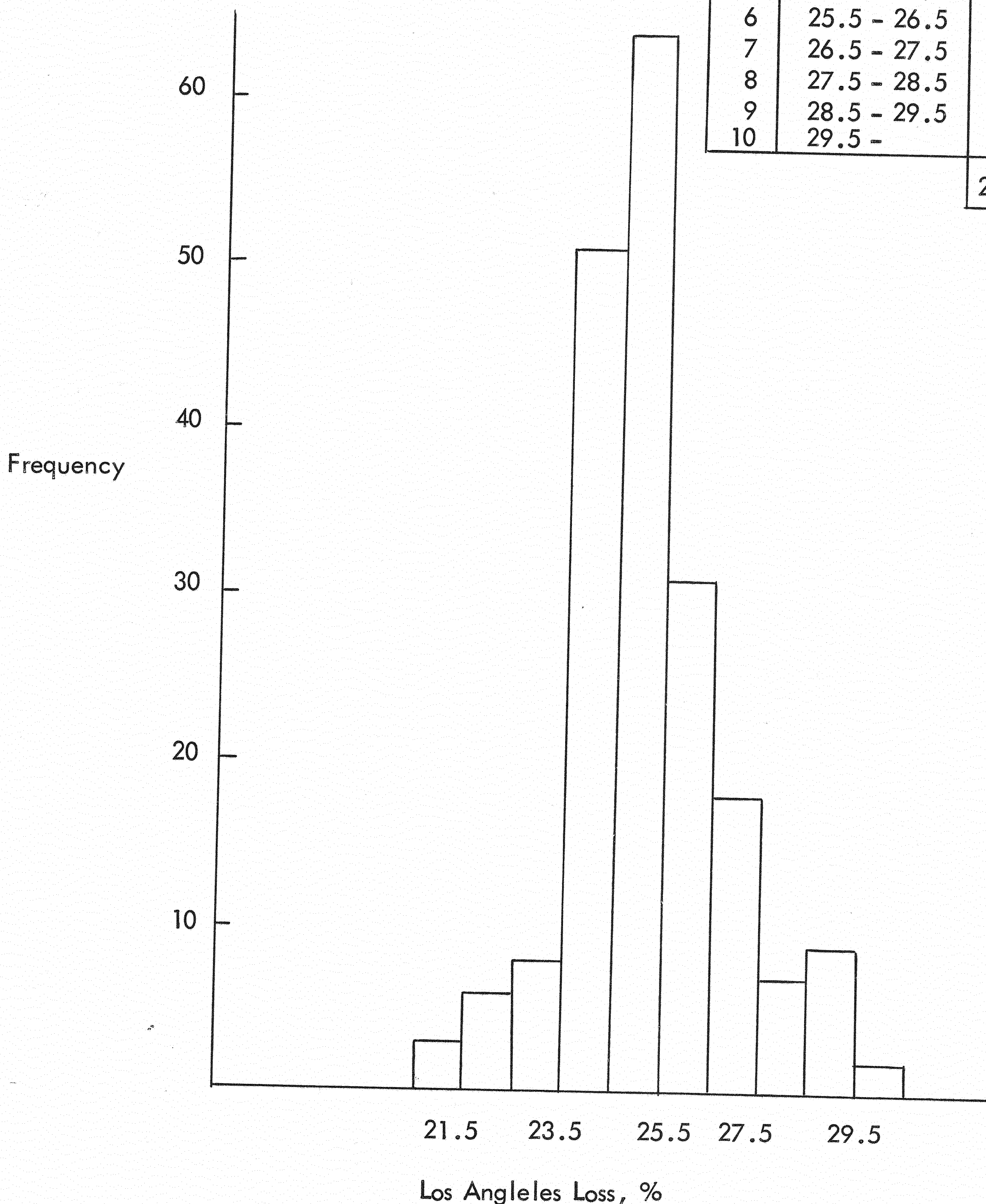


Figure III-115. Los Angles Loss - statistical properties

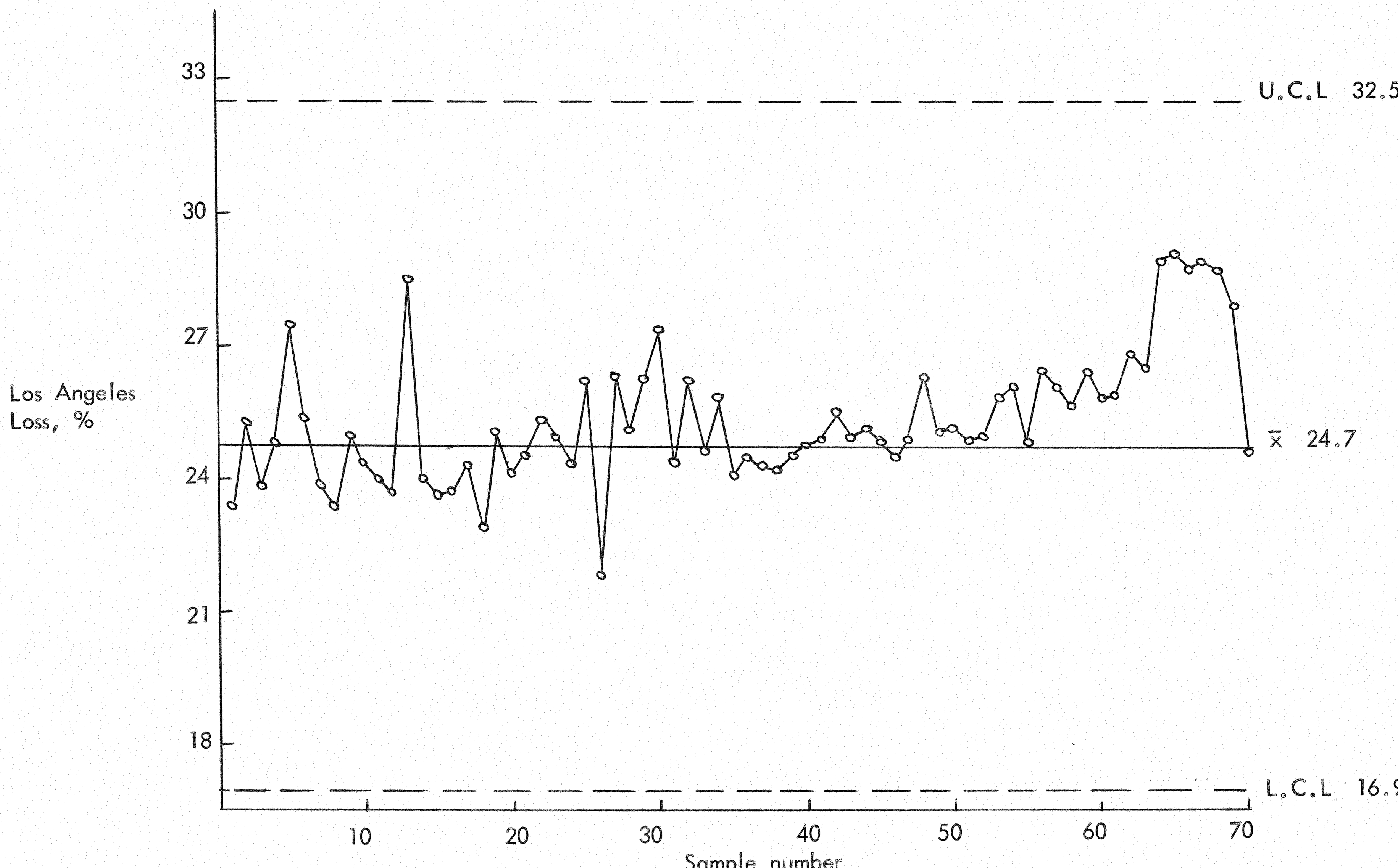


Figure III-116. Los Angeles loss - quality control chart

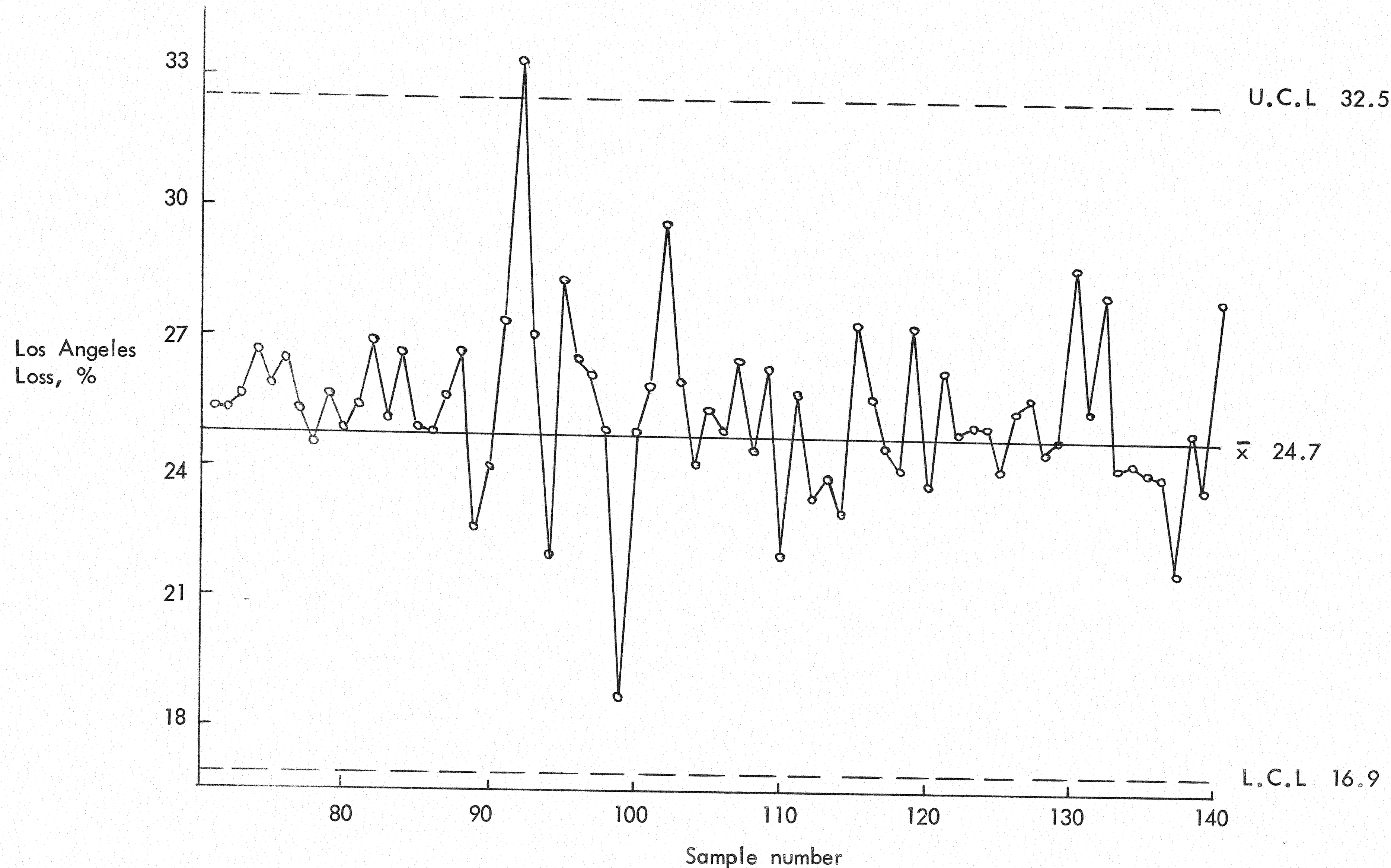


Figure III-116(cont.) Los Angeles Loss - quality control chart

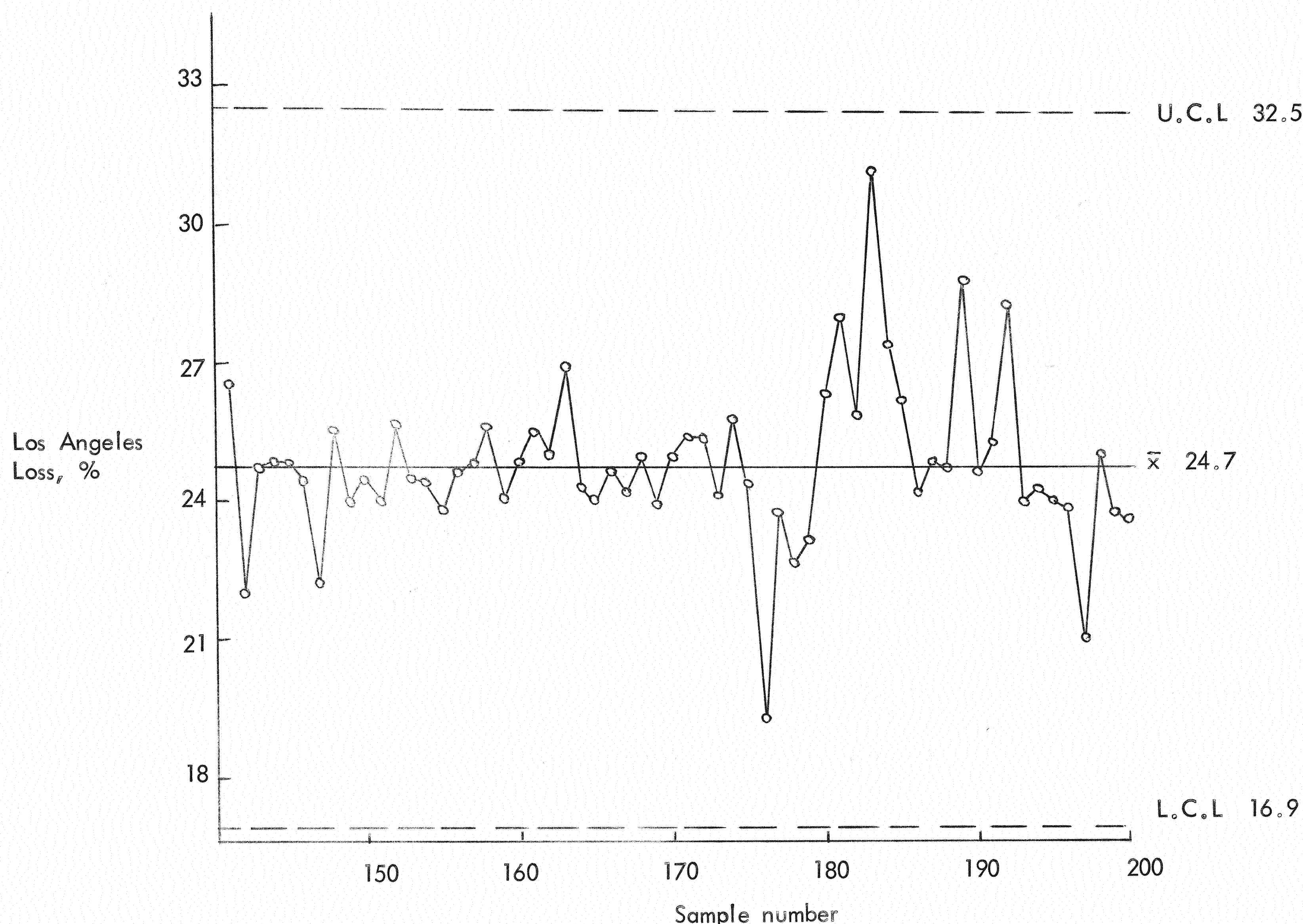
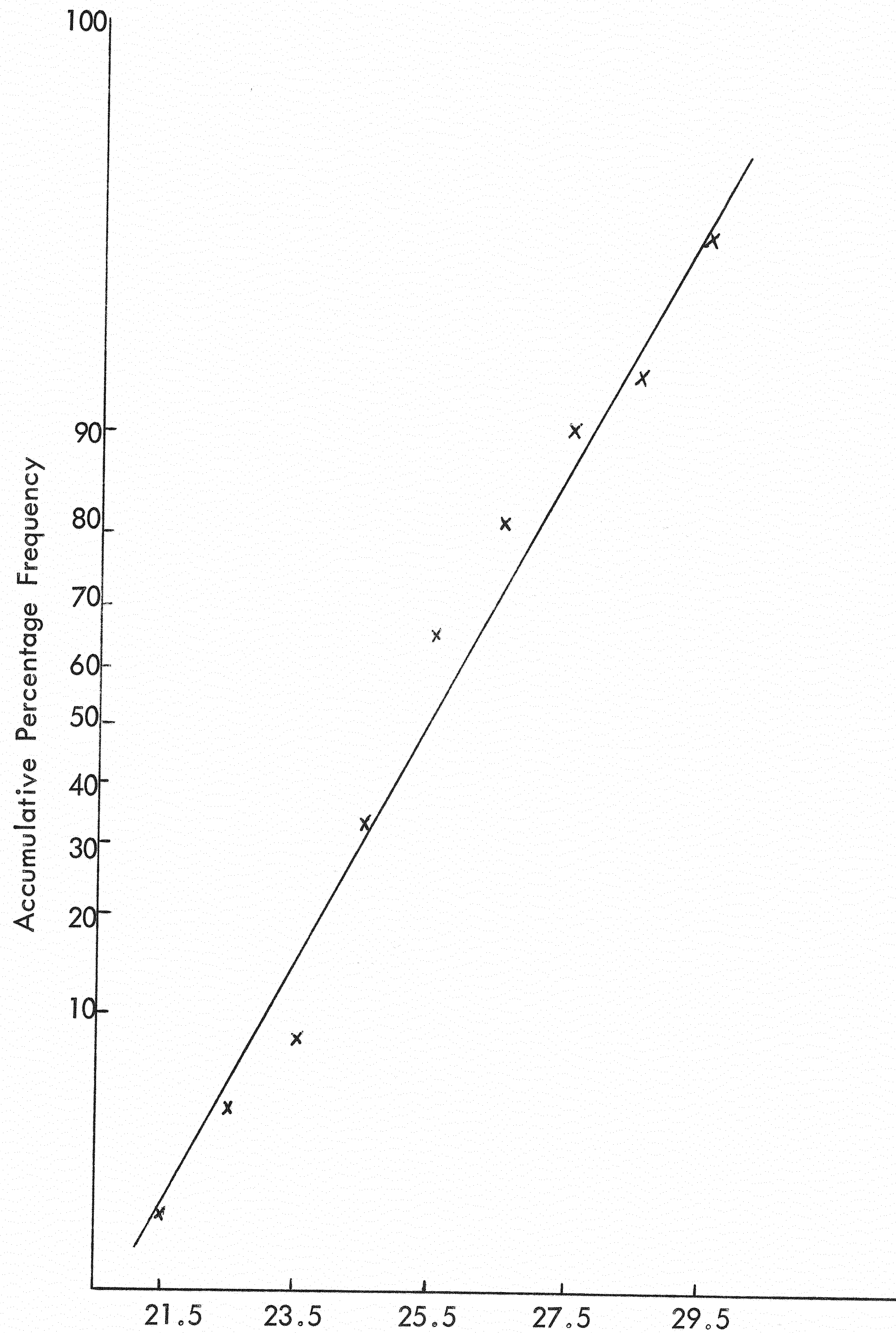


Figure III-116(cont.). Los Angeles Loss - quality control chart



Los Angeles

Figure III-117. Los Angeles Loss - goodness of fit curve

No.	Fineness Modulus Range %	f	%	Cum%
1	1.60 - 1.75	1	0.5	0.5
2	1.75 - 1.90	0	0	0.5
3	1.90 - 2.05	0	0	0.5
4	2.05 - 2.20	2	1.0	1.5
5	2.20 - 2.35	5	2.5	4.0
6	2.35 - 2.50	45	22.5	26.5
7	2.50 - 2.65	54	27.0	53.5
8	2.65 - 2.80	77	38.5	92.5
9	2.80 - 2.95	15	7.5	99.5
10	2.95 - 3.10	1	0.5	100.0
		200	100	

n	200
specs	--
$\overline{x}$	2.56
σ_T	0.40
σ_t^2	0.01
σ_s^2	0.001
σ_a^2	0.146
V	16.3%

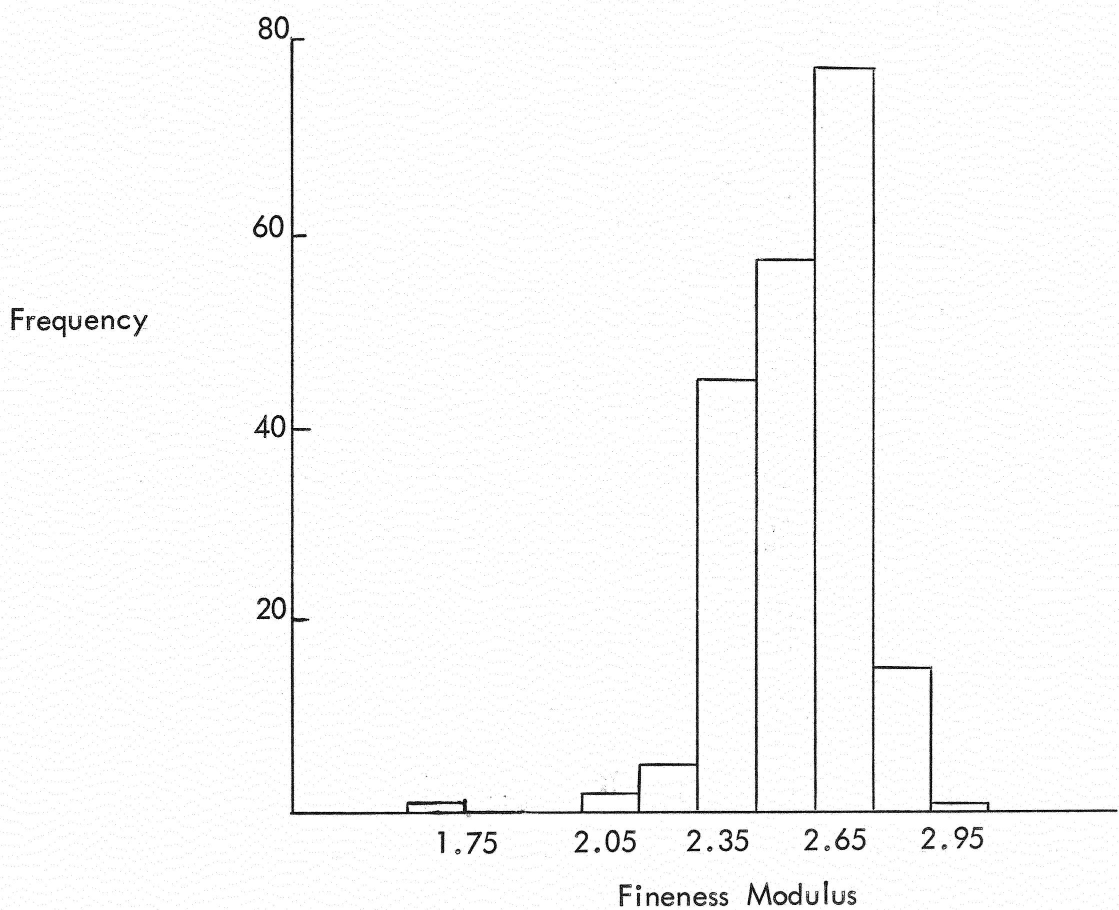


Figure III-118. Fineness Modulus - statistical properties

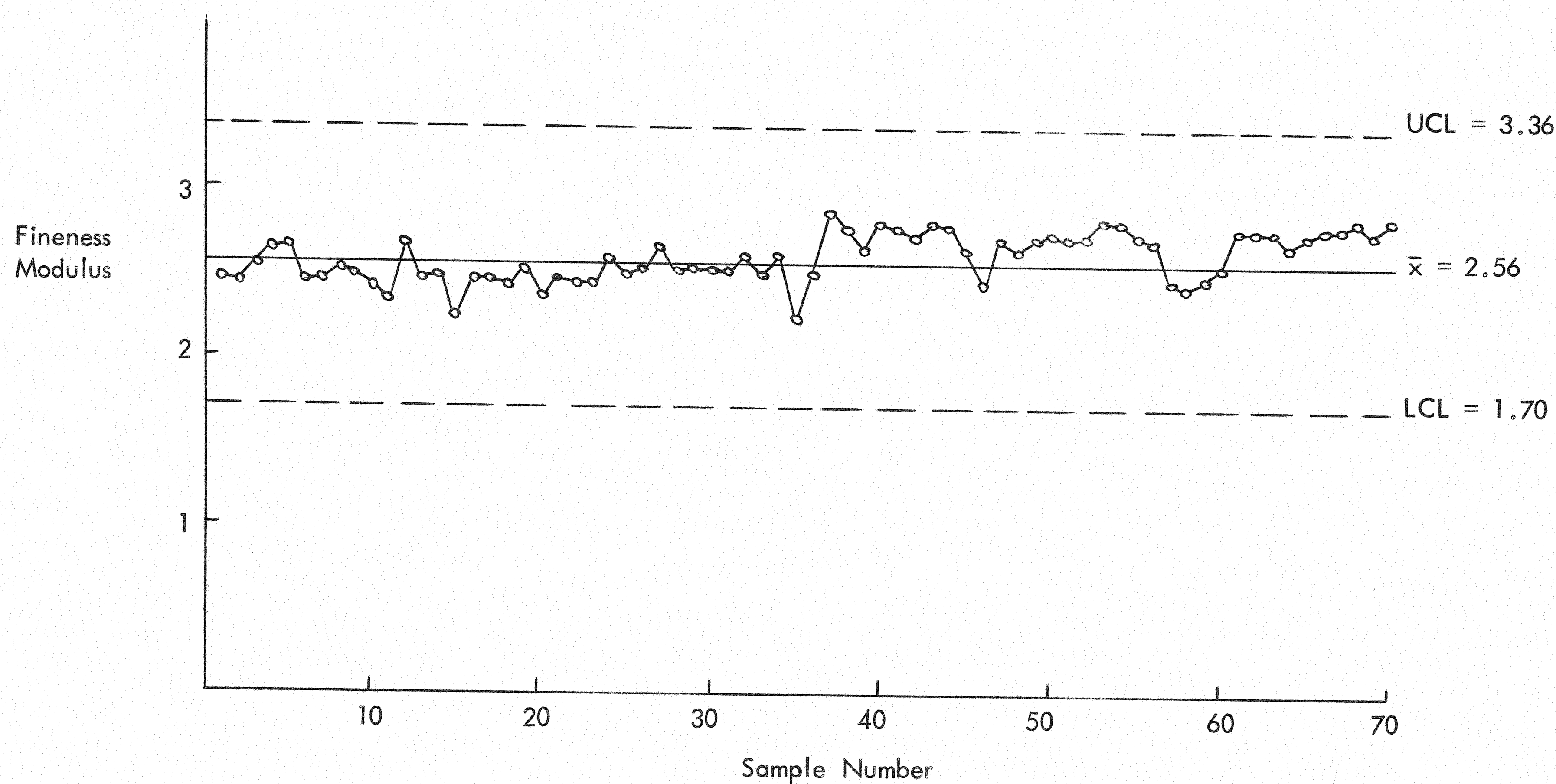


Figure III-119. Fineness Modulus - quality control chart

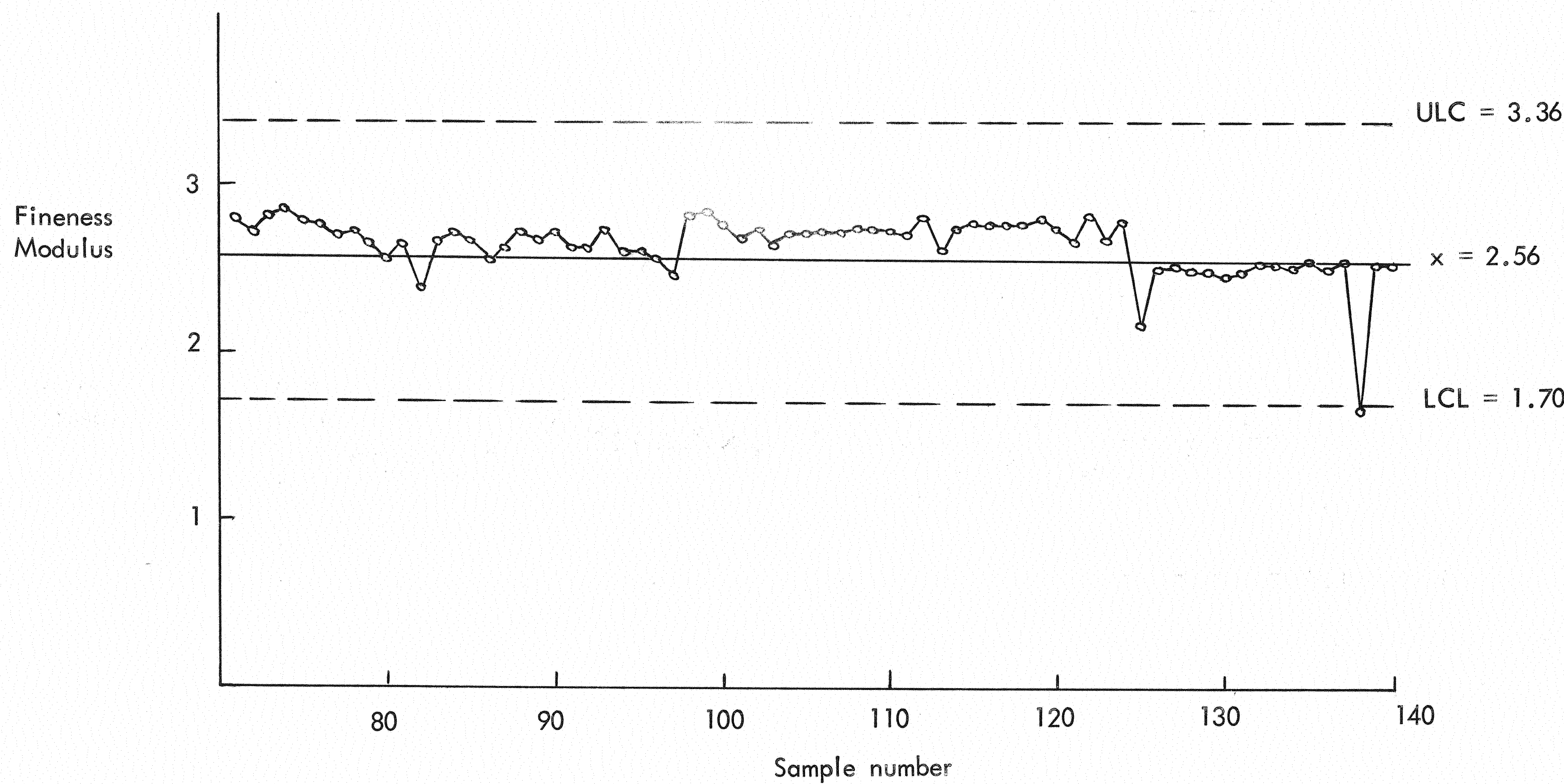


Figure III-119(cont.) Fineness Modulus - quality control chart

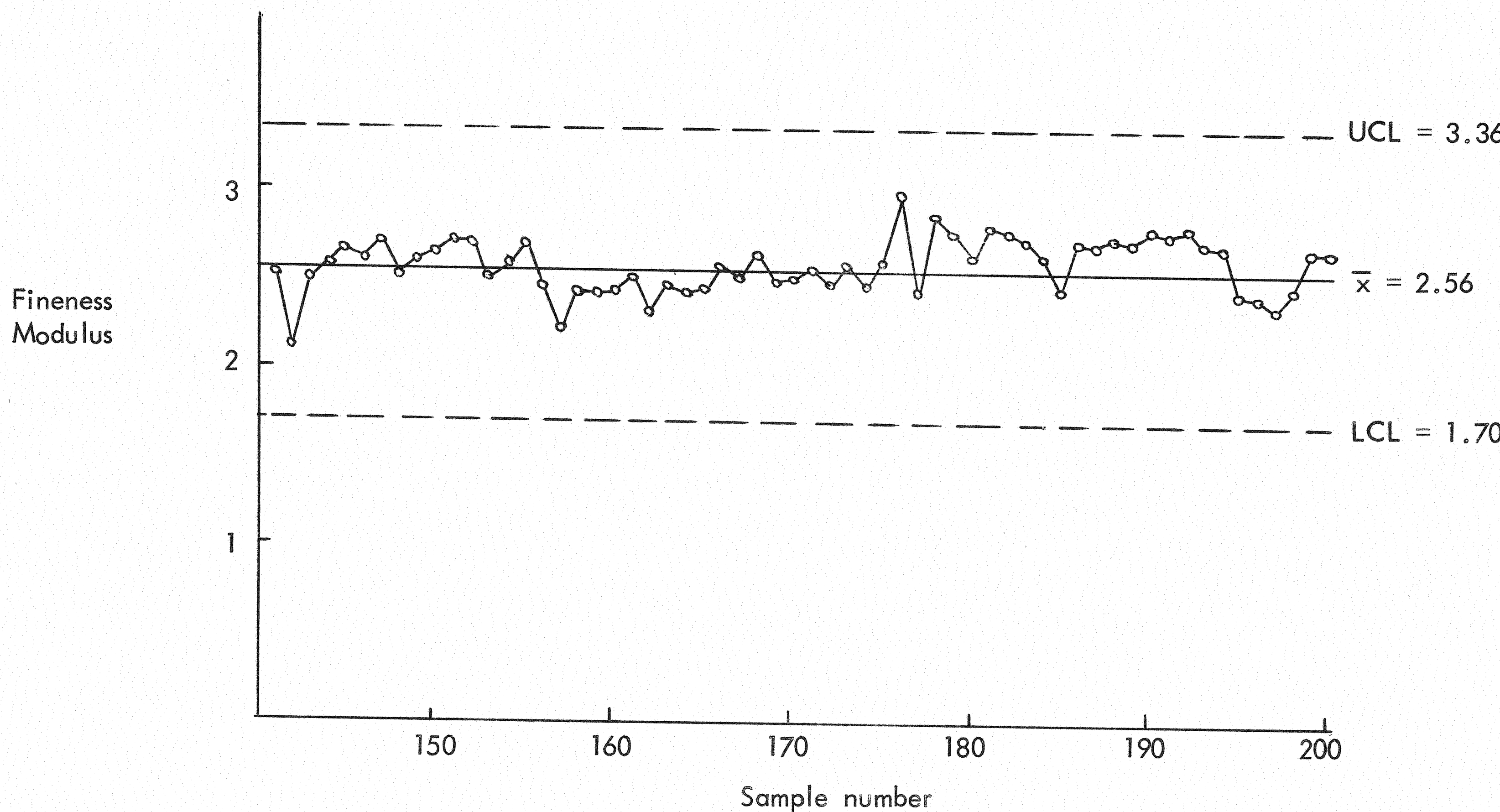


Figure III-119(cont.) Fineness Modulus - quality control chart

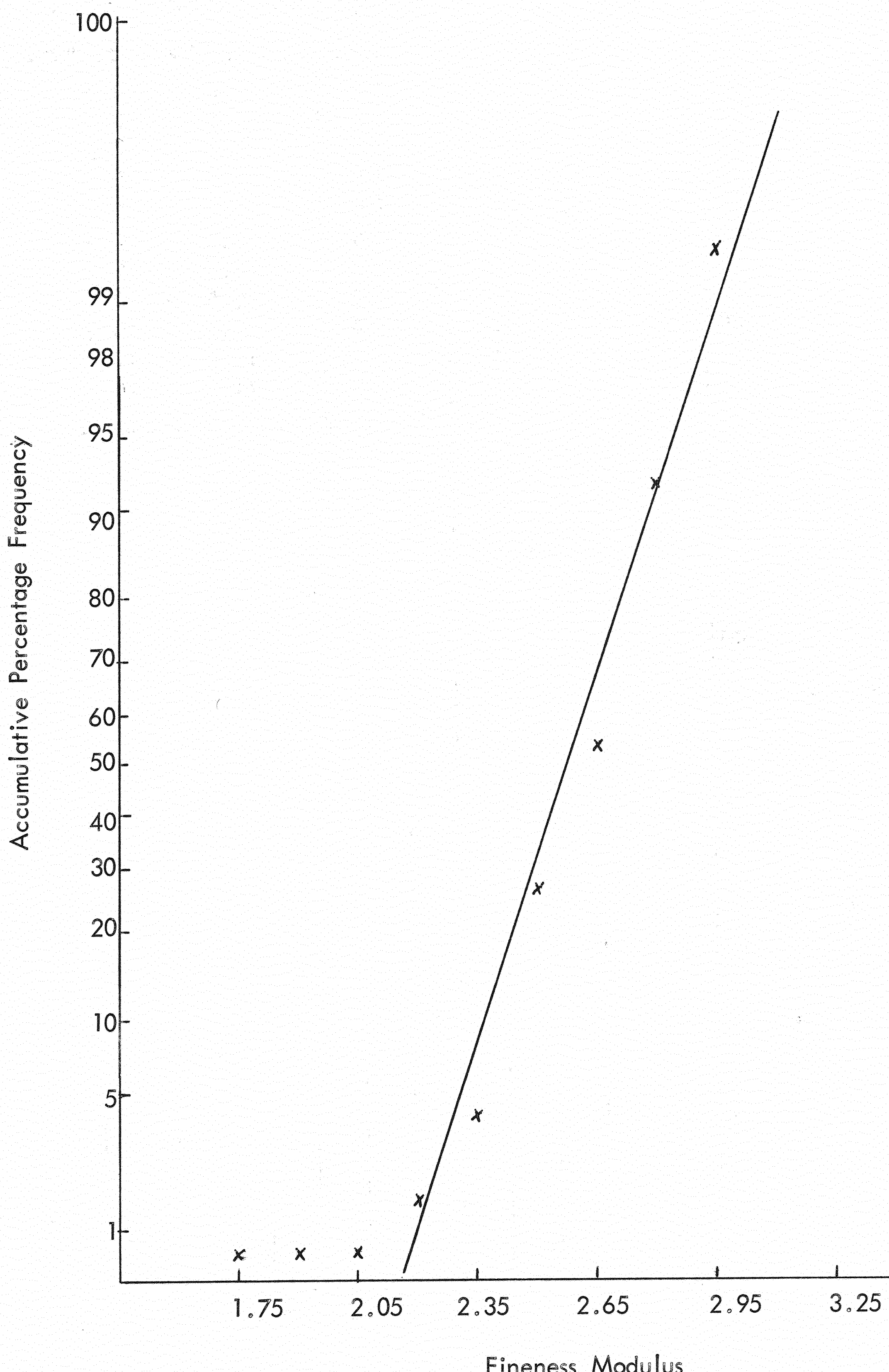


Figure III-120. Fineness Modulus - goodness of fit curve

No.	F.A. Passing #200 Range %	f	%	Cum%
1	1.5 - 2.5	25	12.5	12.5
2	2.5 - 3.5	46	23.0	35.5
3	3.5 - 4.5	62	31.0	66.5
4	4.5 - 5.5	32	16.0	82.5
5	5.5 - 6.5	14	7.0	89.5
6	6.5 - 7.5	11	5.5	95.0
7	7.5 - 8.5	4	2.0	97.0
8	8.5 - 9.5	3	1.5	98.5
9	9.5 - 10.5	1	0.5	99.0
10	10.5 - 11.5	1	0.5	99.5
11	11.5 - 12.5	1	0.5	100.0
		200	100	

n	200
specs	3% max
$\bar{x}$	4.22
σ_T	1.81
σ_t^2	1.6
σ_s^2	0.00
σ_a^2	1.70
V	42.9%

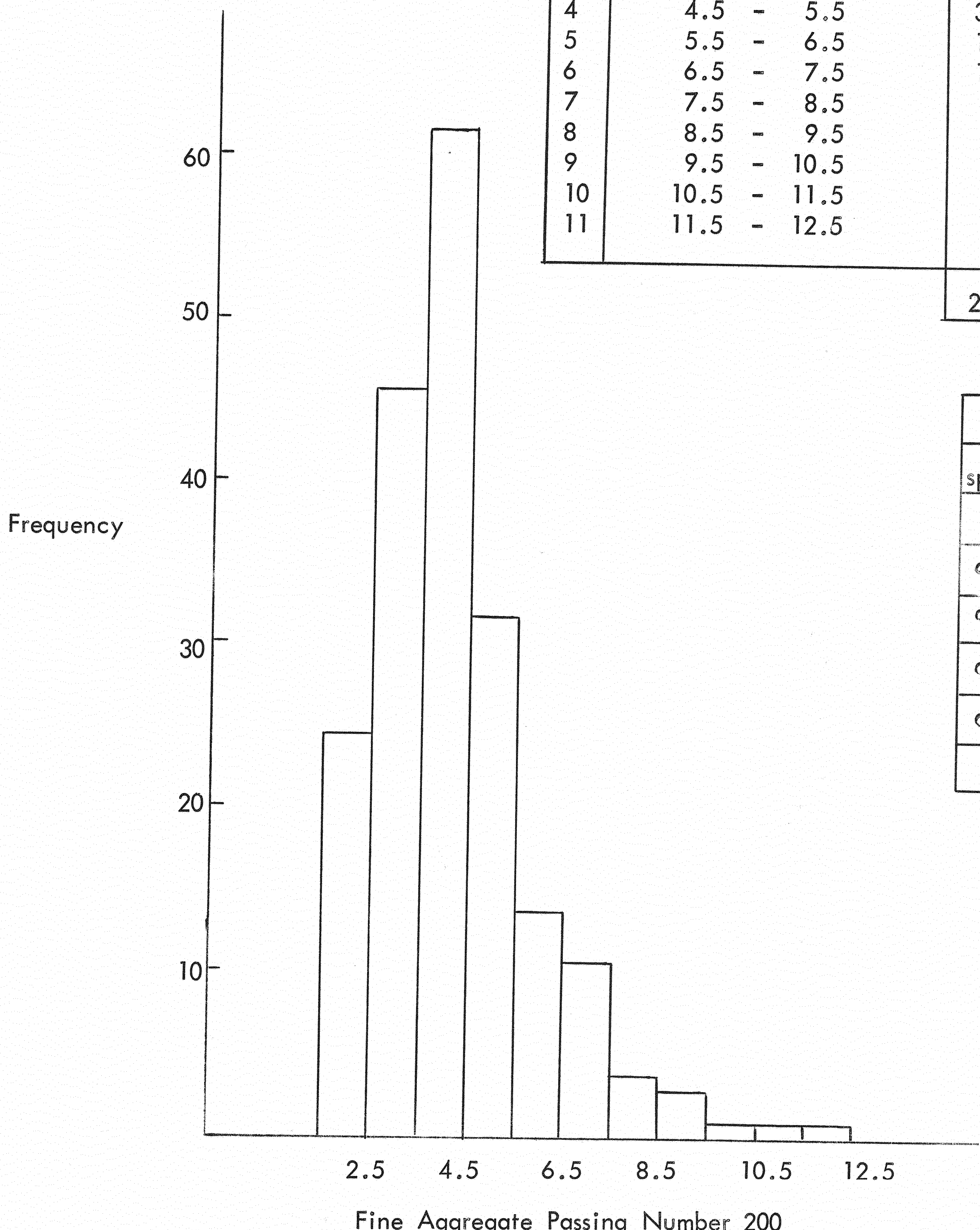


Figure III-121. % Passing No. 200 F.A. - statistical properties

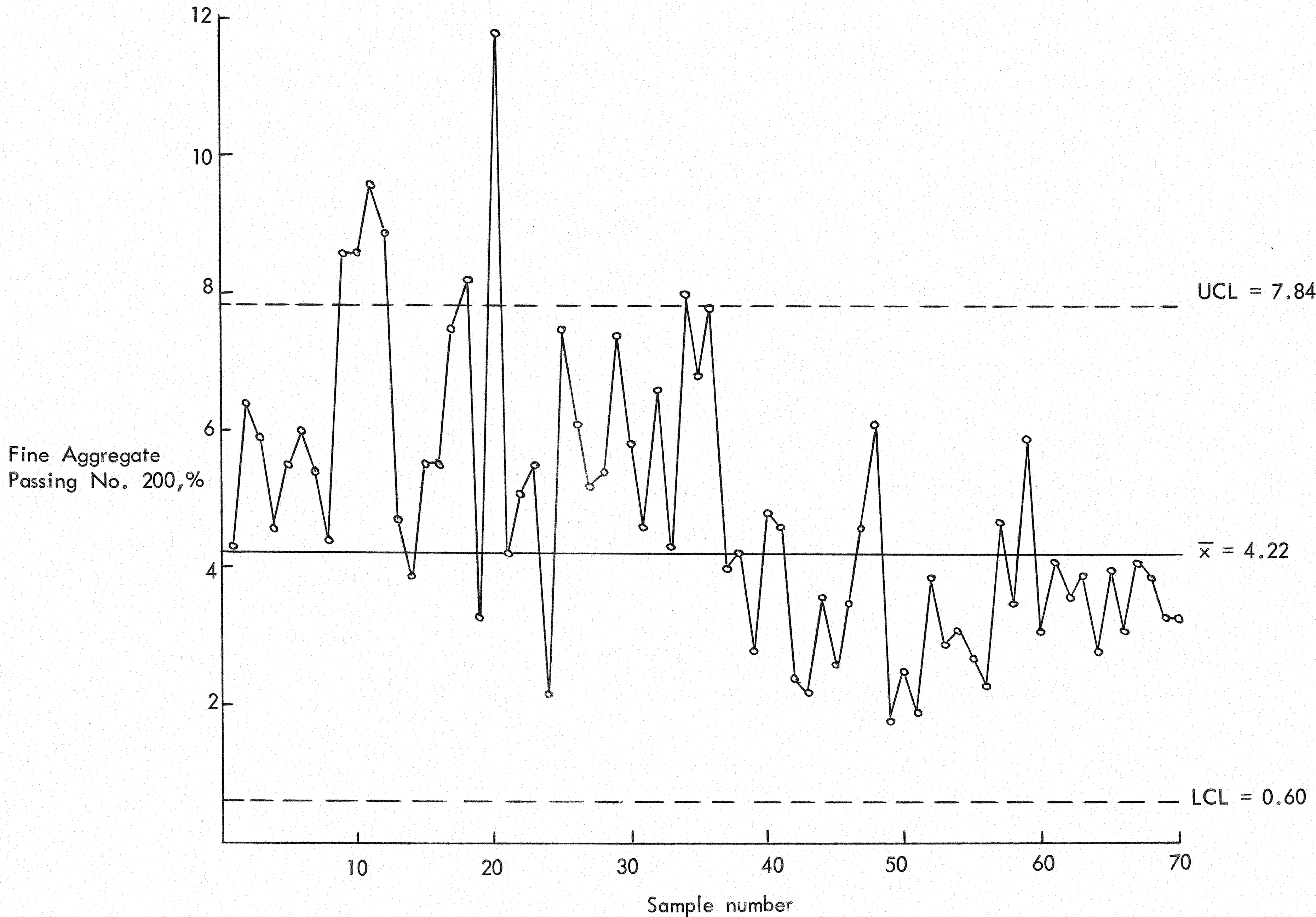


Figure III-122. % Passing No. 200 F.A. - quality control chart

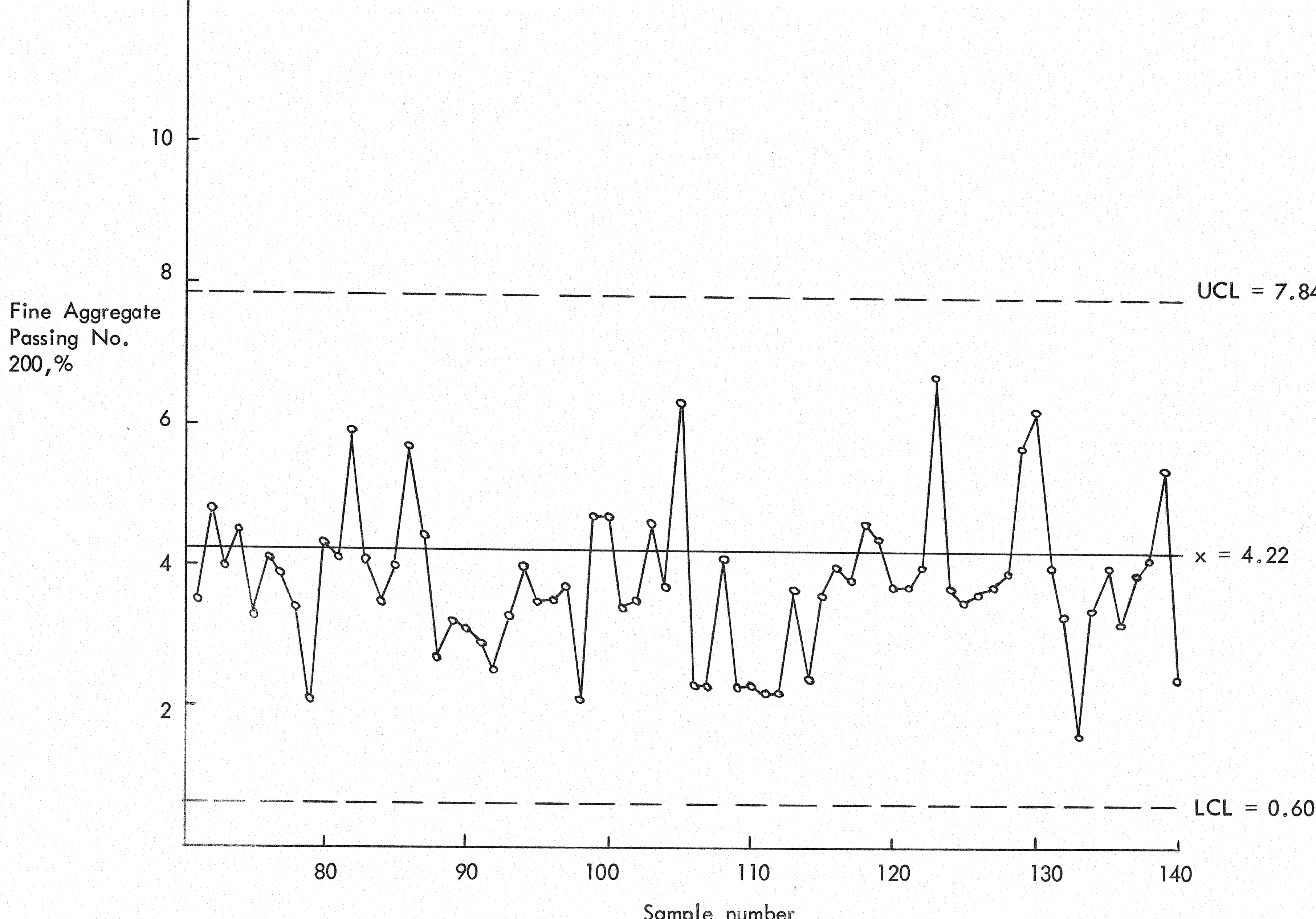


Figure III-122(cont.). % Passing No. 200 F.A. - quality control chart

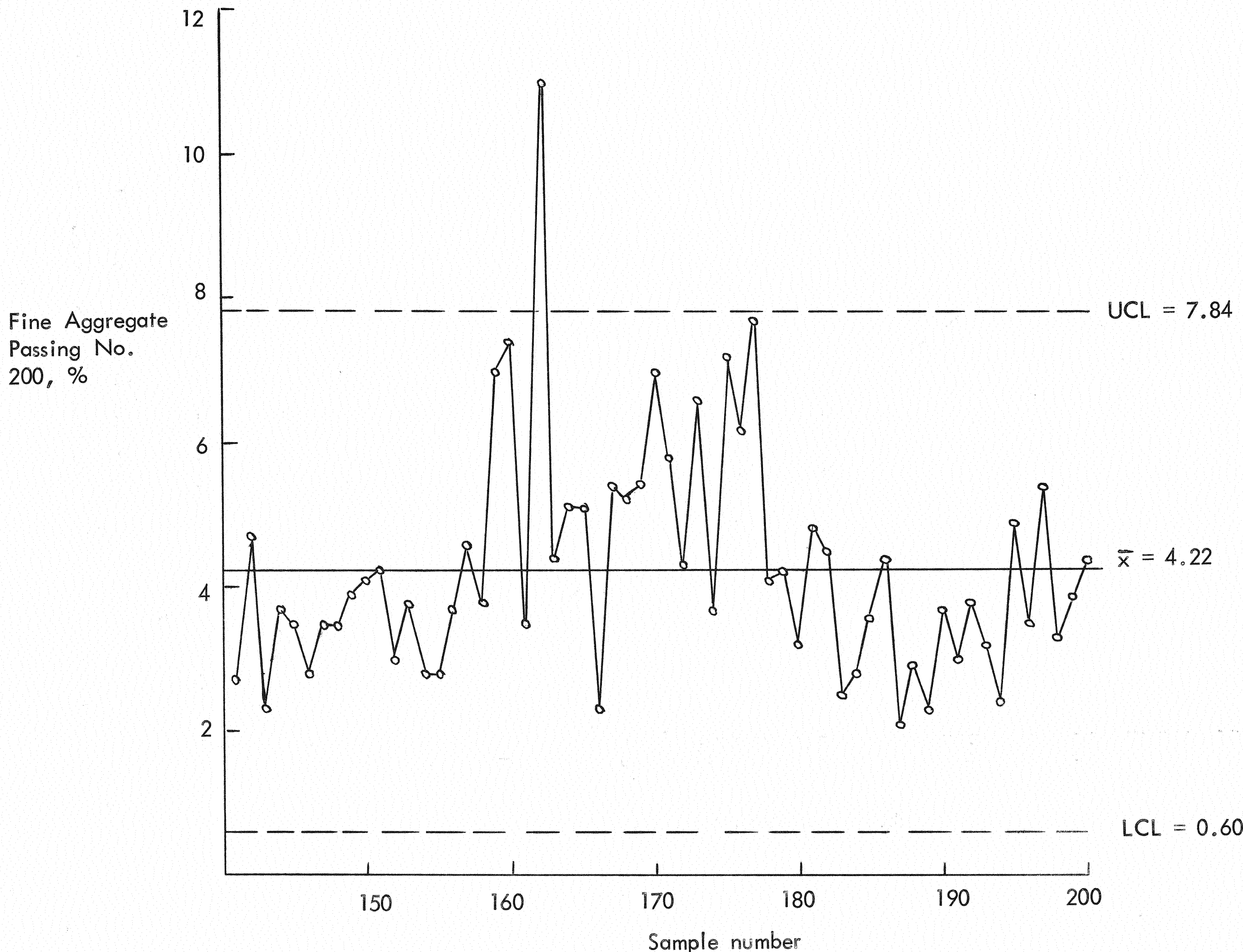


Figure III-122(cont.). % Passing No. 200 F.A. - quality-control chart

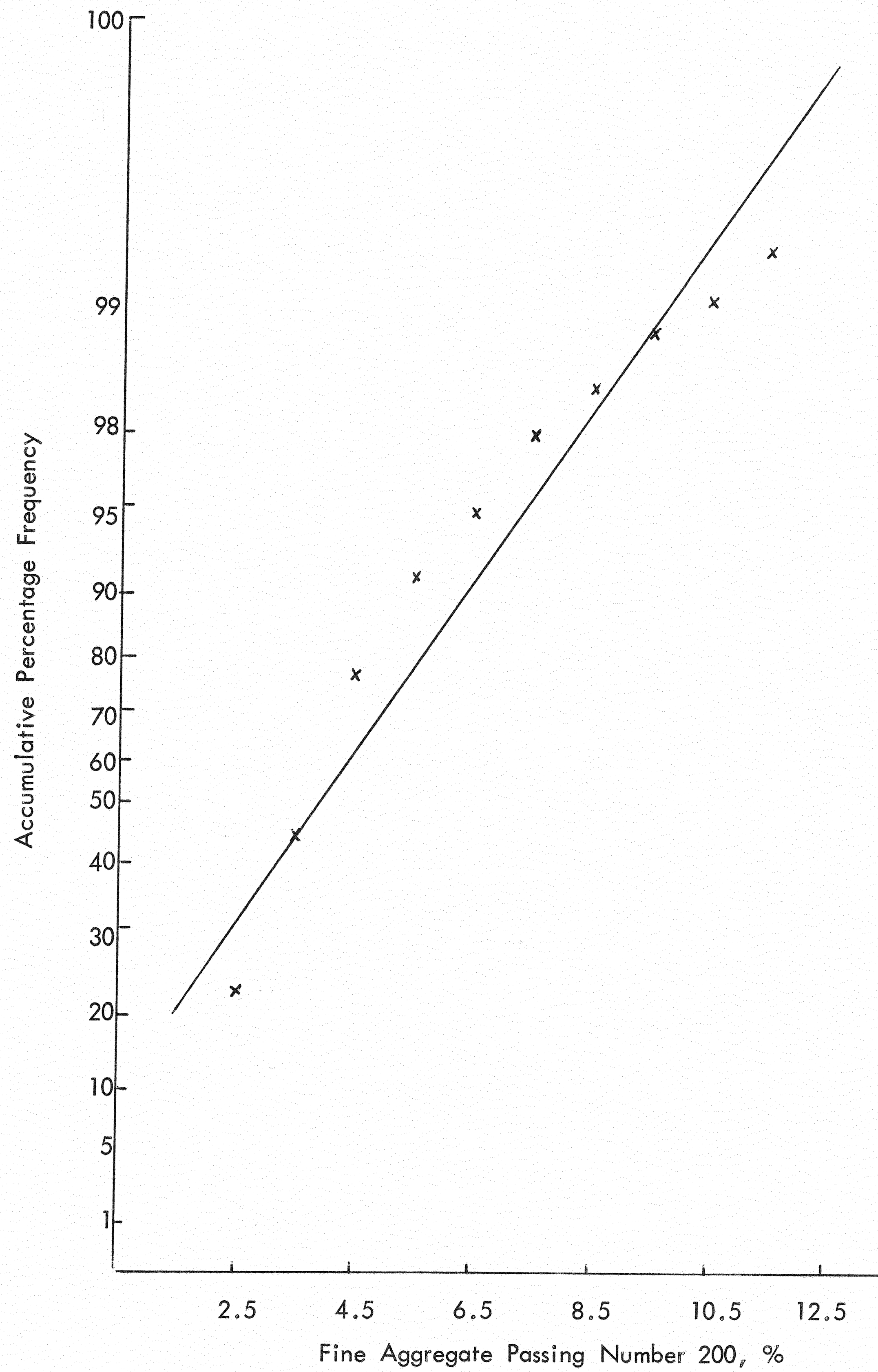


Figure III-123. % Passing No. 200 F.A. - goodness of fit curve

No.	Sand Equivalent Range %	f	%	Cum%
1	60 - 65	21	10.5	10.5
2	65 - 70	22	11	21.5
3	70 - 75	52	26	47.5
4	75 - 80	91	45.5	93.0
5	80 - 85	14	7	100.0
		200	100	

n	200
specs	--
$\bar{x}$	72.9
σ_T	11.7
σ_t^2	6.05
σ_s^2	1.57
σ_a^2	129.9
V	16.1%

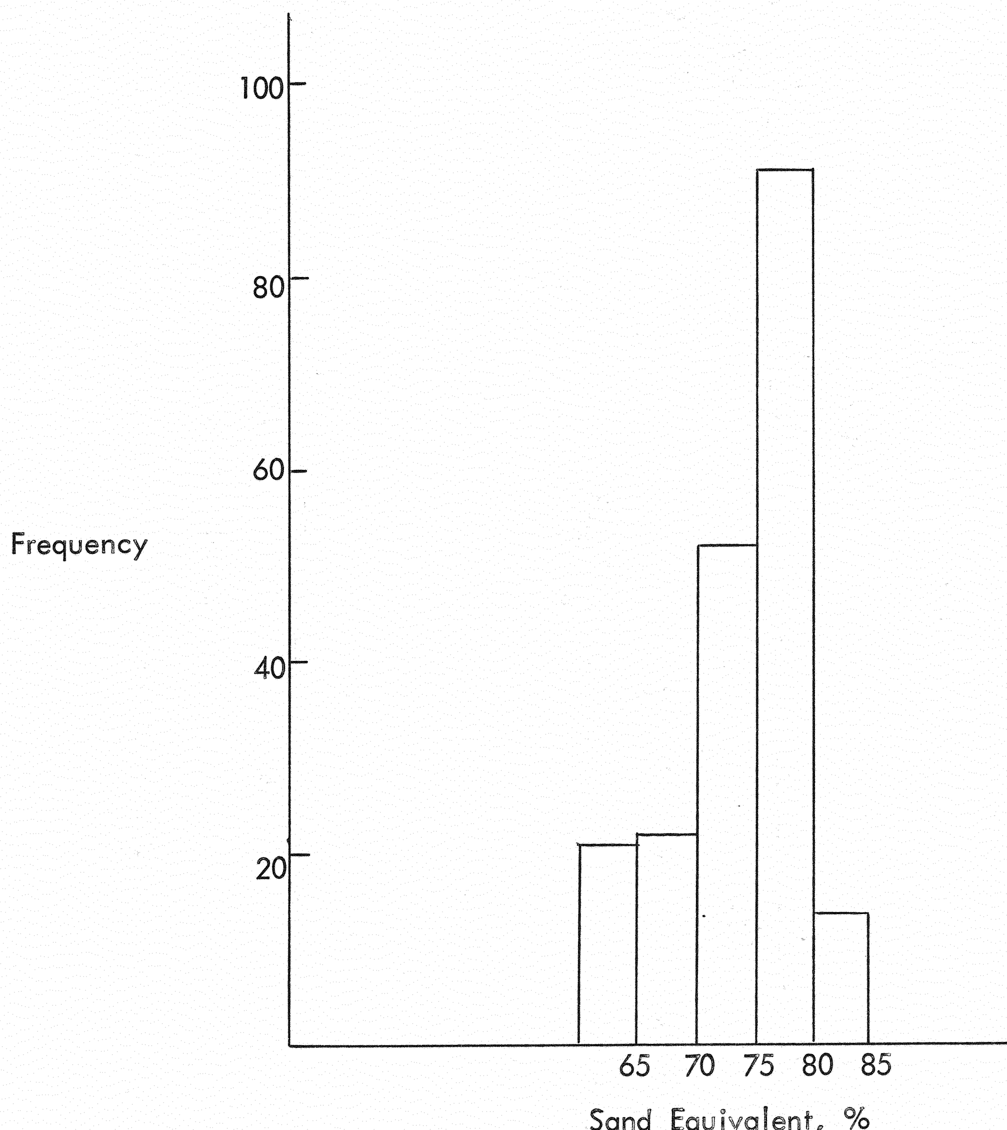


Figure III-124. Sand Equivalent - statistical properties

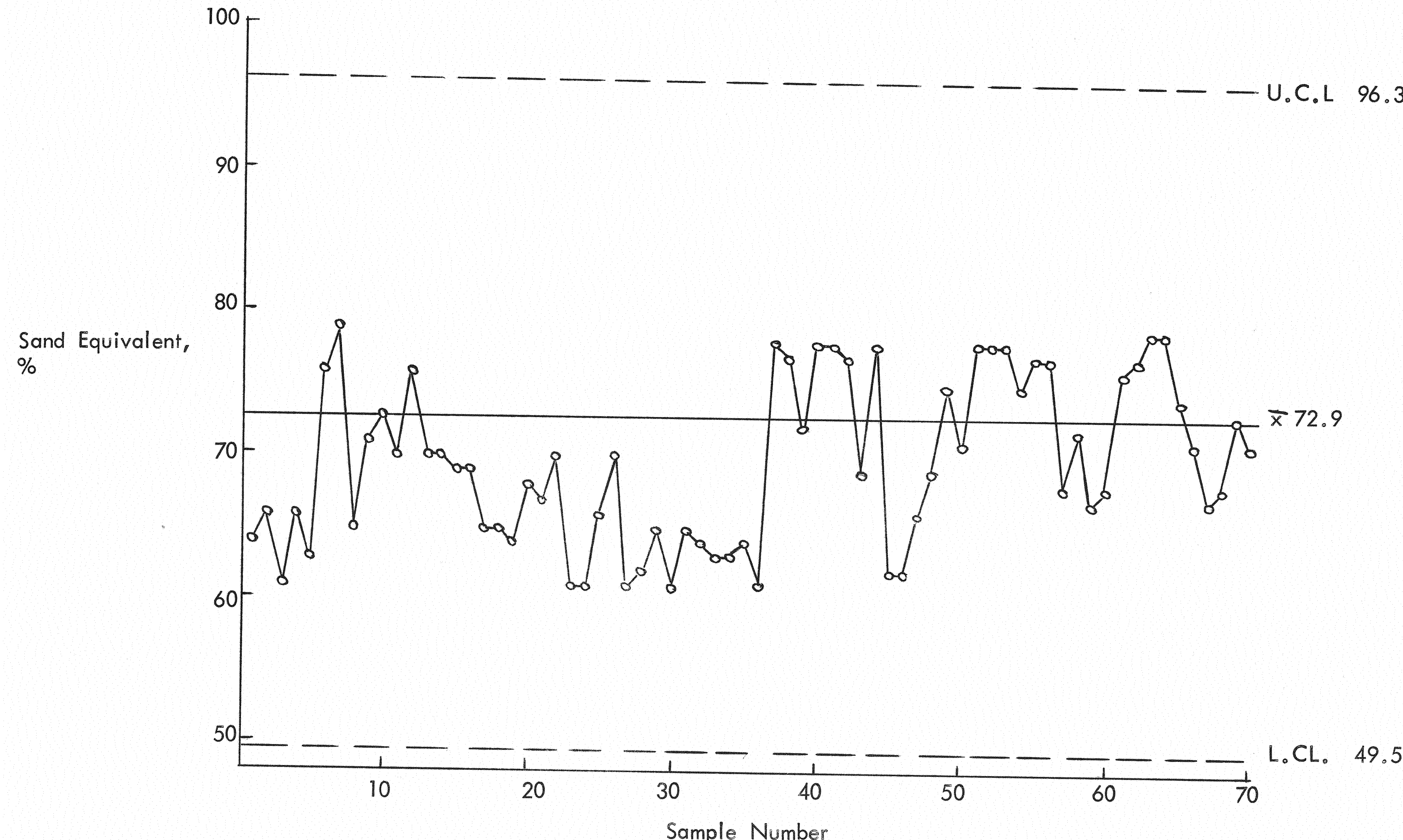


Figure III-125. Sand Equivalent - quality control chart

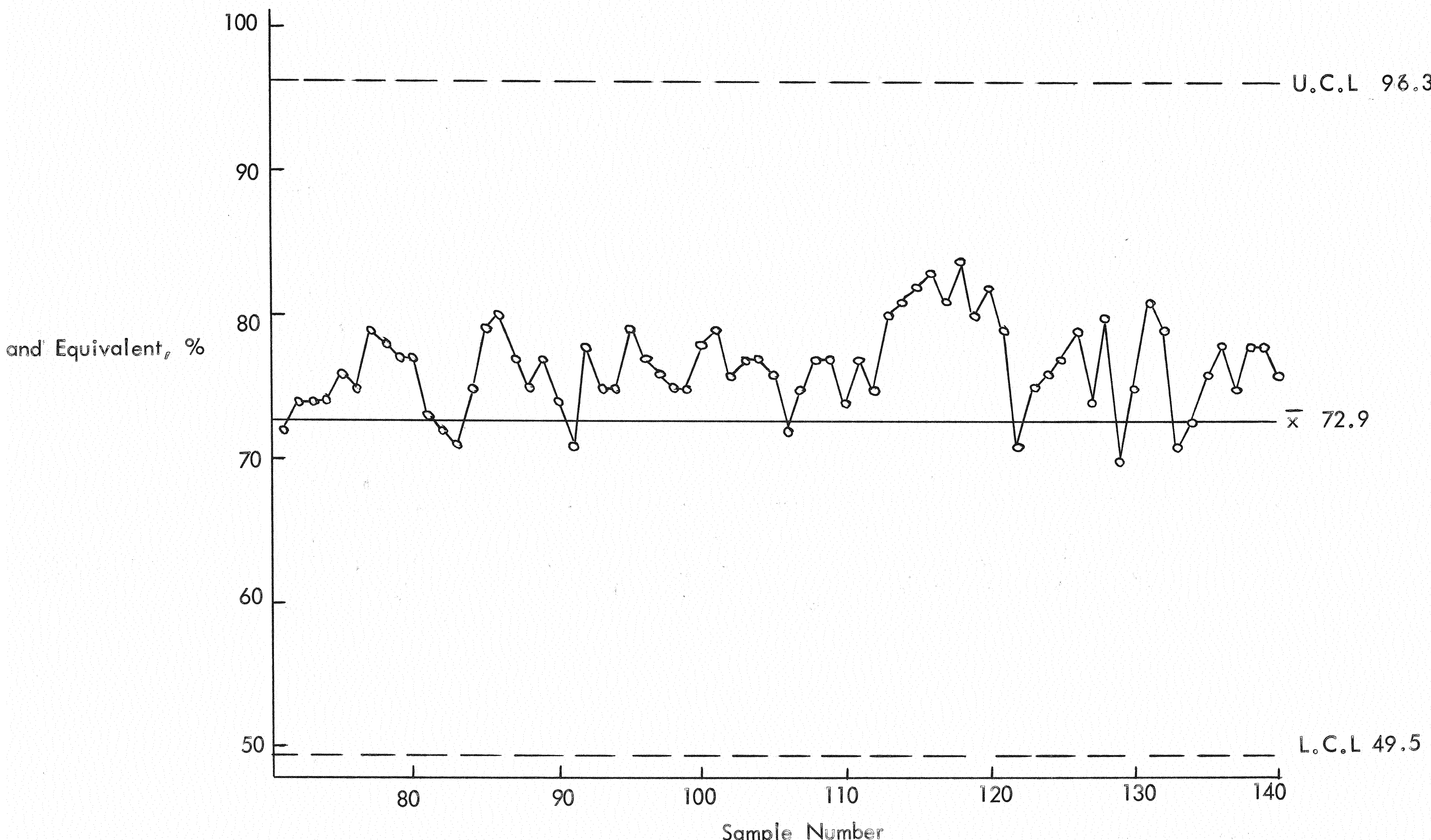


Figure III-125(cont.) Sand Equivalent - quality control chart

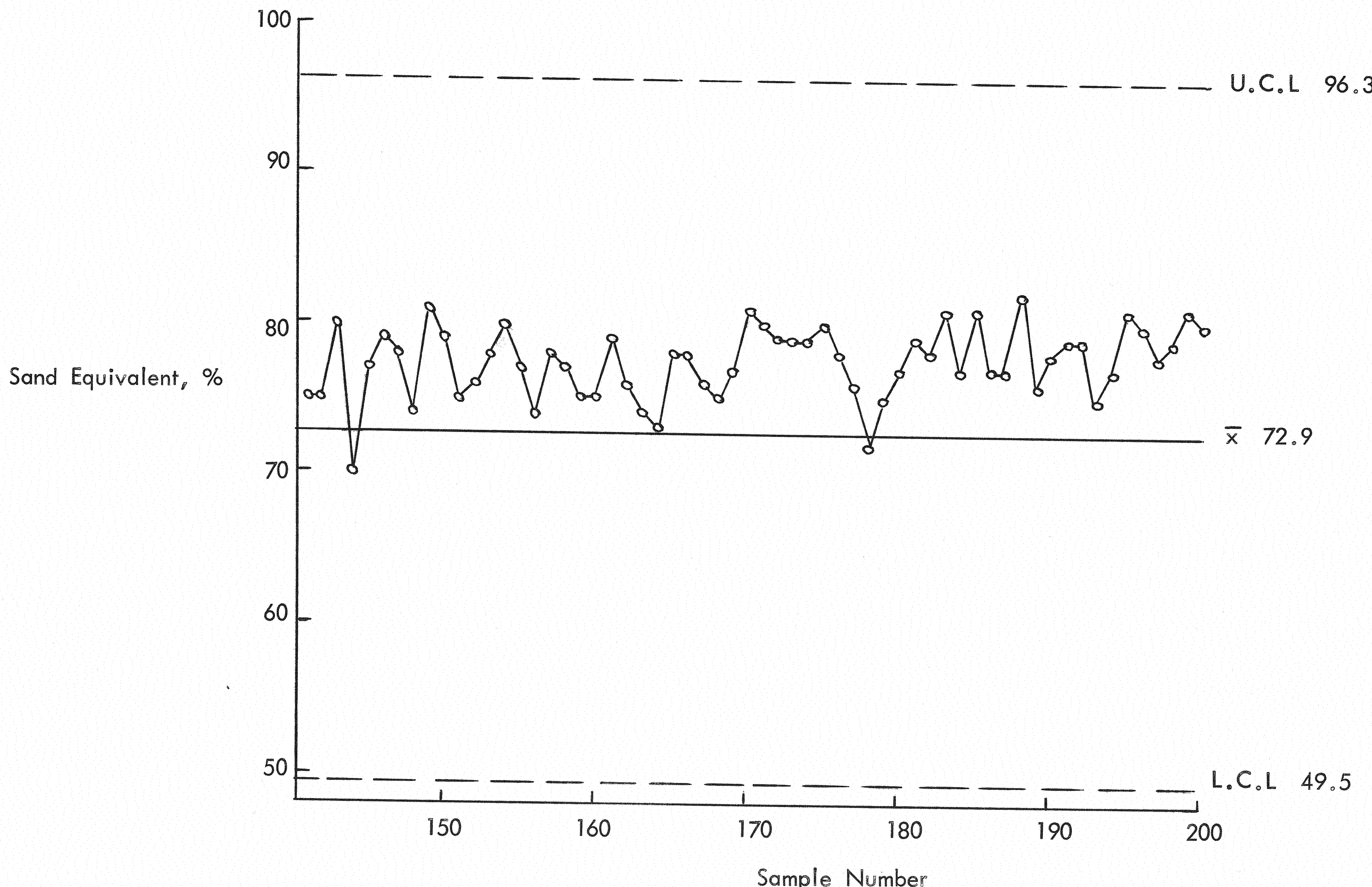


Figure III-125(cont.) Sand Equivalent - quality control chart

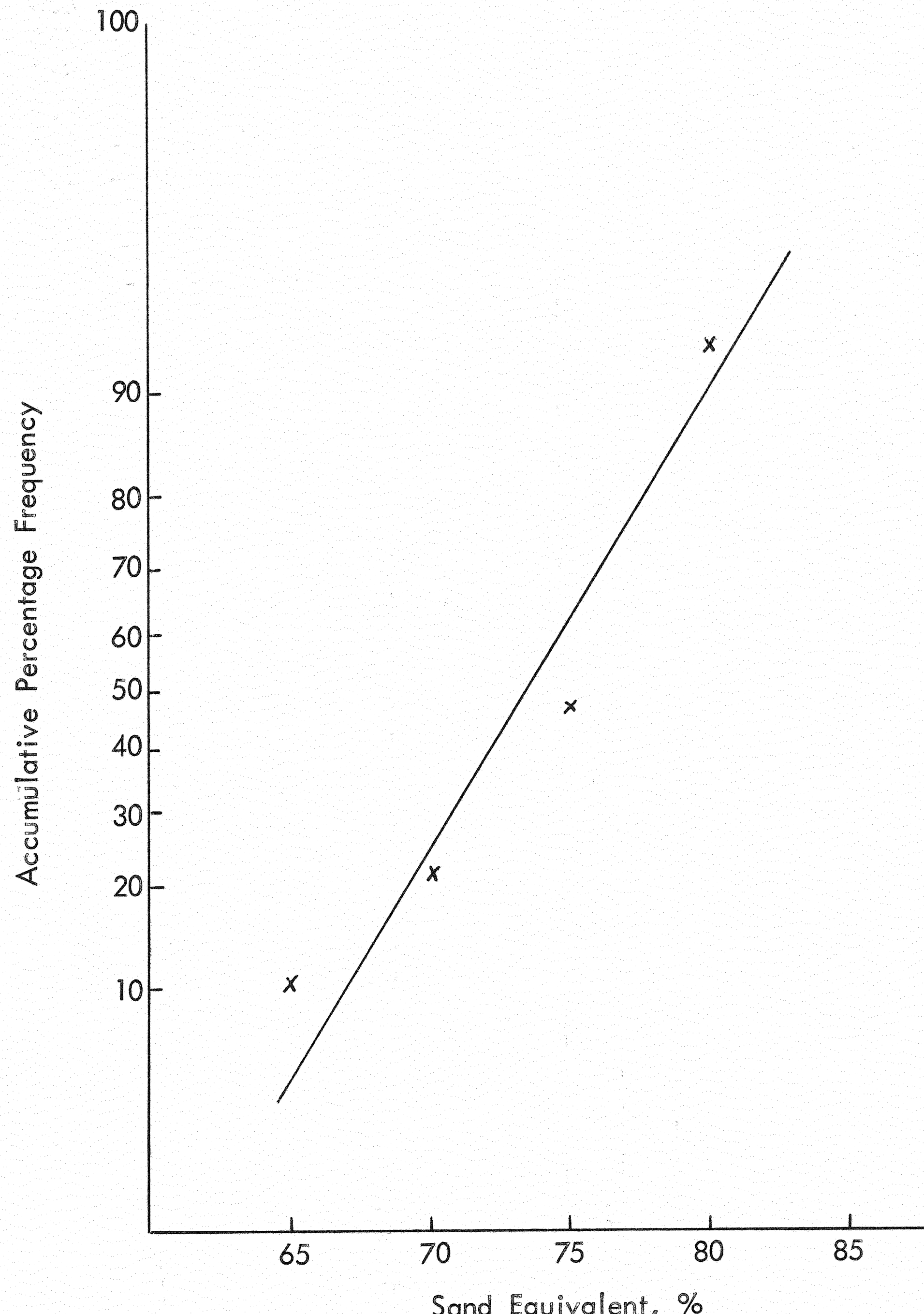
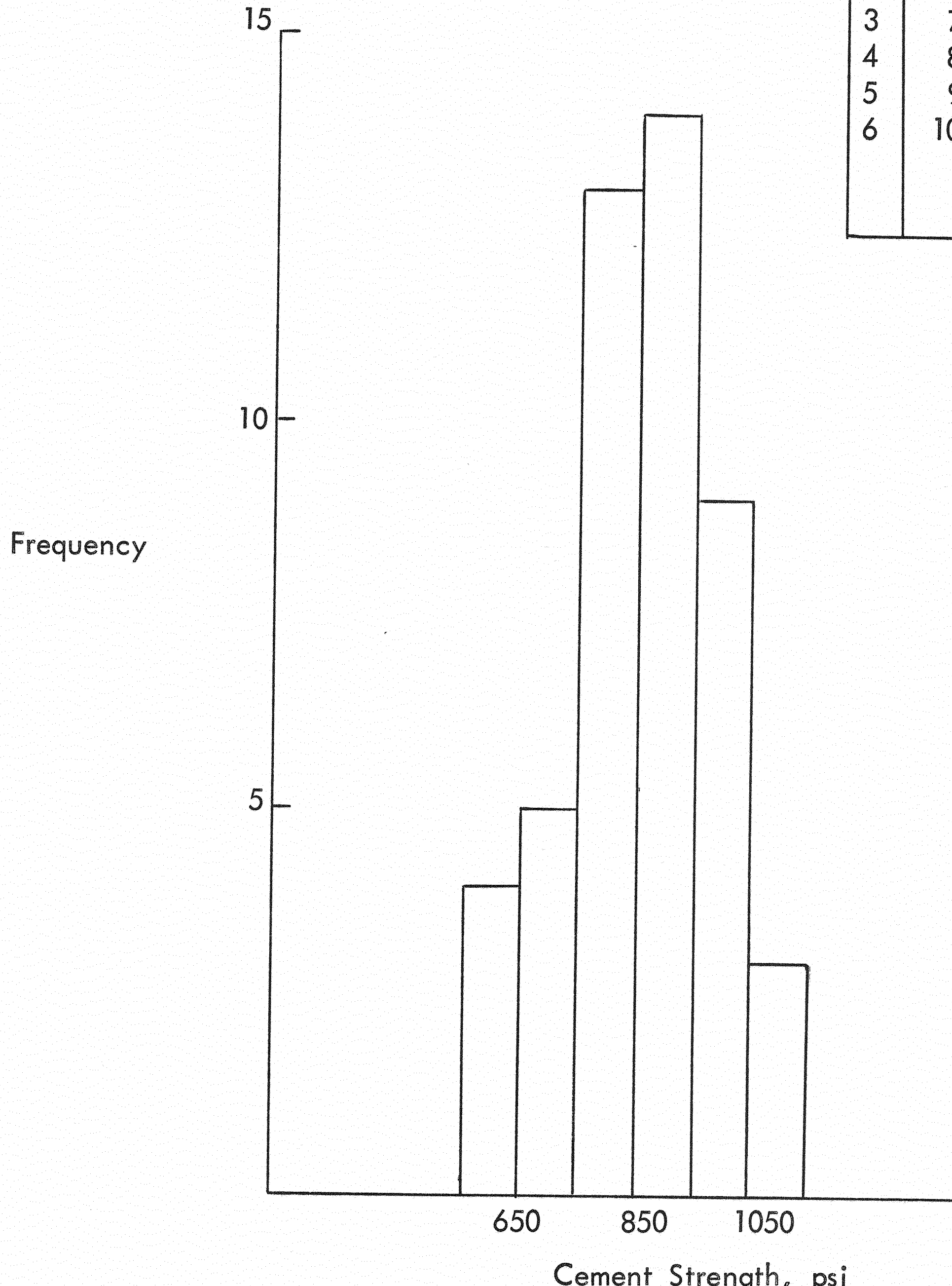


Figure III-126. Sand Equivalent - goodness of fit curve

No.	Cement Strength Range, Psi	f	%	Cum%
1	550 - 650	4	8.3	8.3
2	650 - 750	5	10.4	18.7
3	750 - 850	13	27.1	45.8
4	850 - 950	14	29.2	75.0
5	950 - 1050	9	18.7	93.7
6	1050 - 1150	3	6.3	100
		48	100	



n	48
specs	--
$\bar{x}$	859
σ_T	155
σ_t^2	19590
σ_s^2	0
σ_a^2	4506
V	18.0%

Figure III-127. Cement Strength - statistical properties

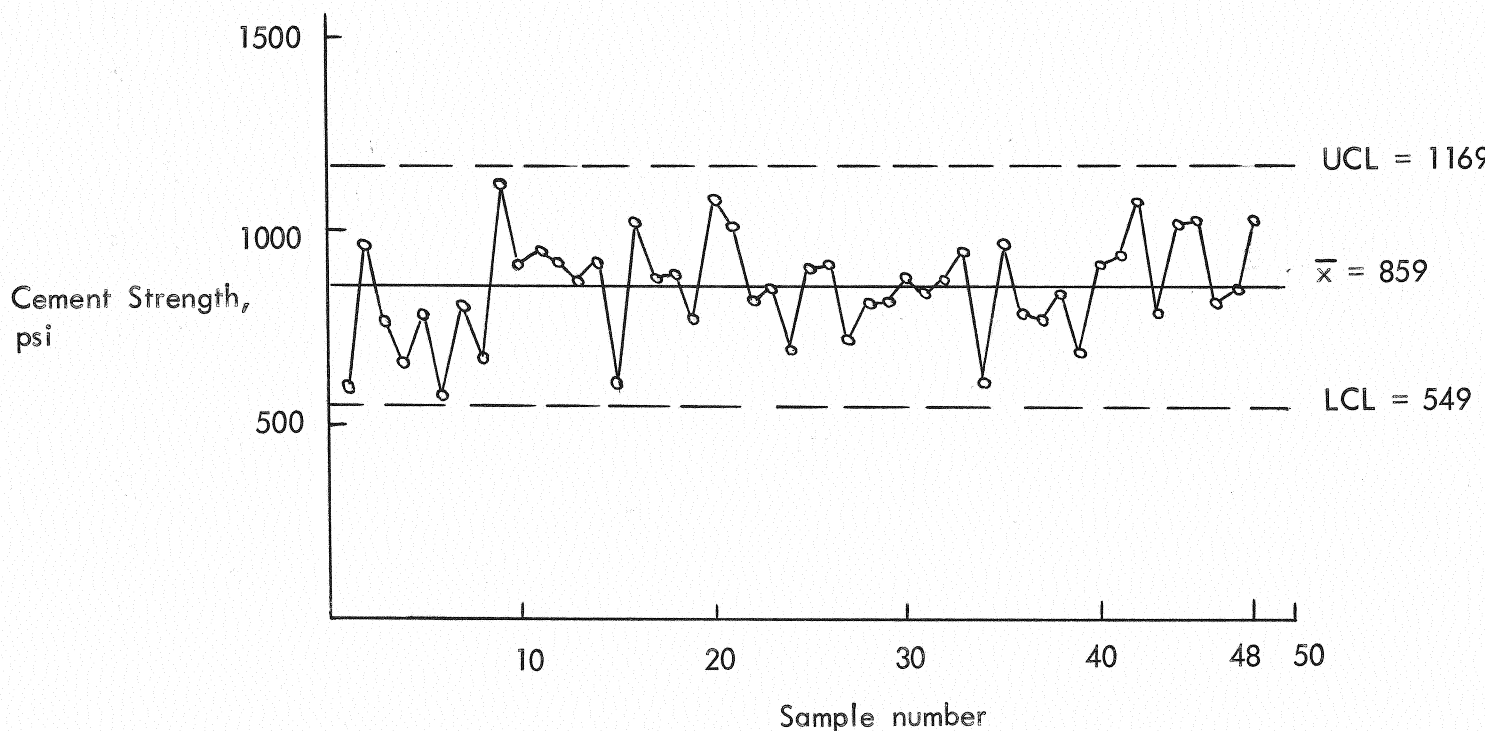


Figure III-128. Cement Strength - quality control chart

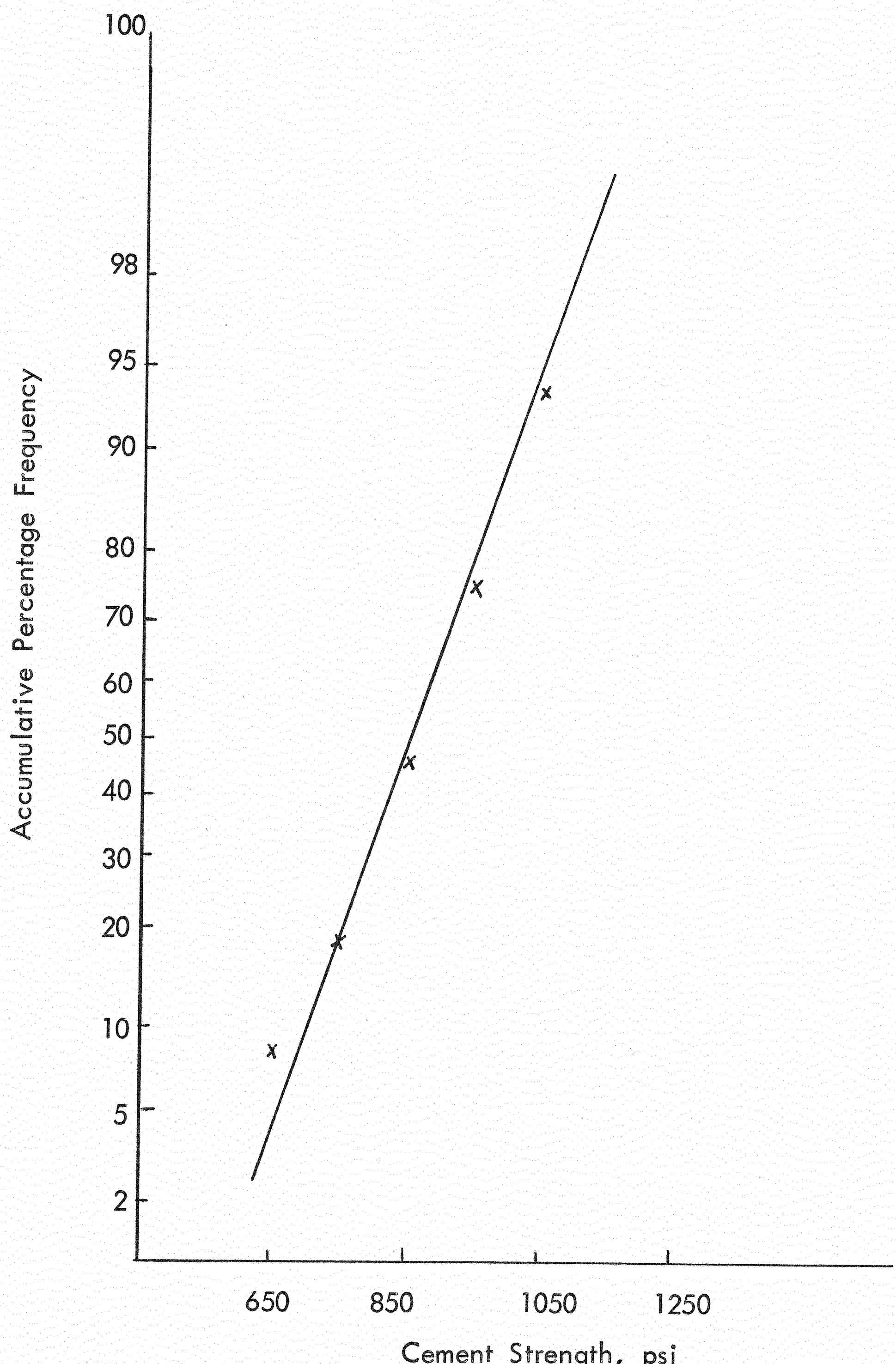


Figure III-129. Cement strength - goodness of fit curve

No.	Cement Air Content Range, %	f	%	Cum%
1	3.90 - 4.20	1	2.1	2.1
2	4.20 - 4.50	2	4.2	6.3
3	4.50 - 4.80	6	12.5	18.8
4	4.80 - 5.10	16	33.3	52.1
5	5.10 - 5.40	17	35.4	87.5
6	5.40 - 5.70	6	12.5	100
		48	100	

n	48
specs	--
$\bar{x}$	5.1
σ_T	0.3
σ_t^2	0.1
σ_s^2	0.001
σ_a^2	0.002
V	5.9%

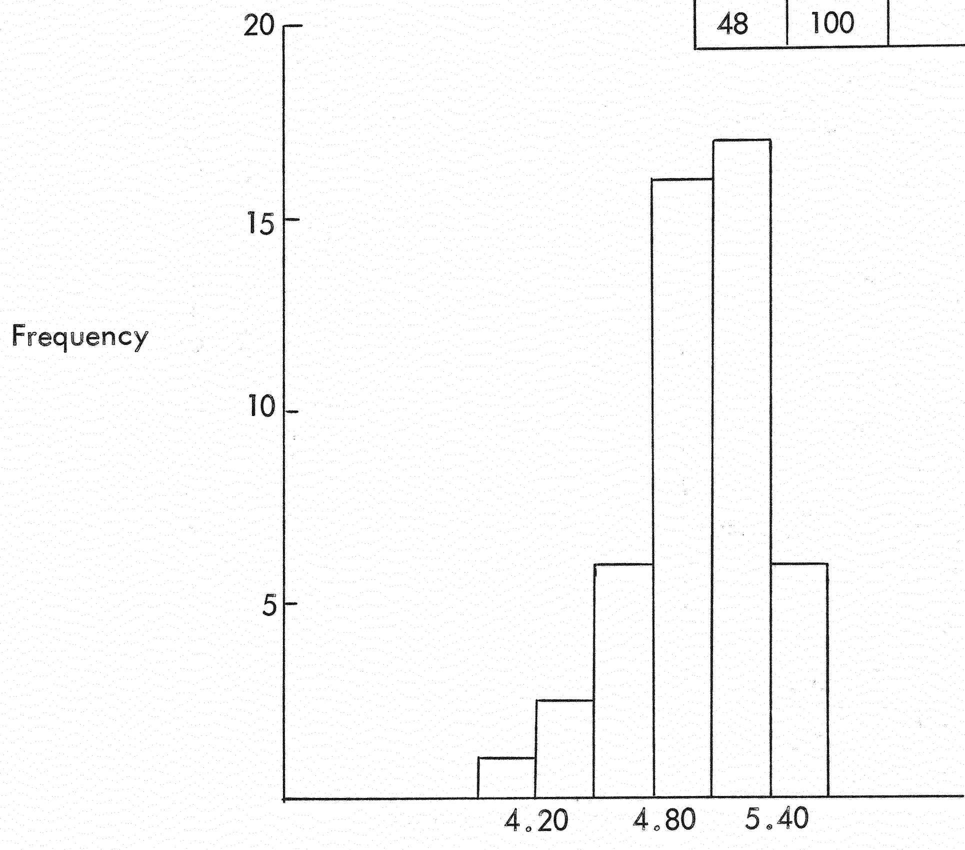


Figure III-130. Cement Air Content - statistical properties

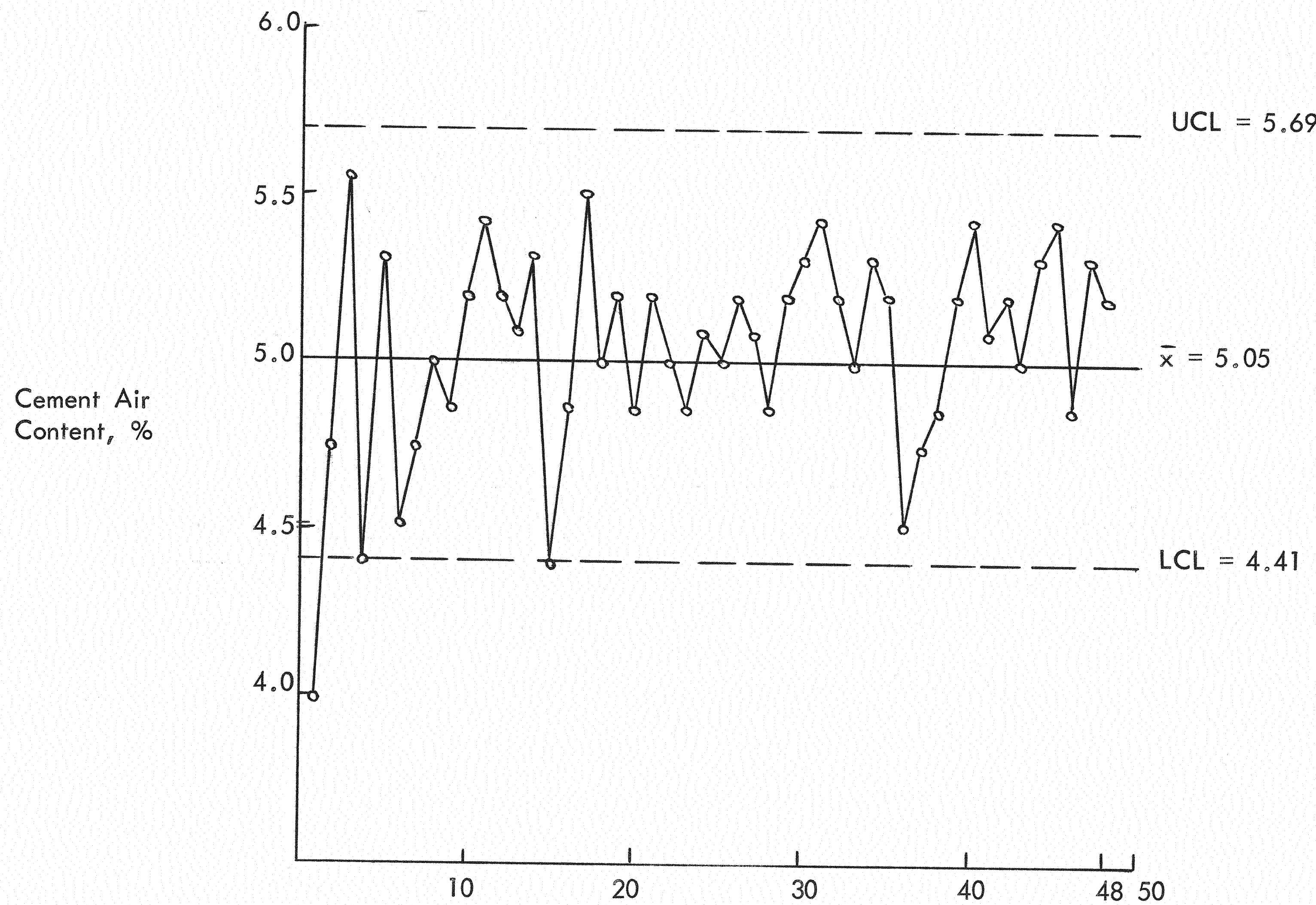


Figure III-131. Cement Air Content - quality control chart

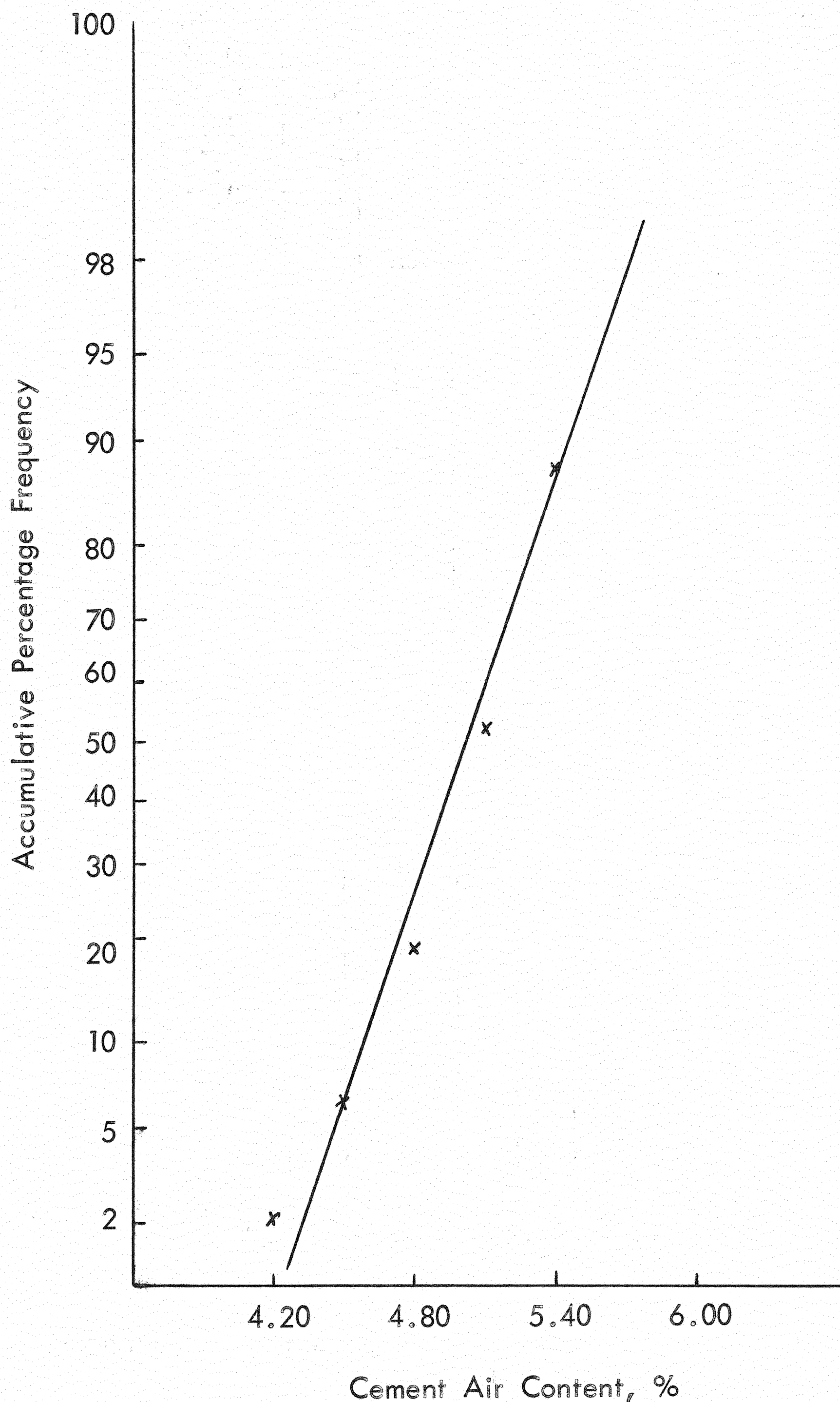


Figure III-132. Cement Air Content - goodness of fit curve

No.	Alkali Content Range, %	f	%	Cum%
1	0.14 - 0.16	2	4.2	4.2
2	0.16 - 0.18	--	0	4.2
3	0.18 - 0.20	3	6.3	10.5
4	0.20 - 0.22	7	14.6	25.1
5	0.22 - 0.24	25	52.0	77.1
6	0.24 - 0.26	9	18.7	95.8
7	0.26 - 0.28	2	4.2	100.0
		48	100	

n	48
specs	--
$\bar{x}$	0.22
σ_T	.03
σ_t^2	0.004
σ_s^2	0.0
σ_a^2	0.0002
V	13.6%

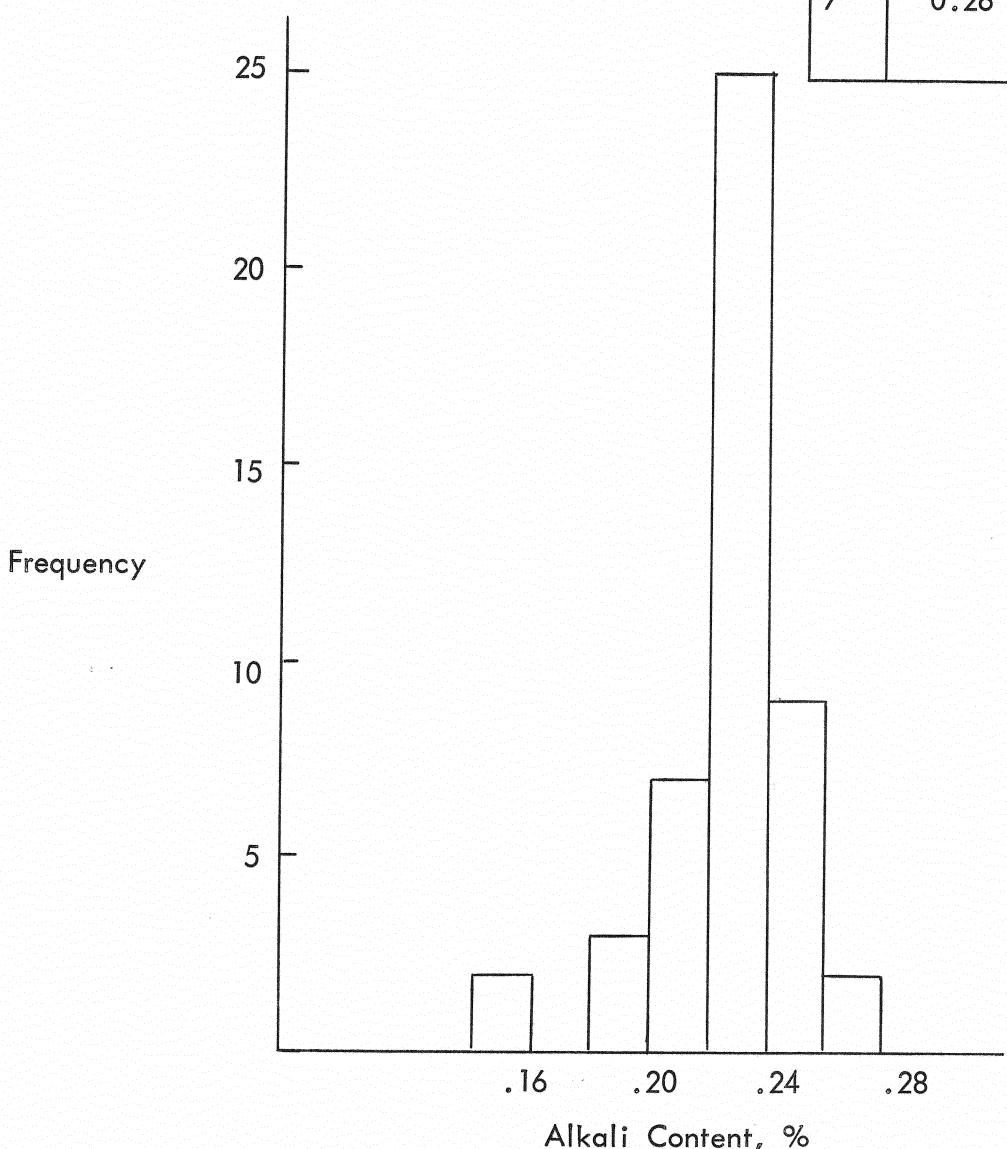


Figure III-133. Alkali Content - statistical properties

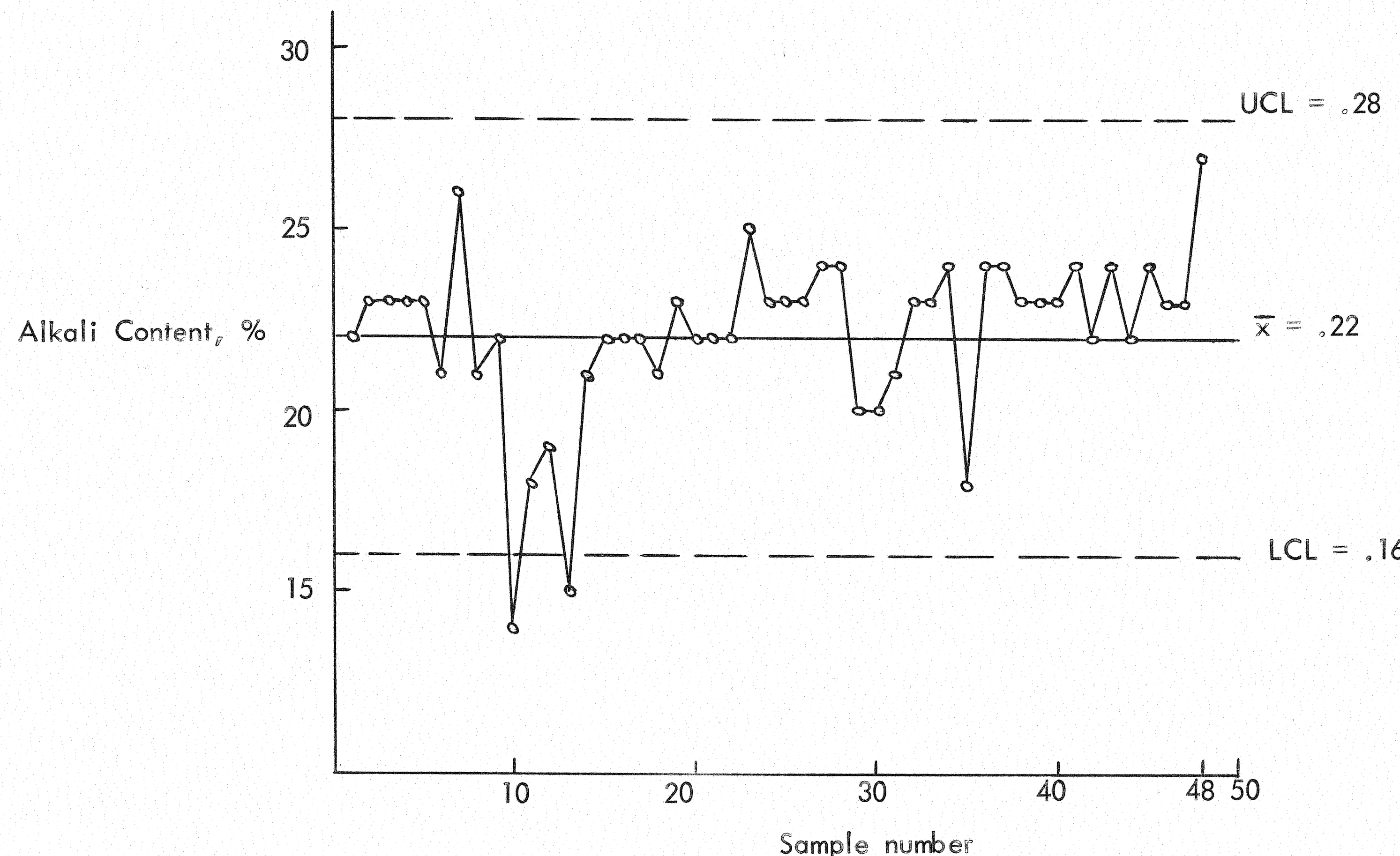


Figure III-134. Alkali Content - quality control chart

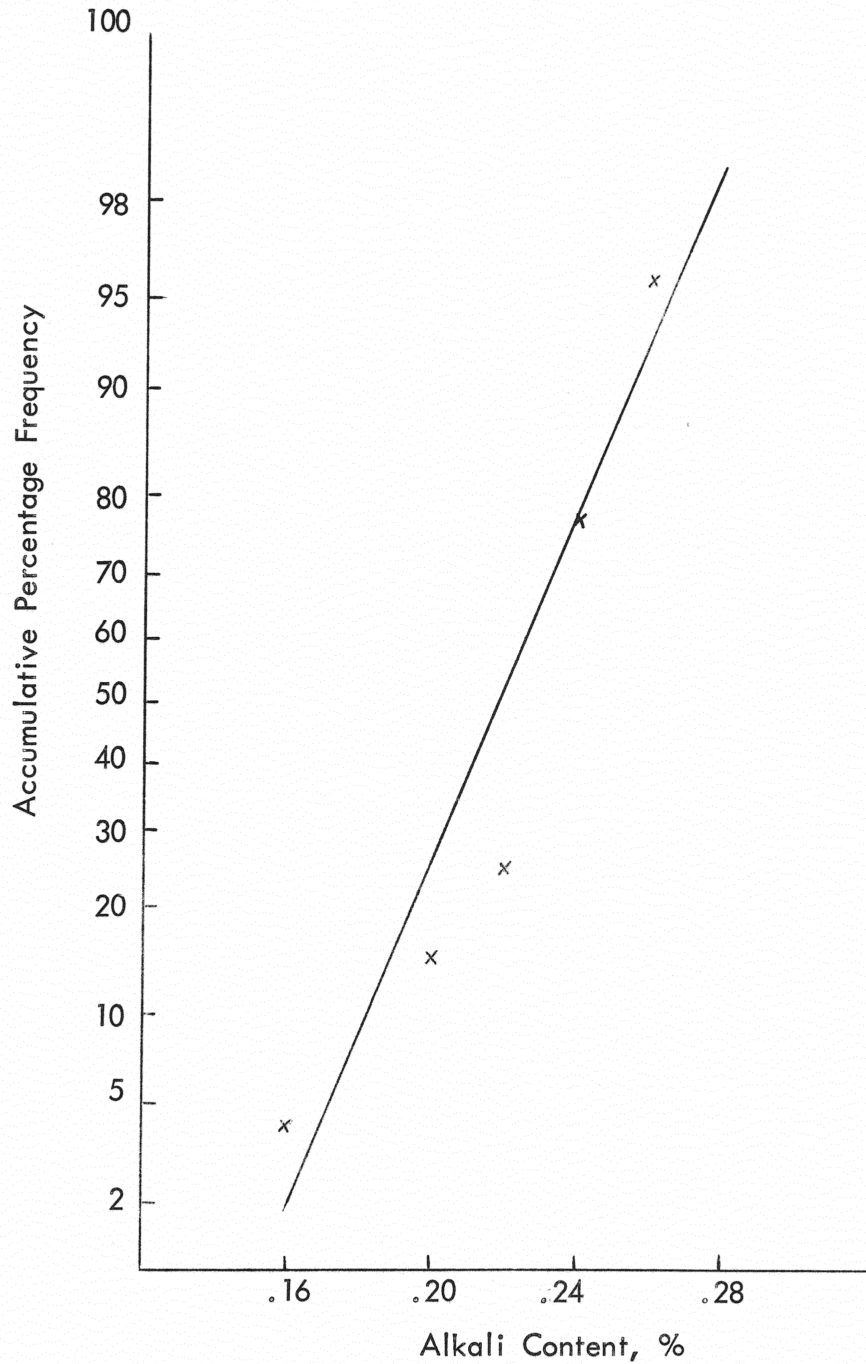


Figure III-135. Alkali Content - goodness of fit curve

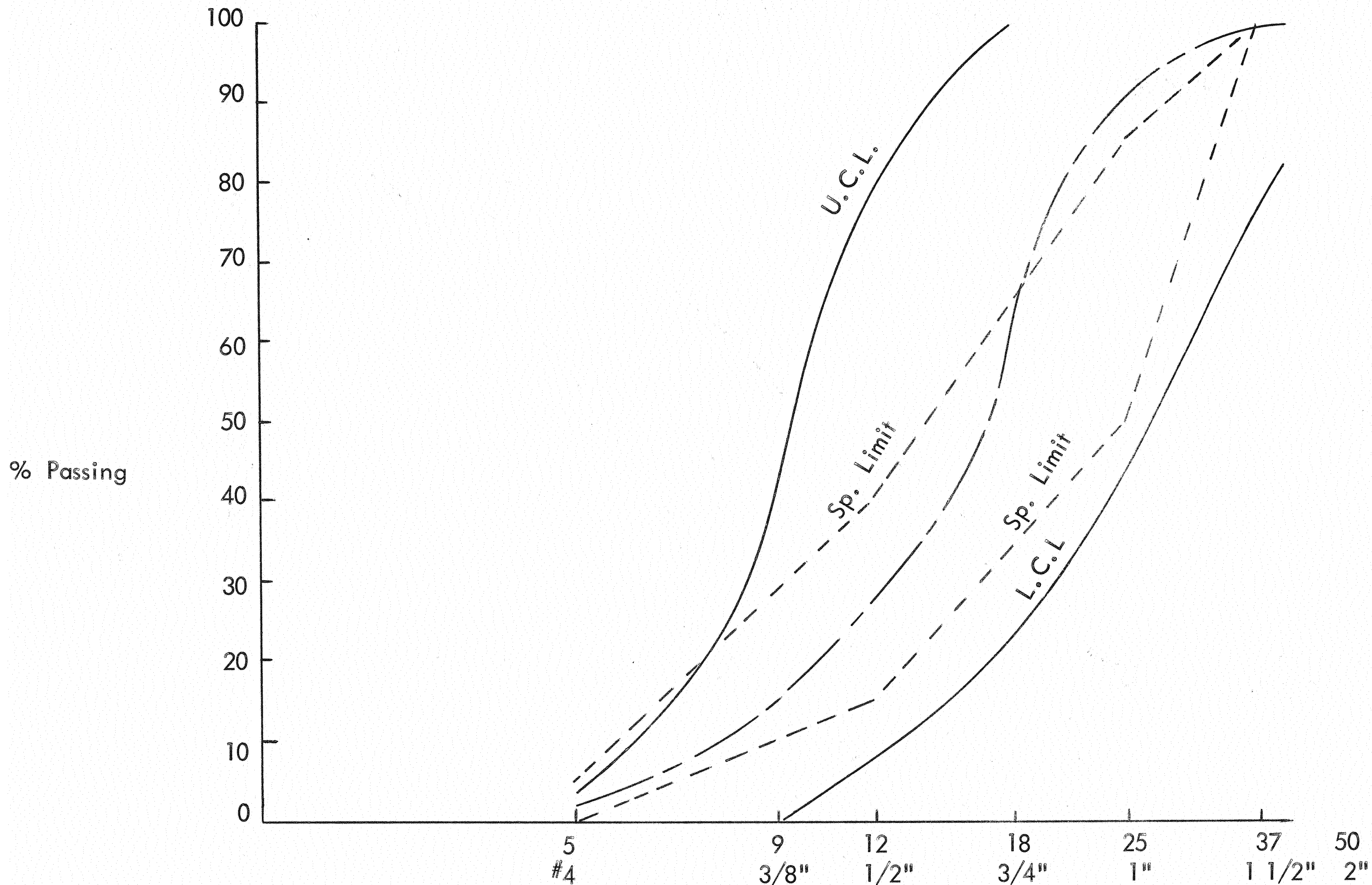


Figure III-136. Gradation Analysis for Coarse Aggregate

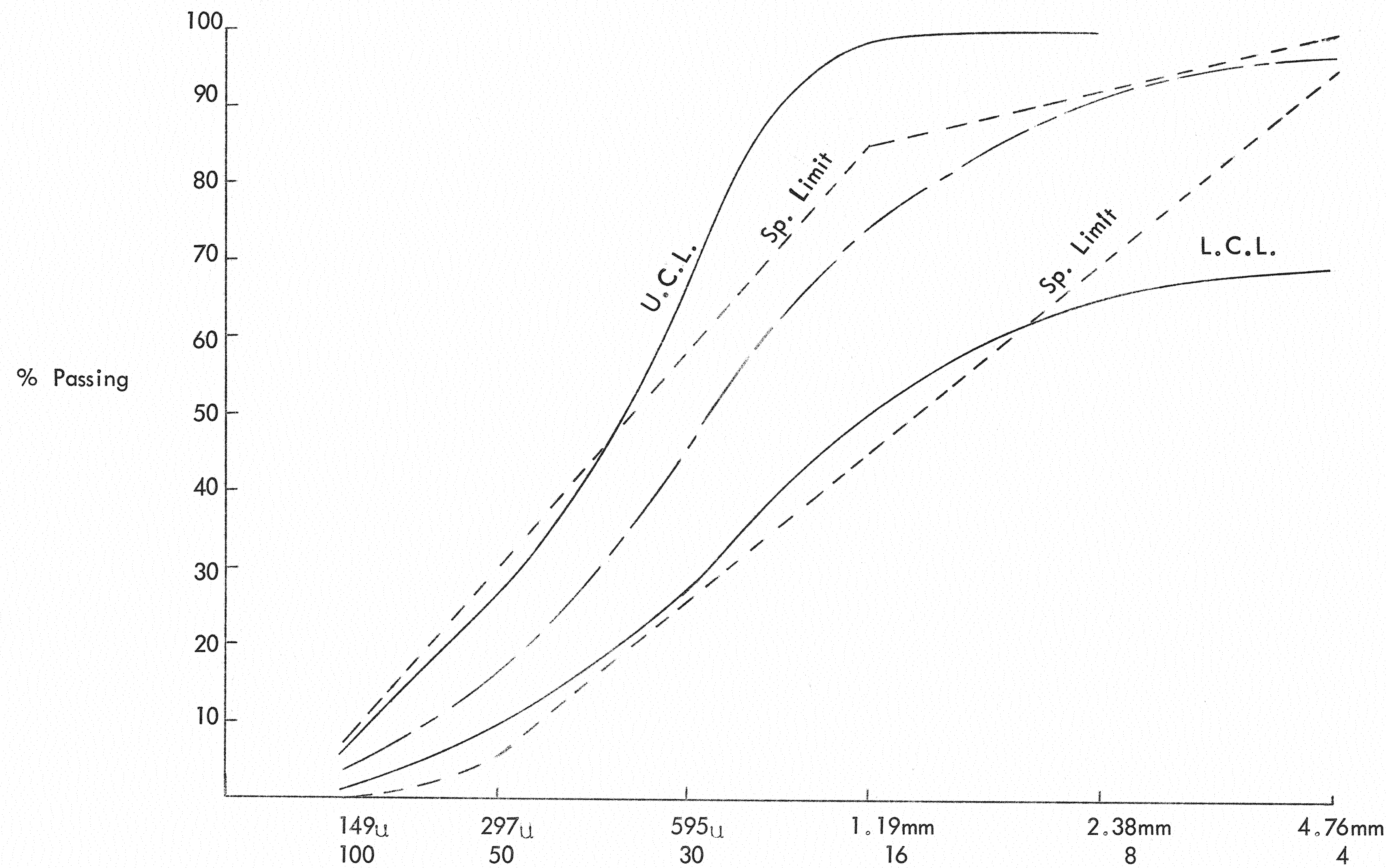
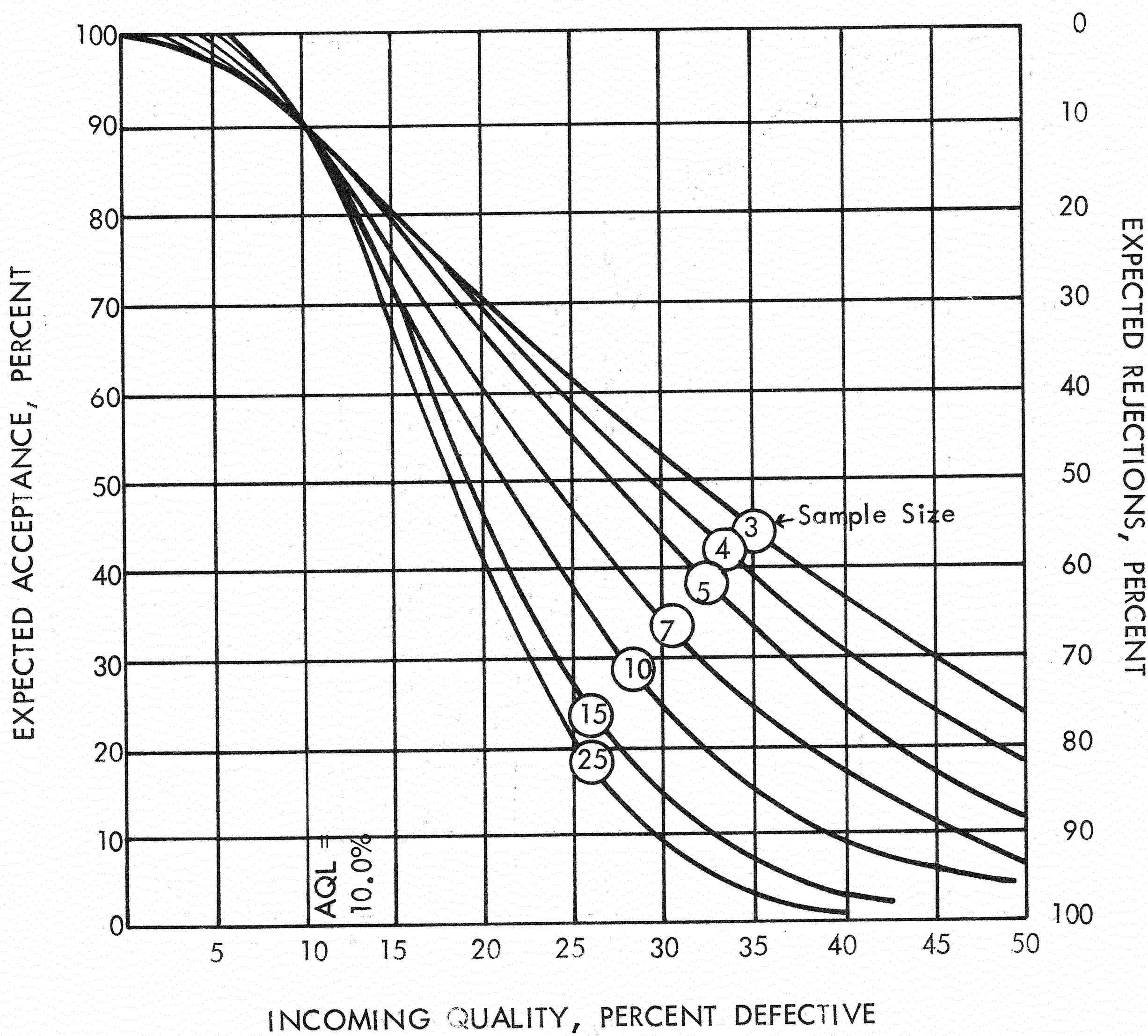


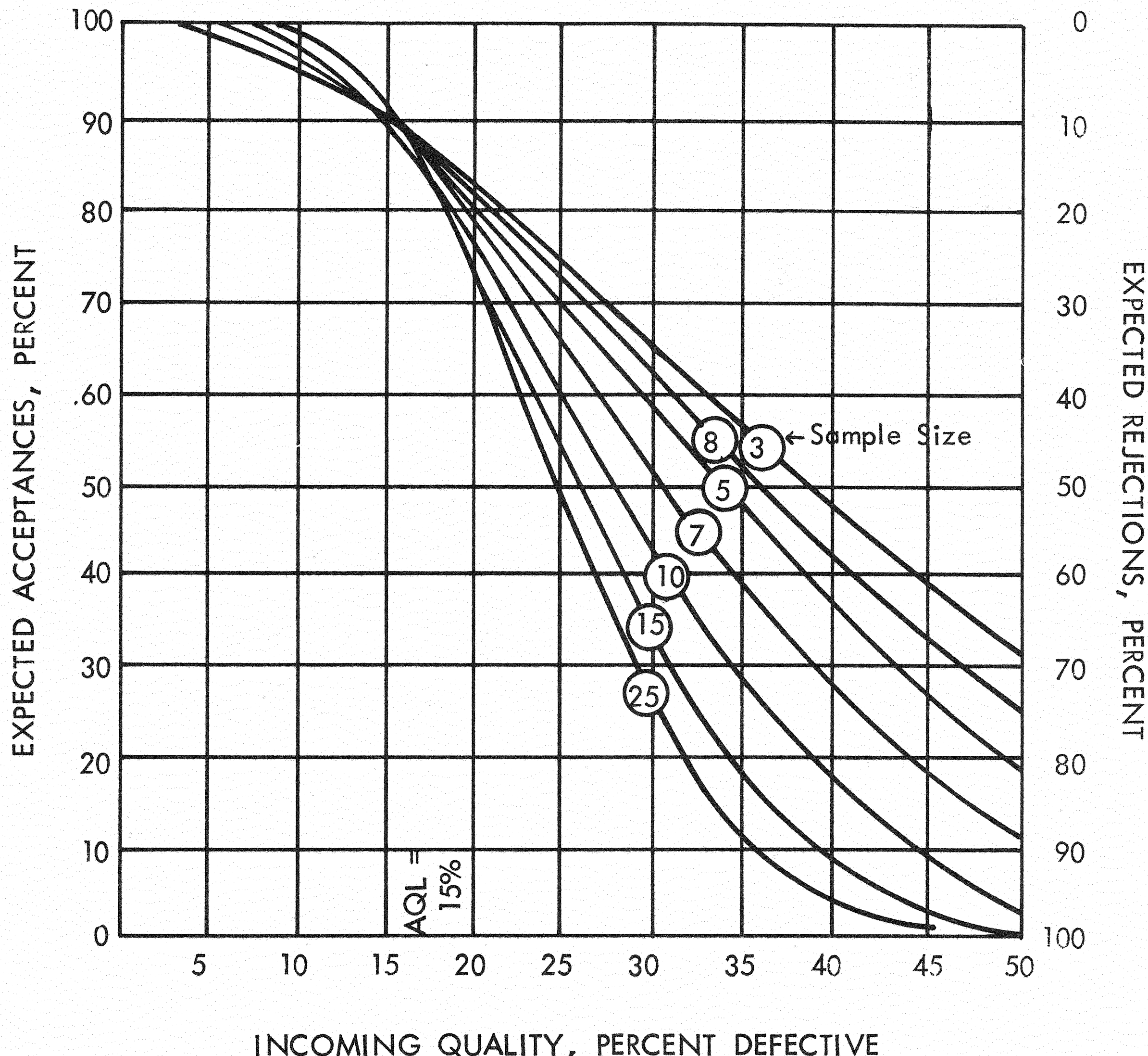
Figure III-137. Gradation analysis of fine aggregate

APPENDIX E

Operation Characteristics - 10 Percent and
15 Percent Defective Materials



Operating Characteristic (O.C.) Curves for AQL of 10%



Operating Characteristic (O.C.) Curves
for AQL of 15%

APPENDIX F

Acceptability Constants

ACCEPTABILITY CONSTANTS, "k", FOR ACCEPTANCE SAMPLING BY VARIABLES, INVOLVING SINGLE SPECIFICATION LIMITS, SELECTED ACCEPTABLE QUALITY (AQL) IN PERCENT DEFECTIVE AND SAMPLE SIZES, "n"

(Based on Sample Standard Deviation and Average)

Sample Size, n	Acceptable Quality Levels (AQL) in Percent Defective							
	0.10	0.65	1.00	2.50	4.00	6.50	10.00	15.00
3				1.12	.958	.765	.566	.341
4			1.45	1.17	1.01	.814	.617	.393
5		1.65	1.53	1.24	1.07	.874	.675	.455
7		1.75	1.62	1.33	1.15	.955	.755	.536
10		1.84	1.72	1.41	1.23	1.03	.828	.611
15	2.42	1.91	1.79	1.47	1.30	1.09	.886	.664
20	2.47	1.96	1.82	1.51	1.33	1.12	.917	.695
25	2.50	1.98	1.85	1.53	1.35	1.14	.936	.712

Notes: Arrows indicate that for low AQL's higher sample sizes and k-values are needed.

Acceptability Constants, k, must be equaled or exceeded by the Acceptability Ratio, Q_L or Q_U, for the sampled lot to be considered acceptable by the sampling plan.

Acceptability Ratio is determined from Upper or Lower Specification Limit, U or L, sample average, X, and sample Standard Deviation, S, using; $Q_U = (U-\overline{X})/S$, and $Q_L = (\overline{X}-L)/S$.

APPENDIX G

Pictorial Representations of Some Field Phases

Sampling of Coarse Aggregates in the Plant

The Cement Truck from Where Cement was Sampled

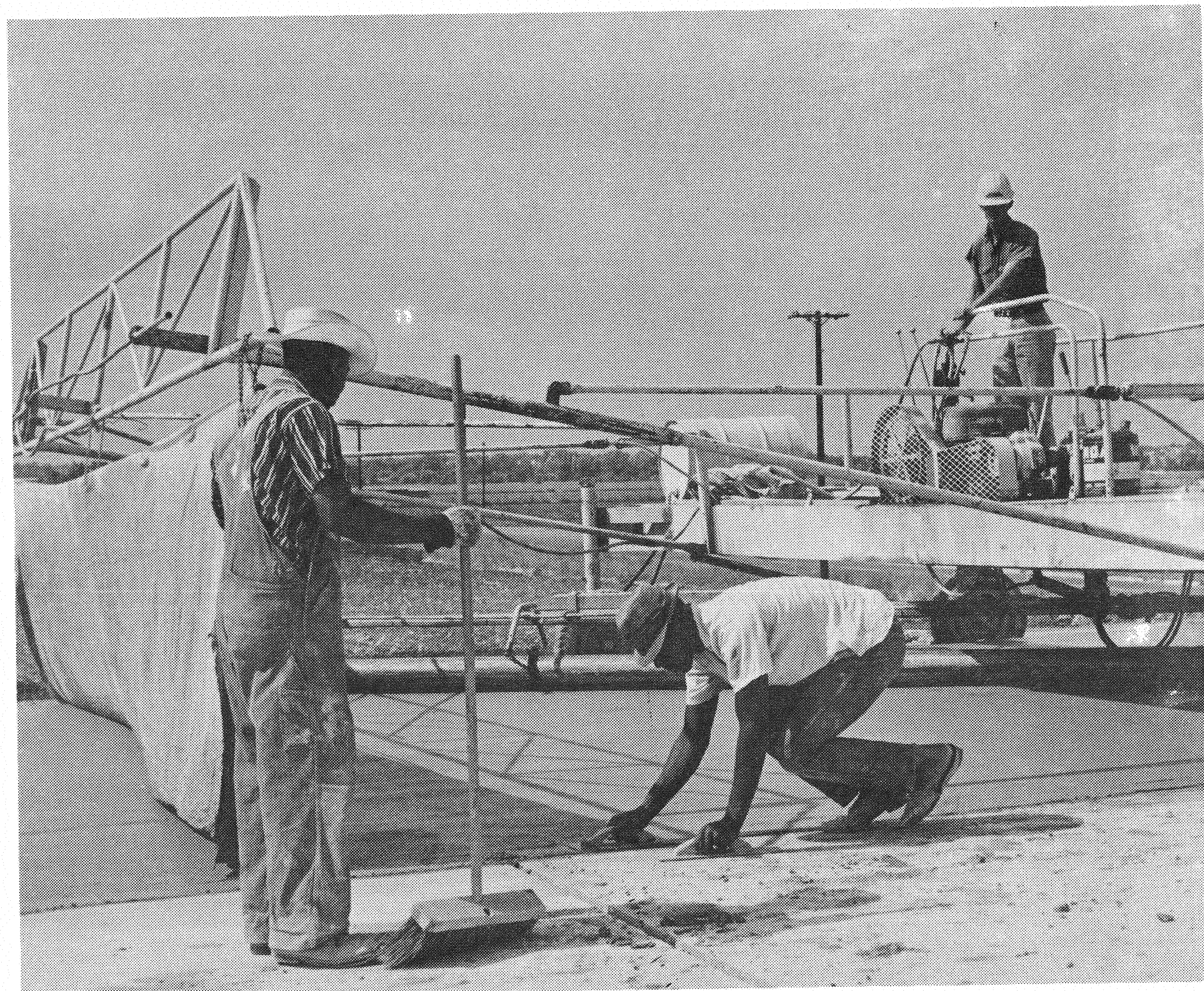
The Aggregate is Proportioned, Mixed, and Put into the Drum Truck
The Cement is Pumped into the Drum Truck

Concrete is Placed on the Base

Sampling Plastic Concrete for Slump, Air Content, and Cylinder Strength

The Slump Test

Testing for Air Content of Concrete in the Field



Finishing the Concrete Pavement

Measurement of Pavement Thickness

Spreading the Curing Compound on the Finished Concrete Pavement