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Contents

Optimum Performance Under a Statistical Specification

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Statistical construction specifications are based on a desired end result and usually employ graduated pay schedules to award payment in proportion to the extent that the end result is achieved. Considerable latitude is given to the contractor in deciding how to best meet the requirements of the specification, and those contractors exercising good quality control can often realize economic benefits by working close to one of the specification limits. How close to this limit the target level should be set is a matter of strategy, and often an optimum strategy does exist. A procedure is presented for selecting the target level most satisfactory to both the consumer seeking a quality product and the producer anticipating a fair profit. An example is given by using a statistical specification for concrete compressive strength. The outcome reveals a previously unrecognized fact: A producer who bids on and produces a concrete that is exactly at the acceptable quality level can expect to suffer a financial loss. The desired profit is achieved by increasing the bid price and the target strength to optimum levels. Specifying agencies must consider the cost of this higher level of quality and, if necessary, modify their specifications accordingly.

Statistical specifications are based on a desired end result. A specification for concrete compressive strength, for example, might define the acceptable quality level (AQL) as a lot of concrete in which no more than 10 percent of the material is below design strength. When the acceptance procedure indicates that this requirement has been met, the lot of concrete is eligible for 100 percent payment. If the tests indicate that more than 10 percent of the lot is below design strength, a graduated pay schedule as shown below is used to determine the appropriate reduced pay factor for the lot. The philosophy of this approach has been explained in several recent publications (1-3).

A typical graduated pay schedule is shown in the table. Material at or above the AQL receives a pay factor of 100 percent whereas seriously deficient material (rejectable quality level or RQL) receives only 50 percent payment. Most agencies reserve the option to require removal and replacement of RQL material. An explanation of the development of acceptance procedures by which the quality of a product is estimated is available from various sources (4-6).

Quality Level	Percentage Below Design Strength	Pay Factor (%)
AQL	≤ 10	100
–	11-20	95
–	21-30	90
–	31-40	75
RQL	> 40	50

Because there is always some level of risk associated with a statistical acceptance procedure, AQL lots may occasionally receive less than 100 percent payment. However, as illustrated in a recent paper (7), the average pay factor for any large quantity of AQL lots will be very close to 100 percent.

An objection to this approach that is frequently raised by concrete producers concerns the manner in which these pay factors are applied. Most specifying agencies apply the pay factors to the in-place cost of construction items. When pay reductions occur, it apparently is customary for general contractors to pass these reductions back to the producer in their entirety, a necessity if the general contractor also happens to be the producer of the concrete. For example, if a producer quotes $\$39.24/\text{m}^3$ ($\$30/\text{yd}^3$) on concrete that becomes worth $\$261.60/\text{m}^3$ ($\$200/\text{yd}^3$) when placed in a structure, even a small pay reduction of only 5 percent would mean a loss to the producer of 5 percent of the in-place cost, or $\$13.08/\text{m}^3$ ($\$10/\text{yd}^3$), a very undesirable result from the producer's standpoint. However, it will be seen that the producer can effectively guard against this with the proper mix design and bidding strategy.

The importance of a producer's degree of quality control is illustrated in Figure 1. Assuming that a normal distribution adequately describes a population of concrete compressive strengths, producers with coefficients of variation (V) of 10 percent and 15 percent must achieve mean strengths of 23.7 MPa (3441 lbf/in^2) and 25.6 MPa (3714 lbf/in^2), respectively, to just meet the requirements of this specification (i.e., produce AQL concrete). Based on curves established by the Portland Cement Association (PCA) (8), this difference in mean strength of 1.9 MPa (273 lbf/in^2) corresponds to about 0.33 sack of cement/m^3 (0.25 sack/yd^3). At a cost of \$2/sack, this amounts to a savings of about $\$0.70/\text{m}^3$ ($\$0.50/\text{yd}^3$) realized by the producer with better quality control. When multiplied by the total production quantity for a project or a construction season, the substantial magnitude of this savings becomes apparent.

However, the question that must be addressed is this: Should either of these producers attempt to produce concrete that is exactly at the AQL or would it be better to aim for a somewhat higher (or lower) level?

Before analyzing this quantitatively, it might be instructive to consider the consequences of two extreme strategies. First, if the producer chooses to use a very low cement factor, he or she will save on the cost of cement; this, however, will lower the mean strength of the concrete to such an extent that the resulting pay reductions will more than offset these savings. In the other instance, if he or she uses too high a cement factor, the average pay factor will increase but not enough to make up for the extra cost. The fact that both strategies are unsatisfactory (at least from the producer's standpoint) suggests that somewhere between these two extremes an optimum level must exist. In this case it can be found relatively easily by using basic information available to most producers.

The technique requires that the operating characteristics of the acceptance procedure be known. Because one should develop these curves when writing a statistical specification, I believe that it is the specifying agency's obligation to furnish this information. Computer simulation (9) or analytical means (10) will provide several individual points for the upper portion of each operating-characteristic curve that is required. Smooth curves are then fitted through these points, preferably by regression analysis or other mathematical curve-fitting technique, so that an equation is obtained for each curve. Typical operating-characteristic curves are shown in Figure 2.

GENERAL OPTIMIZATION PROCEDURE

The basic procedure for determining the optimum target strength for concrete governed by a statistical specifica-

Figure 1. Mean strength required for AQL concrete for two quality control levels.

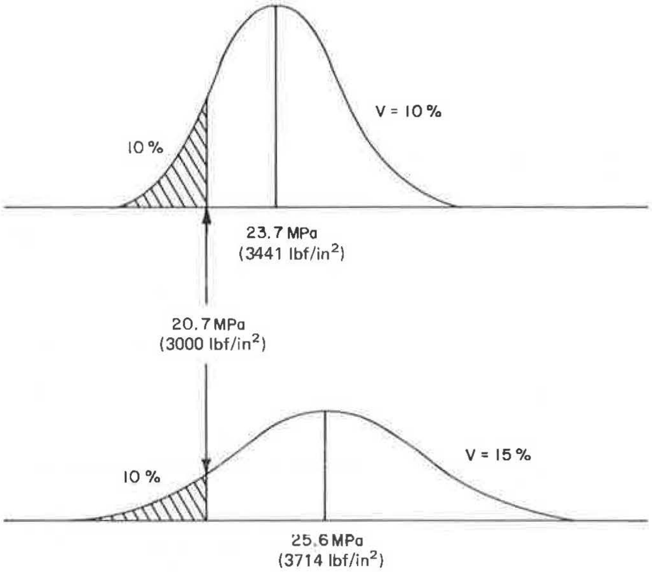


Figure 2. Typical operating-characteristic curves.

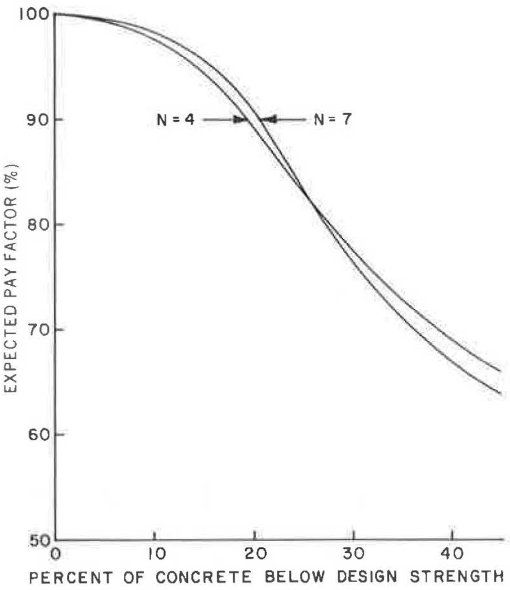
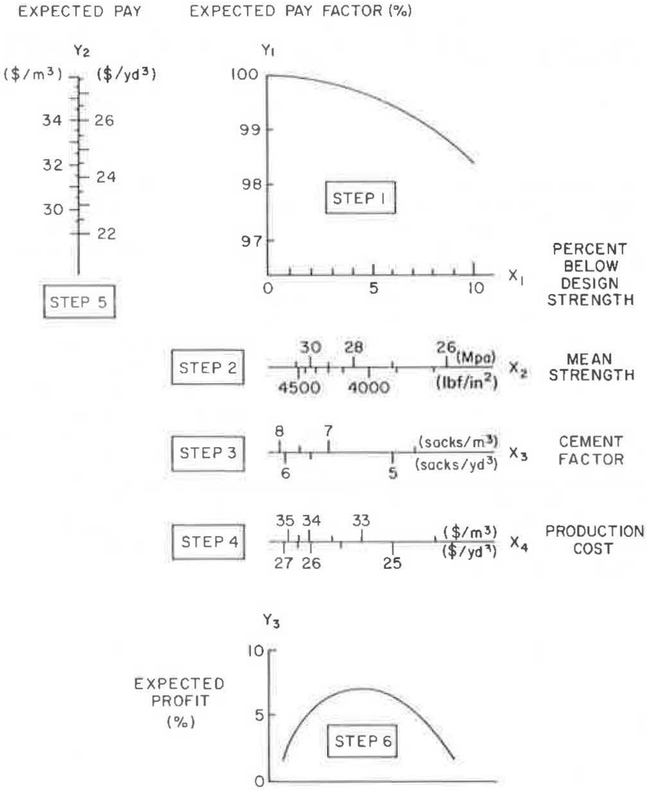


Figure 3. Diagram of optimization procedure.



tion follows the six steps illustrated in Figure 3 and listed below.

1. Plot the operating-characteristic curve for the sample size being used and the particular producer's coefficient of variation. (If the specification is of the variability-unknown type, sample size alone determines the curve.) The quality level (percentage of concrete below design strength) appears on axis X_1 and the corresponding expected pay factors are found on axis Y_1. This information would normally be obtained from the specifying agency.
2. Use a table of the standard normal distribution to transform axis X_1 into axis X_2, the mean strength of concrete necessary to produce the amount of defective material given on axis X_1.
3. Using production data available to most producers, transform axis X_2 into axis X_3, the cement factors required to produce the mean strengths given on axis X_2.
4. Basic cost data are then used to transform axis X_3 into axis X_4, production cost per unit quantity of concrete.
5. Axis Y_1 must then be transformed into axis Y_2, expected pay per unit quantity of concrete. This must be done in a realistic manner, which will usually mean that pay reductions (a) are based on the in-place bid price of a construction item and (b) are passed in their entirety back to the producer.
6. Because axes X_4 and Y_2 give production cost and expected pay for different quality levels, it is now a simple matter to plot several points to determine which quality level yields the greatest expected profit on axis Y_3. The corresponding target strength is then read from axis X_2.

BASIC INFORMATION REQUIRED

To illustrate the application of this procedure, the following basic information will be assumed.

The concrete design strength is 20.7 MPa (3000 lbf/in^2), and the coefficients of variation for the two producers in this example are 10 and 15 percent. The operating-characteristic curve relating expected pay factor to percentage of concrete below design strength is known, and production cost for a standard 7.85 sacks/m^3 (6.00 sacks/yd^3) mix is \$35.32/m^3 (\$27/yd^3). The change in production cost for other mixes will be based on a cement price of \$2/sack. The desired profit margin is 7 percent. Pay reductions, based on an in-place bid price for concrete construction of \$261.60/m^3 (\$200/yd^3), will be presumed to be passed back in their entirety to the producer of the concrete.

Most producers have data that would enable them to determine the cement factor necessary to achieve any specific level of mean strength. However, because this information is not readily available to me, the PCA curves referred to previously will be used for this step.

Although the optimization procedure could be accomplished by constructing the several transformed axes shown in Figure 3, this is not actually necessary. Instead, the procedure can be carried out in tabular form by using successive values of X_1 and calculating the corresponding values of X_2, X_3, X_4, Y_1, Y_2, and Y_3. Then, because Y_3 represents expected profit, the optimum point can be read directly (or interpolated) from the table along with the appropriate mean strength level.

TYPICAL CALCULATIONS

A typical calculation for a coefficient of variation of V = 10 percent and a single quality level of X_1 = 5 percent will follow these five steps.

First, although the operating-characteristic curve could be used graphically, it will be more convenient to use in equation form. The equation may be of any form that provides a good fit of the points on the curve from $X_1 = 0$ out to the AQL value. An expression that seems to satisfy this requirement quite well is

$$Y_1 = \sin(a - bX_1) \qquad (1)$$

where

Y_1 = expected pay factor expressed as a decimal,
X_1 = percentage of concrete below design strength expressed as a decimal,
$a = \pi/2 = 1.571$, and
b = a factor to be determined for each sample size for a variability-unknown specification.

The sine argument is in units of radians, and, for this example, a coefficient of b = 1.821 will be used.

Second, calculate the required mean strength from the equation

$$X_2 = D/(1 + ZV) \qquad (2)$$

where

D = design strength in megapascals,
Z = z-score corresponding to an area of X_1 under the normal curve, and
V = coefficient of variation expressed as a decimal.

For values of D = 20.7 MPa (3000 lbf/in^2), Z = -1.645 corresponding to $X_1 = 0.05$, and V = 0.10, this yields X_2 = 24.8 MPa (3591 lbf/in^2).

Third, here again it will be convenient to put the relationship of strength to cement factor in equation form. This may be done by regression analysis or other mathematical curve-fitting technique. The PCA relationship can be expressed as follows:

$$X_3 = a - (b - cX_2)^{1/2} \qquad (3)$$

in which the coefficients are a = 10.63 (8.13), b = 66.147 (38.663), and c = 1.8221 (0.007 344 8) and 20.7 MPa (3000 lbf/in^2) $\leq X_2 \leq$ 34.5 MPa (5000 lbf/in^2).

For the mean strength of X_2 = 24.8 MPa (3591 lbf/in^2) obtained in the second step, the equation yields a cement factor of X_3 = 6.05 sacks/m^3 (4.62 sacks/yd^3).

In the fourth step the unit cost to produce the mix is calculated from the equation

$$X_4 = a - b(c - X_3) \qquad (4)$$

where

X_3 = cement factor obtained in the third step,
a = cost of standard mix of \$35.32/m^3 (\$27/yd^3),
b = cost of cement of \$2/sack, and
c = standard cement factor of 7.85 sacks/m^3 (6.00 sacks/yd^3).

This yields X_4 = \$31.72/m^3 (\$24.25/yd^3).

Fifth, expected pay (Y_2) is obtained from the expression

$$Y_2 = P_1 - P_2(1 - Y_1) \qquad (5)$$

where

Y_1 = expected pay factor expressed as a decimal,
P_1 = bid price of concrete per cubic meter, and
P_2 = in-place cost of concrete per cubic meter.

However, before this calculation can be made, a trial bid price must be assumed by selecting a cement factor that seems adequate and then calculating the appropriate bid price. (If the final outcome is unsatisfactory, a different selection would be made and this portion of the procedure repeated.) Based on previous trials, suppose that the producer has selected a trial cement factor of 6.38 sacks/m^3 (4.88 sacks/yd^3) on which to bid.

By substituting this value for X_3 in Equation 4, the cost to produce this mix is found to be \$32.38/m^3 (\$24.76/yd^3). To obtain a 7 percent profit margin, this value is multiplied by 1.07 to yield a bid price of \$34.65/m^3 (\$26.49/yd^3). The in-place cost of the concrete is \$261.60/m^3 (\$200/yd^3), and the expected pay factor is determined from Equation 1 to be 0.9959. Substituting these values into Equation 5, the expected pay is found to be Y_2 = \$33.58/m^3 (\$25.67/yd^3).

Sixth, and finally, expected profit (Y_3) for the quality level and bid price chosen for this series of calculations is obtained from the equation

$$Y_3 = 100[(Y_2 - X_4)/X_4] \qquad (6)$$

where Y_2 is expected pay of \$33.58/m^3 (\$25.67/yd^3) and X_4 is production cost of \$31.72/m^3 (\$24.25/yd^3). This yields Y_3 = 5.86 percent.

These calculations would be repeated for several different values of X_1 in order to locate the quality level that optimizes expected profit. If the maximum attainable profit is found to be unsatisfactory, the producer selects a different cement factor, calculates a new bid price, and repeats the procedure.

In actual practice, this would be a laborious and time-consuming task if it were necessary to perform these steps manually. Fortunately, it is not difficult to computerize this procedure. The data in Tables 1 and 2 were obtained in this manner and establish the conditions necessary for the two producers to realize the desired 7 percent profit margin. Several interesting observations can be made from the data in Tables 1 and 2.

The last column (Y_3) lists the expected profit at various quality levels and indicates that neither producer should attempt to operate close to the AQL (10 percent of the concrete below design strength). The appropriate levels are 3 and 4 percent below design strength for the better (V = 10 percent) and the poorer (V = 15 percent) producer, respectively. In this example, both producers would actually lose money by producing concrete exactly at the AQL.

The better producer can achieve a 7 percent return by bidding on a mix of 6.38 sacks/m^3 (4.88 sacks/yd^3) and then producing a mix of 6.20 sacks/m^3 (4.74 sacks/yd^3) with an expected mean strength of 25.5 MPa (3695 lbf/in^2). In order to achieve the same return, the poorer producer

Table 1. Calculation results for a 10 percent coefficient of variation.

Percentage Below Design (X_1)	Mean Strength (X_2) (MPa)	Cement Factor[a] (X_3) (sacks/m^3)	Production Cost[b] (X_4) (\$/m^3)	Expected Pay Factor (Y_1) (¢)	Expected Pay (Y_2) (\$/m^3)	Expected Profit (Y_3) (¢)
1	27.0	6.51	32.63	99.98	34.61	6.05
2	26.0	6.30	32.24	99.93	34.48	6.96
3	25.5	6.20	32.01	99.85	34.27	7.05
4	25.1	6.11	31.85	99.74	33.97	6.65
5	24.8	6.05	31.72	99.59	33.58	58.6
6	24.5	5.99	31.61	99.41	33.09	4.70
7	24.3	5.95	31.52	99.19	32.54	3.22
8	24.1	5.91	31.44	98.94	31.89	1.41
9	23.9	5.87	31.38	98.66	31.16	-0.70
10	23.7	5.85	31.31	98.35	30.33	-3.12

Note: 1 MPa = 145 lbf/in^2; 1 m^3 = 1.3 yd^3.

[a] Bid mix = 6.38 sacks/m^3 (4.88 sacks/yd^3).
[b] Bid price = \$34.65/m^3 (\$26.49/yd^3).

Table 2. Calculation results for a 15 percent coefficient of variation.

Percentage Below Design (X_1)	Mean Strength (X_2) (MPa)	Cement Factor[a] (X_3) (sacks/m^3)	Production Cost[b] (X_4) (\$/m^3)	Expected Pay Factor (Y_1) (¢)	Expected Pay (Y_2) (\$/m^3)	Expected Profit (Y_3) (¢)
1	31.8	7.77	35.15	99.98	36.13	2.77
2	29.9	7.22	34.06	99.93	36.00	5.68
3	28.8	6.95	33.51	99.85	35.77	6.78
4	28.1	6.76	33.13	99.74	35.47	7.05
5	27.5	6.62	32.86	99.59	35.08	6.76
6	27.0	6.51	32.65	99.41	34.61	6.02
7	26.6	6.42	32.46	99.19	34.05	4.88
8	26.2	6.34	32.31	98.94	33.41	3.37
9	25.9	6.28	32.18	98.66	32.67	1.52
10	25.6	6.23	32.06	98.35	31.85	-0.66

Note: 1 MPa = 145 lbf/in^2; 1 m^3 = 1.3 yd^3.

[a] Bid mix = 7.09 sacks/m^3 (5.42 sacks/yd^3).
[b] Bid price = \$36.17/m^3 (27.65/yd^3).

must bid on a mix of 7.09 sacks/m^3 (5.42 sacks/yd^3) and then produce a mix of 6.76 sacks/m^3 (5.17 sacks/yd^3) with an expected mean strength of 28.1 MPa (4069 lbf/in^2).

To achieve the desired profit margin, the better producer must use a cement factor 0.35 sacks/m^3 (0.27 sacks/yd^3) higher than that required for AQL concrete, while the corresponding increase for the poorer producer is 0.54 sacks/m^3 (0.41 sacks/yd^3). This will raise the mean strengths by approximately 1.7 MPa (250 lbf/in^2) and 2.4 MPa (350 lbf/in^2) and increase the production costs by about \$0.70/m^3 (\$0.50/yd^3) and \$1.05/m^3 (\$0.80/yd^3), respectively, over those for AQL concrete.

It was observed when Figure 1 was discussed that the better producer could produce AQL concrete about \$0.70/m^3 cheaper than the poorer producer. Comparing the two rows for 10 percent below design strength in Tables 1 and 2, the actual difference in production cost is seen to be \$32.06 - \$31.31 = \$0.75/m^3 (\$24.51 - \$23.94 = \$0.57/yd^3). However, since neither producer should operate at the AQL, it is more appropriate to make the comparison at their respective optimum levels. The somewhat larger difference in production cost in this case is \$33.13 - \$32.01 = \$1.12/m^3 (\$25.33 - \$24.47 = \$0.86/yd^3).

From the standpoint of the consumer, who must ultimately foot the bill for the concrete, it is more meaningful to compare the bid prices that enable these two producers to just achieve the desired profit margin. The difference in this case is \$36.17 - \$34.65 = \$1.52/m^3 (\$27.65 - \$26.49 = \$1.16/yd^3). Because of superior quality control, the better producer can either (a) settle for a return of 7 percent and substantially underbid the other producer or (b) raise the bid somewhat, realize a greater profit, and still remain competitive. (The typical calculations described previously appear as the fifth row in Table 1.)

IMPLEMENTATION BY PRODUCERS

Producers must recognize that the optimum level is not a level that will eliminate pay reductions altogether. It is instead a level at which the likelihood of pay reductions and the cost of production are balanced in a way that enables the producer to realize the greatest profit margin. Although large departures from the optimum must be avoided, this balance is not delicate enough to present a serious problem to the knowledgeable producer.

Ideally, the optimum level would be determined by a computer program such as that used to generate Tables 1 and 2. If this is not feasible, the typical calculations described previously illustrate how the method can be practiced with a hand calculator. (Inexpensive, programmable models that can simplify this task considerably are now available.) Because of the many factors to be taken into account, it is unlikely that a simpler method that is accurate in all cases will be found. However, for the benefit of those producers who might have difficulty with this procedure, the following rule of thumb is offered as a guide.

1. Determine the mean strength necessary to produce concrete that is exactly at the AQL. This can be accomplished by using Equation 2, a z-score corresponding to the AQL, and a coefficient of variation representing the producer's established level of quality control.
2. Bid on a mix that has a target strength approximately 3.4 MPa (500 lbf/in^2) higher than that of AQL concrete.
3. Produce a mix that has a target strength approximately 1.7 MPa (250 lbf/in^2) higher than that of AQL concrete.

This recommendation is based on the results of a sensitivity analysis by using a computer program developed for this study and is appropriate under conditions generally similar to those assumed in the example. Very costly construction work or a large coefficient of variation might warrant still greater increases in bidding and production target strengths, whereas, for less costly work or very good quality control, smaller increases may suffice. In addition, the sensitivity analysis indicated that this approach becomes more favorable to the producer as the design strength increases. This is so because the strength versus cement factor curve tends to level off at higher cement factors, the difference in cement factor between the bid mix and the production mix increases, the bid price is correspondingly higher, and, as a result, so is the profit margin. In keeping with the philosophy of end-result specifications, the final decision regarding bidding and production strategies should remain the responsibility of the supplier of the concrete.

If a concrete producer does elect to use either the optimization procedure or the rule of thumb, several results can be expected. For example, the bid price and mean strength will approach optimum levels, which will enable the producer to realize the desired profit margin, and the number of lots receiving pay reductions will be reduced. There will also be a small increase in cost to compensate for the added strength of the concrete. The magnitude of this increase will depend on the manner in which the strength is raised but would normally be less than 1 percent of the in-place cost.

In the case of concrete pavement, the additional strength would provide an increase in expected service life. In the case of bridge decks and other structures subject to salt intrusion and spalling distress, the higher-strength mix will usually be less permeable and thus will provide greater durability.

The decrease in the frequency of pay reductions resulting from the increase in target strength will promote a smoother implementation of specifications of this type and will create a better working relationship among all parties involved.

By means of calculations similar to those used in the optimization procedure, it is possible to check how the two producers in the example would have fared if they had used the rule of thumb. The better producer would have bid \$35.02/m^3 (\$26.77/yd^3), which is higher than necessary; produced a target strength of 25.5 MPa (3691 lbf/in^2), which is almost exactly at the optimum level; and realized a profit of 8.1 percent, which is greater than the planned value of 7.0 percent because of the higher bid price. The poorer producer would have bid slightly low at \$35.98/m^3 (\$27.51/yd^3), produced a target strength somewhat below optimum at 27.3 MPa (3964 lbf/in^2), and realized a profit of 6.0 percent, down a bit from the desired return of 7.0 percent. In sharp contrast to this, if these two producers had bid on AQL concrete and then produced at that level, they would have incurred losses of -6.8 and -6.4 percent, respectively.

EFFECT ON SPECIFYING AGENCIES

Specification writers will note that the specification used in this example tends to force an increase in quality to a level well above the AQL because this is the most advantageous choice for the producer. It is my belief that this will usually be the case with specifications of this type, although it can be demonstrated that an extremely lenient pay schedule can produce the opposite effect by causing the optimum point to fall below the AQL.

Once contractors begin to understand how their strategies affect their performance, it is likely that they will tend to operate at optimum levels to maximize profits. Specifying agencies will then be receiving (and paying for) the optimum quality level, not the AQL. Because the optimum level appears to be relatively stable over a fairly broad range of conditions, it may be possible for specification writers to exercise some control over its location by making appropriate modifications of the graduated pay schedule. It is suggested that, at the very least, specifying agencies should check the approximate location of the optimum level to assure that it is reasonably close to the desired quality level.

SUMMARY AND CLOSING REMARKS

The optimization procedure can be an effective tool for both contractors and specifying agencies. It allows the contractor to determine in advance what the bid price and target level should be to achieve the desired profit margin. It also provides the specifying agency with knowledge and control of the level of quality a specification will tend to produce. This should lead to a better contractual relationship, in which the consumer obtains quality at a price that enables the producer to realize a fair profit.

The optimization procedure can readily be applied to other statistical specifications, although the application is easiest when there is a single factor that controls quality and cost (such as the cement factor in the example). The method is also applicable to specifications that have both lower and upper limits, such as would be the case for asphalt content of bituminous concrete. In this case, axis X_1 (percentage outside specification limits) would increase in both directions from zero, and the operating-characteristic curve for pay factor would be bell shaped with a maximum at $X_1 = 0$. Also, axes X_2 and X_3 would be identical because the factor controlling cost (asphalt content) is the same factor on which acceptance is based.

The example points out that it will usually be advisable to aim for a level of quality well above what is defined as acceptable. It also illustrates an advantage of good quality control, which enables a better producer to offer a lower bid price and still realize a greater profit margin.

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Acceptance Sampling of Neoprene Joint Sealers

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This paper describes an investigation of acceptance-sampling procedures for 3.1-cm (1.25-in) neoprene joint sealer. Background information is presented on the manufacturing process and quality-control techniques. Historical data dealing with rejection rates and property variability are discussed. Various types of sampling plans are discussed before the appropriate plan is chosen. The proposed acceptance plan is analyzed by using operating-characteristics curves, and the correct sampling location and the variability within a lot are determined.

In the past, acceptance sampling of construction materials was based on sampling plans that placed great emphasis on testing method and less emphasis on the number of samples needed to characterize a lot. Often the number of samples was chosen by rule of thumb, and many of these plans have since been found to be inefficient because the risks taken were large and the quality levels accepted varied greatly.

The New York State Department of Transportation (DOT), by designing new statistically based acceptance-sampling plans, is attempting to eliminate sampling plans that fall into this category. Such plans are a part of quality assurance but are not used for direct control of the production process. Their purpose is to provide a buyer with a consistent procedure, which has known risks and quality levels, for accepting or rejecting lots. This report describes the development of an acceptance-sampling plan for 3.1-cm (1¼-in) neoprene joint sealer. Similar reports have already been published on steel reinforcing bars (1) and structural paints (2).

BACKGROUND

Neoprene joint sealer is made by extruding polychloroprene through a die. After extrusion it is usually cut into convenient lengths for handling and curing. The material is then cured by a process that varies from manufacturer to manufacturer. After curing, the lengths are glued together to form large rolls. These are placed in cartons or wrapped on cable reels to form a lot for shipment to the job site.

At either the manufacturing plant or the job site, an inspector samples the lot and forwards these samples to New York DOT's Materials Bureau for testing. The joint sealer is tested for the following properties: (a) strength (aged and unaged), (b) elongation (aged and unaged), (c) hardness (aged and unaged), (d) recovery [at two temperatures, -29 and 100°C (-20 and 212°F)], and (e) force deflection.

Current test procedures and specifications limits for these properties are listed below (1 MPa = 145 lbf/in^2; t°C = (t°F - 32)/1.8; 1 cm = 0.39 in). If test results are satisfactory the lot is approved for use; if unsatisfactory the lot is rejected and cannot be used.

Property	ASTM Test Method	Requirements	
		Min	Max
Tensile strength, MPa	D 412	14	
Ultimate elongation	D 412	250	
Hardness, type A durometer	D 2240	50	60
Aged tensile strength, % change			-20
Aged ultimate elongation, % change			-20
Aged hardness, point change			+10
Oil swell (ASTM Oil No. 3, 70 h at 100°C), % change of weight			45
Recovery under 50 percent deflection, %			
After 70 h at 100°C		85	
After 22 h at -29°C		85	
Deflection condition, force, kg/cm			
Compressed to 2.5 cm			0.54
Compressed to 1.5 cm			2.16

In judging the efficiency of this sampling plant, one must evaluate several factors, such as how many samples are being taken, what the risks involved in judging acceptance with that many samples are, where the samples are being taken, and whether sampling from those locations provides a representative sample. In addition, data are needed on the distributional form of the properties tested, variability of those properties, and historical rejection data. All this information must be combined with quality-control theory and engineering judgment to design a statistically based acceptance-sampling plan.

Operating-Characteristics Curve

The efficiency of existing sampling plans must be determined if new plans are to be compared with them. A common method for evaluating efficiency and the risks associated with a sampling plan is the construction of an operating-characteristics (OC) curve for the plan. The general concepts and terms associated with OC curves will be presented, but no attempt will be made to detail how these curves are derived. A complete description of the OC-curve theory can be found in most good texts on quality control (3).

An OC curve of the type considered in this report shows the probability of accepting lots that have varying fractions defective. The curves are based on the assumption that, if one has a series of lots with the same fraction defective, a percentage of the bad lots will be found and rejected. In real life, the fraction defective in a series of lots is usually changing, and the curves thus are not exact measures of risk but are good indicators of what to expect on the average from the sampling plan.

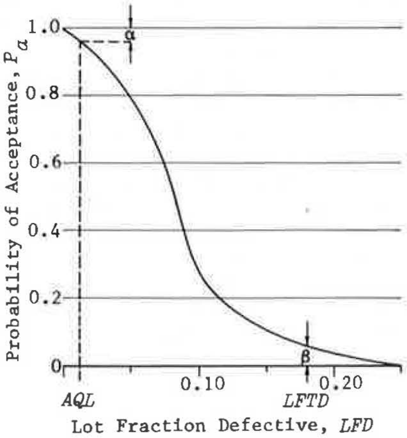
The following parameters are needed to develop OC curves and are defined as

1. Acceptable quality level (AQL): The acceptable quality level is the fraction of defective material in a lot that can easily be tolerated without impairing performance and can be accepted without reservation;
2. Manufacturer's risk (α): Manufacturer's risk is the chance one is willing to take of rejecting acceptable lots;
3. Lot-tolerance fraction defective (LTFD): The lot-tolerance fraction defective is the lot fraction defective that can barely be tolerated and still meet the engineering requirements imposed on the product;
4. Consumer's risk (β): Consumer's risk is the chance one is willing to take of accepting rejectable lots; and
5. Sample size (η): Sample size is the number of production units that must be sampled and tested to ensure that not more than β percent of the lots containing a fraction defective equal to the LTFD are accepted in any plan for which α, β, AQL, and LTFD are specified.

It is usually impossible to set all five parameters. When four have been set, the fifth parameter is automatically determined.

A typical OC curve is shown in Figure 1. The curve shows the relationship between α, β, AQL, and LTFD. The consumer's risk of accepting a lot of bad material—that is, of having a fraction defective greater than or equal to LTFD--is equal to or less than β. The producer's risk of having a lot of good material rejected—or a fraction defective less than or equal to AQL—is equal to or less than α.

Figure 1. General OC curves.



Theoretically, the AQL, LTFD, α, and β are chosen by the consumer, and the sample size η results from these choices. However, engineering decisions reached after studying product variability, rejection rates, and product criticality often require modification of the risks and quality levels.

Historical Data

Results of routine acceptance testing under the present sampling plan were collected and analyzed for the years 1968 through 1976. Rejection data are summarized in Table 1. These data are used later in this report for determining appropriate risks and quality levels. The data analysis revealed that, out of the 770 lots submitted for testing, 198 or 25.7 percent of the lots were rejected. The data analysis also determined the failure rate for each property tested (Table 2). The properties with the highest rejection rates are 1.5-cm ($^5/_8$-in) force deflection, unaged strength, and -29 and 100°C (-20 and 212°F) recovery. The data revealed two important factors. First, overall quality of lots submitted was low; second, two or three properties were the main causes of rejec-

Table 1. Rejection rates for various manufacturers.

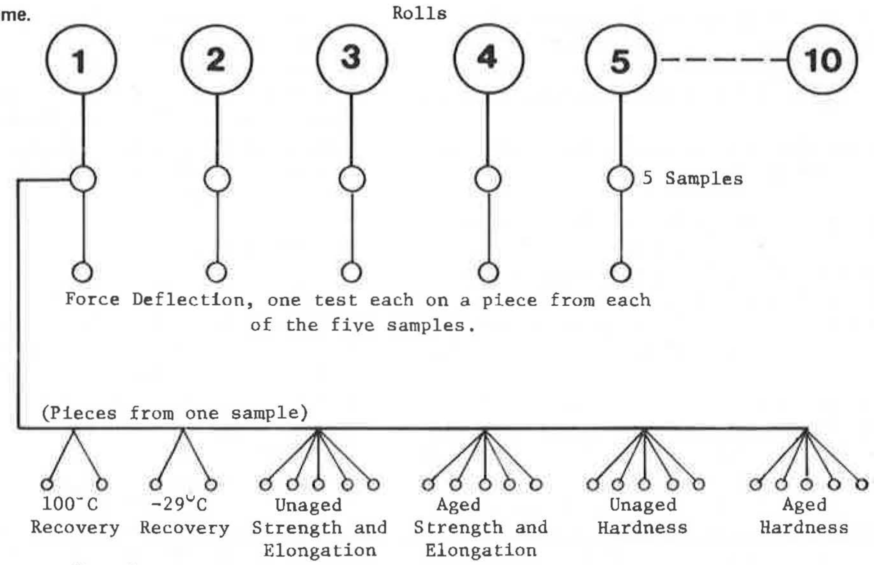
Manufacturer	Year	No. of Lots Submitted	No. of Lots Rejected	Percentage of Lots Rejected
A	1968	69	14	20.3
	1969	5	2	40.0
	1970	136	51	37.5
	1971	57	25	44.0
	1972	56	11	19.6
	1973	41	7	17.1
	1974	45	7	15.6
	1975	9	1	11.1
	1976-1977	7	2	28.6
B	1968	56	6	10.7
	1969	2	0	0.0
	1970	31	2	6.9
	1971	8	2	25.0
	1973	2	0	0.0
C	1970	39	10	34.5
	1971	29	17	58.6
	1974	9	7	77.8
	1975	2	2	100.0
D	1968	18	3	16.7
	1969	22	14	63.7
E	1968	7	7	100.0
	1969	19	0	0.0
	1970	78	5	6.4
	1971	7	0	0.0
	1972	5	1	20.0
	1974	17	1	5.9
	1975	4	1	25.0
All manufacturers combined		770	198	25.7

Table 2. Rejection rates by properties.

No. of Lots	Year	Unaged Strength	Unaged Elongation	Unaged Hardness	Recovery 100° C	Recovery -29° C	2.5-cm Force Deflection	1.5-cm Force Deflection
150	1968	36	2	0	2	4	6	41
48	1969	12	2	0	0	1	1	6
274	1970	18	0	2	10	16	10	37
101	1971	10	1	1	11	13	4	13
61	1972	12	0	7	12	18	3	11
43	1973	4	0	2	0	7	0	1
71	1974	3	0	4	4	4	0	3
15	1975	0	0	0	1	0	0	2
Percentage rejected by property		12.0	0.6	2.0	5.0	8.0	2.2	16.0

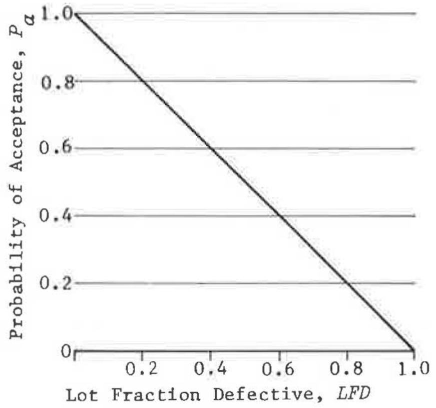
Note: t°C = (t°F - 32)/1.8; 1 cm = 0.39 in.

Figure 2. Present sampling scheme.



Note: t°C = (t°F - 32)/1.8.

Figure 3. OC curve for single sample.



tion. The importance of this information will become evident later in this report.

PRESENT ACCEPTANCE PLAN

The present sampling plan calls for sampling of each lot. A lot is defined by New York State specifications as a specific size and style of joint sealer produced in a reasonably continuous manner. A physical lot is made up of cartons or small rolls of sealer. Large telephone reels, described as about 1.5 m (5 ft) in diameter and 1.5 m wide, may be used, but only one reel can make up a lot. The number of samples taken from each lot varies with the number of rolls or cartons (units) forming the lot; when the number of units to be sampled exceeds the lot size, for example, all units in the lot are sampled. Sampling frequency used is listed below.

Lot Size (no. of cartons or rolls)	Total Units Sampled	Rejection Number
1-50	5	1
51-150	20	2
151-280	32	3
281-500	50	4

Lot rejection occurs when the number of sample failures equals or exceeds the rejection number. Historical data show that the number of cartons or rolls submitted in a single lot has never exceeded 50. Thus, only the lowest level of sampling has ever been done. As a result, it was decided not to consider the other sampling levels when judging the plan.

Samples are obtained by cutting a 2.7-m (9-ft) length from either end of each roll being sampled and testing them for compliance with current specifications. Failing the criteria for one or more properties means rejecting the lot.

Aged and unaged properties of tensile strength, elongation, and hardness are judged by the average of two readings from one sample. Force deflection is judged by a single test result for each 2.7-m sample taken. An example is shown in Figure 2, where a lot consisting of ten rolls is submitted for acceptance. The plan calls for one 2.7-m sample from either end of five randomly selected rolls. Each length is submitted to testing for force deflection. If one or more of the five test results show failure, the lot is rejected. The other properties are judged by readings obtained from only one of the five samples, and the other four samples are not tested.

Five readings each are taken for aged and unaged strength, aged and unaged elongation, and aged and unaged hardness, and from them a median is found for each property. If the median complies with the specification limit for that property, the lot is accepted; otherwise it is rejected. Recovery is judged on the average of two readings taken from the same sample. If the average falls within specification limits, the lot is accepted for that property; otherwise it is rejected.

Lot Specification

For an efficient sampling plan, a rational lot must be found that should, to provide reasonable property variations within the units, be formed from a number of production units produced under the same conditions and from the same materials. The present lot, as described at the beginning of this chapter, consists of rolls or cartons of a particular size sealer extruded in a continuous manner from a vat of material. The description of a lot just given meets the qualifications of a rational lot. Therefore, the present lot as described by state specifications is acceptable.

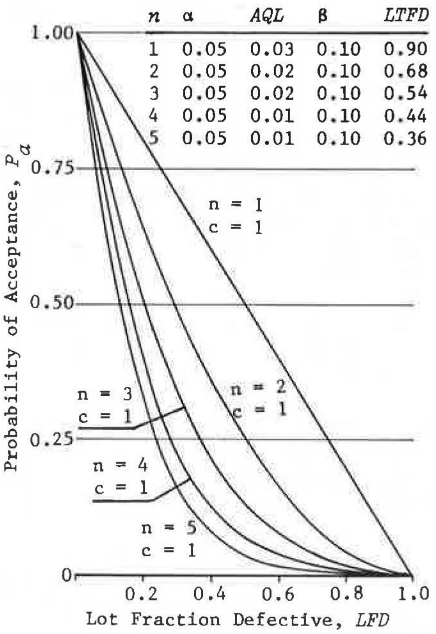
Operating-Characteristics Curves for the Current Plan

The current plan was designed without benefit of an OC curve, so it was necessary to construct one. After studying the present plan, we decided that there were, in fact, two distinct plans. Therefore, because each sampling plan is normally associated with its own particular curve, two OC curves had to be constructed.

The first plan is used to judge hardness, strength, and elongation. As described earlier, each property is judged from the median value of five test results obtained from one sample. This value is compared with the specification limits to determine compliance. Acceptance or rejection is based on one sample. The probability of acceptance for a sample size of one is one minus the fraction defective. The resulting OC curve is a 45° line as shown in Figure 3. This is not an efficient plan. If a lot is 50 percent defective, only a 50 percent chance of rejecting or accepting it exists.

It should be emphasized that the lot is not judged from five test results, since the median is determined from five readings. Those five readings are taken to obtain one valid estimate of the property for that one sample, and thus the median becomes a point estimator. The recovery test also falls into the one-sample plan based on the average of two readings, but that average represents only one sample. The OC curve in Figure 3 is also valid for recovery testing.

Figure 4. OC curves for current acceptance plans.



The second plan applies to sampling and testing force deflections. These properties are judged from each sample's test results, which are compared with the specification limits. If all results comply with the specifications, the lot is accepted; if one or more test results fail, it is rejected. The actual number of samples taken for force deflections can range from one to five. The plan requires five samples, but, for a lot of fewer than five cartons or reels, all are sampled. There is an OC curve for each sample size.

The sampling plan for force deflections resembles an attribute plan. Attribute sampling judges each sample's test results as either acceptable or rejectable. If the number rejected equals or exceeds a specified rejection number, the lot is rejected. The current plan has a rejection number equal to one; sample size can vary from one to five. The OC curves drawn from testing force deflections are shown in Figure 4. The efficiency of the plan decreases sharply with each reduction in sample size. For example, consider two lots—one of five rolls, the other of three. If each lot had a fraction defective equal to 0.30, the probabilities of acceptance for the five- and three-roll lots would be 16 and 33 percent, respectively. The probability of acceptance is doubled with a reduction of two samples.

The OC curves show that force deflection is the only

Table 3. Historical variability.

		Manufacturer A			Manufacturer B			Manufacturer C			Manufacturer D			Manufacturer E		
Property	Year	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD
Unaged strength	1968	62	14.9	0.6	-	-	-	-	-	-	56	17.2	0.7	18	14.6	0.7
	1969	-	-	-	19	14.9	0.6	-	-	-	-	-	-	22	13.7	1.2
	1970	130	15.7	0.6	78	15.8	0.9	29	14.0	0.6	32	16.5	0.7	-	-	-
	1971	57	15.2	0.5	-	-	-	36	14.6	1.5	-	-	-	-	-	-
Unaged elongation	1968	62	292	11	-	-	-	-	-	-	56	309	15	18	280	13
	1969	-	-	-	19	274	16	-	-	-	-	-	-	22	269	17
	1970	130	340	15	78	295	19	29	278	16	32	318	22	-	-	-
	1971	57	317	14	-	-	-	29	303	43	-	-	-	-	-	-
Unaged hardness	1968	62	51	1	-	-	-	-	-	-	56	52	1	18	52	1
	1969	-	-	-	19	54	2	-	-	-	-	-	-	22	52	1
	1970	127	53	2	78	53	2	29	52	1	32	52	1	-	-	-
	1971	57	54	2	-	-	-	29	50	2	-	-	-	-	-	-
100°C recovery	1968	62	89	2.9	-	-	-	-	-	-	56	94	1.6	16	91	4.5
	1969	-	-	-	19	90	3.4	-	-	-	-	-	-	15	91	2.9
	1970	129	88	1.8	78	90	2.1	29	93	1.7	32	87	1.6	-	-	-
	1971	57	88	2.5	-	-	-	29	87	4.5	-	-	-	-	-	-
-29°C recovery	1968	62	91	5.0	-	-	-	-	-	-	56	90	4.6	18	96	2.7
	1969	-	-	-	19	94	2.4	-	-	-	-	-	-	22	89	3.5
	1970	129	86	2.2	78	90	3.2	29	88	2.2	32	84	2.4	-	-	-
	1971	57	85	2.8	-	-	-	29	88	1.9	-	-	-	-	-	-
2.5-cm force deflection	1968	68	0.72	0.14	-	-	-	-	-	-	57	0.73	0.16	18	0.60	0.08
	1969	-	-	-	19	0.75	0.09	-	-	-	-	-	-	22	0.65	0.11
	1970	133	0.86	0.16	78	0.91	0.08	29	1.27	0.09	32	0.78	0.05	-	-	-
	1971	57	0.78	0.14	-	-	-	29	0.88	0.22	-	-	-	-	-	-
1.5-cm force deflection	1968	68	2.49	1.09	-	-	-	-	-	-	57	1.41	0.34	18	1.59	0.35
	1969	133	1.85	0.61	19	1.02	0.10	-	-	-	-	-	-	22	1.95	0.33
	1970	-	-	-	78	1.43	0.25	29	1.27	0.26	32	1.21	0.11	-	-	-
	1971	57	1.43	0.36	-	-	-	29	1.42	0.27	-	-	-	-	-	-

Note: t°C = (t°F - 32)/1.8; 1 cm = 0.39 in.

property for which enough samples are taken to achieve reasonable quality levels and risks. The risks are larger for smaller lot sizes. However, only when the lot is made up of one roll or carton do the risks equal those taken for all other properties. Even when the lot size is two, force-deflection testing would only accept a 0.25 fraction-defective lot 53 percent of the time. The other properties with the same fraction defective would be accepted 75 percent of the time.

The risks associated with most properties are great, and the probability of accepting only material of reasonable quality is not high. A better plan is needed, preferably a single plan that could cover all properties.

VARIABILITY EXPERIMENT

The current sampling plan requires that the samples be cut from either end of the roll. This procedure is used for convenience and to reduce waste. As a result all samples come from either the beginning or the end of the roll. At the time of the present testing, no study had ever been conducted to determine if sampling from these locations provided a representative sample. Data on variability between rolls, within a roll, and analytical error could be used to judge whether the sample location was adequate. Historical data were examined for variability, but could only provide variance data from manufacturer to manufacturer and from year to year, as shown in Table 3. An experiment was designed to supply the needed information, which was also used to study the distribution forms of the properties tested.

Experimental Design

Joint sealer was purchased from three manufacturers. Two sent five rolls of sealer and one sent four cartons. For convenience, all rolls and cartons will be referred to as rolls. Each roll was cut into as many 1.5-m (5-ft) lengths as possible, and each length was tested as an individual sample. These were assigned random numbers so that the testing personnel had no idea which length came from which roll.

Five tests were conducted on each sample for aged and unaged elongation, hardness, and strength. Two tests were run for both recovery temperatures. Unfortunately, misunderstandings about the force-deflection testing arose, and as a result repeat testing was not done on each sample. Some rolls, in fact, were not tested for force deflection at all. It was decided that any information gained from analyzing the data on force deflection would be inconclusive and the results from the other properties would be adequate. As a result, no analysis was attempted for force deflection.

Analysis of variance (ANOVA) techniques were used to study the experimental data. ANOVA is used to break the variability of a process into particular factors that are then compared to determine those that have the most influence on overall variability. This experiment considered the following four factors: roll-to-roll variability (how much variation existed from roll to roll within a lot), within-roll variability (how much variation existed within a roll), analytical error (the variation remaining after consideration of all other factors, including, in this case, testing error), and overall variability (the total variability of the lot).

Experimental Results and Interpretation

Table 4 shows the experimental results broken down into their various components and Table 5 the percentage that each component contributed to the overall variability. The analysis reveals that analytical error is the major contributor to overall variability in strength and elongation properties. But analytical error does not play a major role for hardness and recovery, for which the major factors are roll-to-roll and within-roll variation.

It is often difficult to put ANOVA results into practical terms. In this experiment it is fairly obvious what is meant by roll-to-roll and within-roll variation but not what analytical error represents. Graphs will be used to contrast high and low analytical error in the hope that this will clear up any confusion.

Figure 5 has two graphs showing low analytical error. They represent hardness data for manufacturer C from one roll. The ANOVA shows that analytical error contributes only 4 percent of the overall variability. Graph B shows the range of the five test results used to obtain the individual averages in graph A. The average range of all the samples is 1.2, which indicates that the spread within five test readings is small compared to the spread of all the individual samples. The result is low analytical error.

Figure 6 shows high analytical error. It represents aged elongation data for manufacturer C from one roll. ANOVA shows 71 percent of the overall variability is attributable to analytical error. Graph A represents the average of five test values for each sample; the total range of the averages is 22. Graph B shows the range of the five test results used to obtain the individual average in graph A; the average range is 28. ANOVA indicates high analytical error. In other words, the range of five test results obtained from one 1.5-m (5-ft) length can be equal to or greater than the range of averages of all the samples combined.

Although there is no substantial proof, most of the high analytical error is believed to be testing error. This is supported by the fact that the results for both strength and elongation are obtained almost simultaneously from one testing method; both have high analytical error as well. These statements should not be interpreted to mean that the testing is done improperly. The other properties have low analytical error. The inherent variation involved in the testing for strength and elongation may be large and difficult or impossible to reduce. Because investigation of testing methods is beyond the scope of this study, no further work was conducted in this area.

The main objective of this experiment was to determine whether sampling at the beginning or end of a roll provided a representative sample. The analysis showed that variation can be large within a roll or even a small section of roll. Therefore, any one location is as adequate as any other, and a sampling at the beginning or end of a roll does prove to be representative.

Distribution Form

Certain sampling plans require that the properties tested follow a normal distribution. No historical data were available to establish distribution form. The data obtained for two of the three manufacturers in the experiment were tested for normality using χ^2 analysis. Because of the results obtained from these two manufacturers it was judged unnecessary to test the third. The data were analyzed within a roll, and the results are given in Table 6. Some properties were accepted as normally distributed; others were not. The results were consistent from producer to producer. A property that failed for manufacturer B also failed for manufacturer A.

If a sampling plan that assumed normality were used, serious errors could result in judging properties that are not normally distributed. If one only used the plan on normally distributed properties, another plan would be needed for the remaining properties. It is desirable to have only one plan, since multiple plans for one ma-

Table 4. Experimental within-lot variance.

		Roll to Roll			Within Roll			Analytical Error			Overall	
Property	Manufacturer	S^2	S	%	S^2	S	%	S^2	S	%	S^2	S
Unaged strength	A	0.292	0.54	77	0.096	0.31	8	0.883	0.94	69	1.254	1.12
	B	0.040	0.20	28	0.302	0.55	36	0.168	0.41	59	0.815	0.90
	C	0.656	0.81	116	0.168	0.41	15	0.038	0.20	28	1.162	1.08
Aged strength	A	0.182	0.43	61	0.132	0.36	12	0.790	0.89	72	1.102	1.05
	B	0.082	0.29	41	0.036	0.19	6	0.490	0.70	80	0.604	0.78
	C	0.572	0.76	108	0.104	0.32	11	0.268	0.52	28	0.947	0.97
Unaged elongation	A	NV[a]	-	-	17	4	7	221	15	93	238	15
	B	68	8	23	36	6	13	189	14	64	293	17
	C	27	5	9	98	10	33	172	13	58	297	17
Aged elongation	A	94	10	31	11	3	4	198	14	65	303	17
	B	109	10	27	62	8	15	237	15	58	407	20
	C	37	6	16	30	5	13	160	13	71	227	15
Unaged hardness	A	0.2	0.5	3	5.6	2.4	78	1.3	1.2	19	7.1	2.7
	B	3.1	1.0	30	2.2	1.2	46	0.8	0.9	24	6.1	1.8
	C	8.1	2.9	42	9.7	3.1	50	1.4	1.2	8	19.2	4.4
Aged hardness	A	0.3	0.5	4	6.1	2.5	78	1.4	1.2	18	7.8	2.8
	B	1.0	1.8	52	1.5	1.5	36	0.8	0.9	12	3.3	2.5
	C	8.2	2.9	43	9.7	3.1	50	1.4	1.2	7	19.3	4.4
100°C recovery	A	7.1	2.7	78	1.6	1.3	18	0.4	0.7	4	9.1	3.0
	B	3.0	1.7	36	3.8	2.0	46	1.5	1.2	18	8.3	2.9
	C	2.3	1.5	8	18.5	4.3	68	6.5	2.6	24	27.3	5.2
-29°C recovery	A	6.9	2.6	43	8.5	2.9	53	0.6	0.8	4	15.9	4.0
	B	3.7	1.7	47	2.9	1.7	37	1.2	1.1	16	7.7	2.8
	C	0.7	0.8	7	6.8	2.6	66	2.7	1.6	27	10.2	3.2

Note: t°C = (t°F - 32)/1.8.
[a]NV = negative variance.

Table 5. Percentage of overall variation attributed to each factor as determined from ANOVA.

Property	Manufacturer	Roll to Roll (%)	Within Roll (%)	Analytical Error (%)
Unaged strength	A	23	8	69
	B	5	36	59
	C	57	15	28
Aged strength	A	16	12	72
	B	14	6	80
	C	61	11	28
Unaged elongation	A	-[a]	7	93
	B	23	13	64
	C	9	33	58
Aged elongation	A	31	4	65
	B	27	15	58
	C	16	13	71
Unaged hardness	A	3	78	19
	B	30	46	24
	C	42	50	8
Aged hardness	A	4	78	18
	B	52	36	12
	C	43	50	7
100°C recovery	A	78	18	4
	B	36	46	18
	C	8	68	24
-29°C recovery	A	43	53	4
	B	47	37	16
	C	7	66	27

Note: t°C = (t°F - 32)/1.8.
[a]Not calculated because of negative variance in original data.

terial can create confusion, increase the probability of testing error, and increase testing costs.

SELECTION OF A SAMPLING PLAN

Different Sampling Plans

A variety of sampling plans are available, and each has its advantages and disadvantages. The three plans most commonly considered for use will be presented with an explanation of why each was or was not considered appropriate for use in accepting neoprene joint sealer.

Screening

Under the screening type of plan every roll submitted is tested. It is expensive and, while it cannot be used when destructive testing is involved, it is used when reliability is critical. The criticality of joint sealer does not require this type of inspection.

Continuous Sampling

Continuous sampling starts off as screening. After a set number of samples are accepted, the sampling rate is reduced. If a defective unit is found, the sampling rate reverts to screening. The cycle continues to repeat as necessary. This type of sampling requires fewer samples than screening but more samples than the lot-sampling schemes discussed next.

Lot Sampling

Lot sampling can be done with two types of plans: variables sampling and attributes sampling. The former requires measuring the property, knowing its distribution, estimating the proportion defective from the distribution parameters, and accepting or rejecting it according to the estimated proportion defective.

This plan, of all those considered, requires the fewest samples but cannot be applied here for several reasons. It requires that the properties inspected be approximately normally distributed, which is not the case for all properties considered here. To achieve the smallest sample size, the plan requires a known standard deviation. Historical data presented in Table 3 show that variation changes from manufacturer to manufacturer and from year to year. Thus, variation could not be considered known and sample sizes would increase. A variables plan would also require a separate plan for each property. For these reasons, it was judged inappropriate.

Figure 5. Low analytical error (aged hardness).

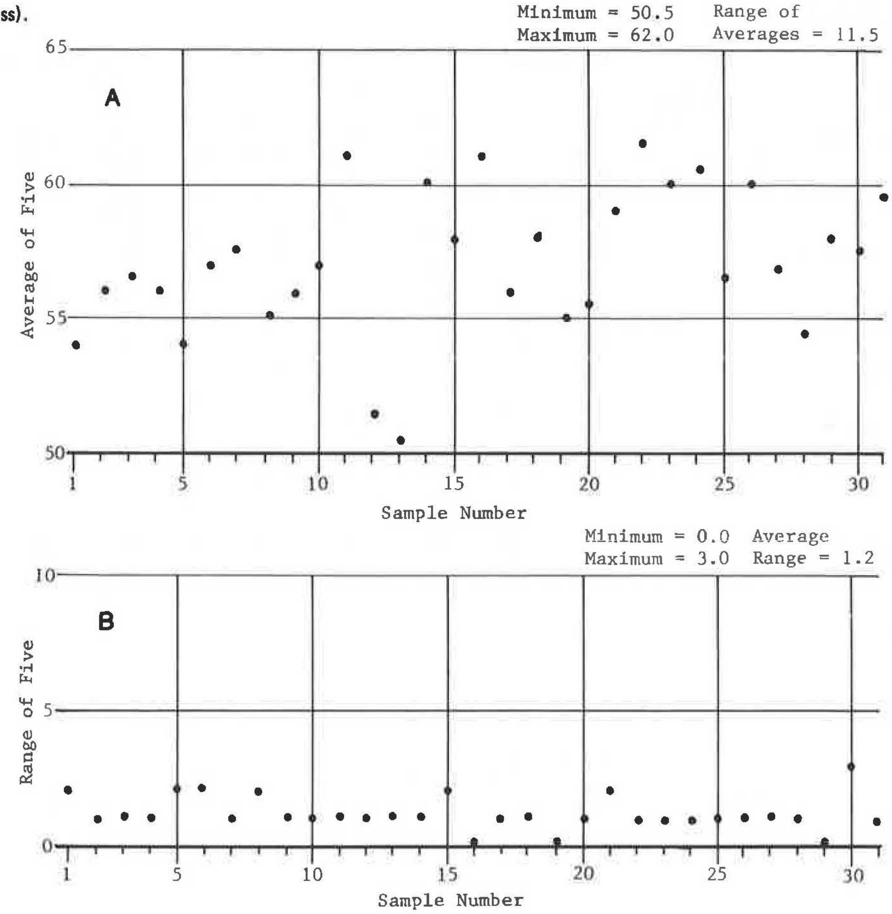


Figure 6. High analytical error (aged elongation).

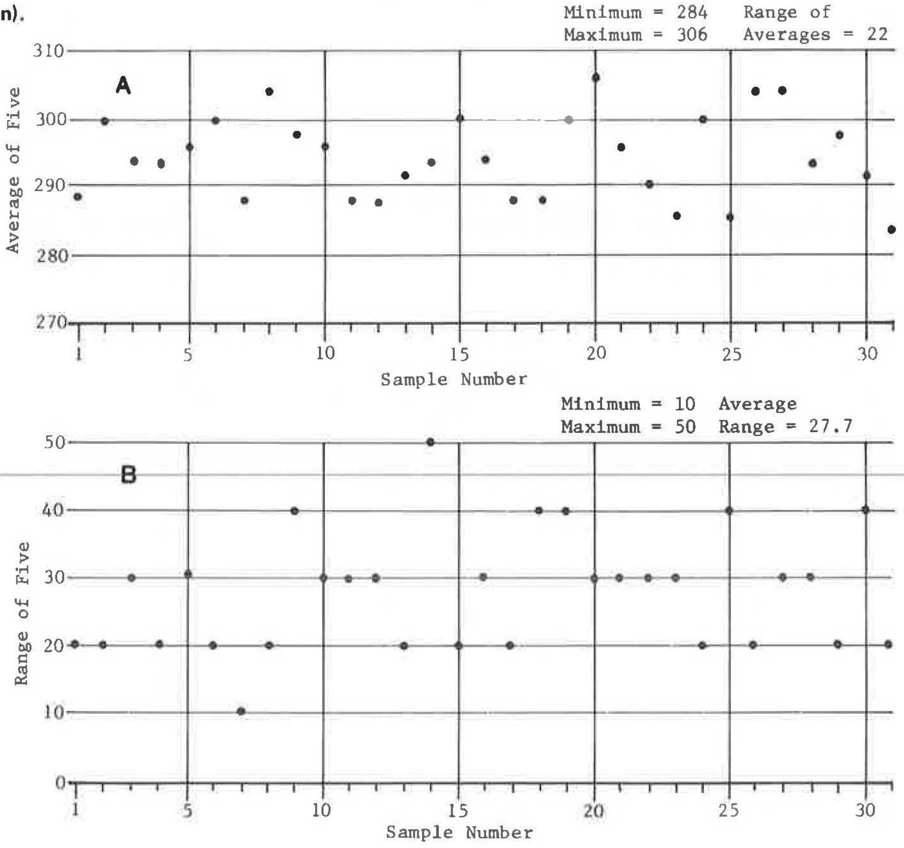


Table 6. χ^2 analysis.

Property	Manufacturer	Roll	N	Calculation (χ^2)	Accept (H_0)	Reject (H_0)
Unaged strength	B	1	195	23.12		-
		2	195	35.94		-
		3	195	29.14		-
		4	195	27.93		-
		5	195	8.22	-	
	C	1	150	5.81	-	
		2	150	20.54		-
		3	150	21.10		-
		4	150	5.76	-	
		5	150	5.49	-	
Unaged hardness	B	1	195	26.10		-
		2	195	46.22		-
		3	195	26.73		-
		4	195	99.28		-
		5	195	38.07		-
	C	1	150	60.27		-
		2	150	25.72		-
		3	150	70.22		-
		4	150	22.76		-
		5	150	155.04		-
Unaged elongation	B	1	195	21.44		-
		2	195	60.87		-
		3	195	20.13		-
		4	195	28.30		-
		5	195	26.94		-
Unaged elongation	C	1	150	34.73		-
		2	150	27.45		-
		3	150	24.13		-
		4	150	15.24		-
		5	150	20.73		-
100°C recovery	B	1	78	6.74	-	
		2	78	5.99	-	
		3	78	10.54	-	
		4	78	23.91		-
		5	78	5.42	-	
	C	1	60	14.48	-	
		2	60	27.43		-
		3	60	2.79	-	
		4	60	4.62	-	
		5	60	1.19	-	
-29°C recovery	B	1	78	10.88	-	
		2	78	28.27		-
		3	78	11.97	-	
		4	78	6.71	-	
		5	78	3.20	-	
	C	1	60	34.56		-
		2	60	13.28	-	
		3	60	1.89	-	
		4	60	34.71		-
		5	60	7.94	-	

Notes: $t°C = (t°F - 32)/1.8$.
For H_0 the distribution is normal; H_0 is tested at the 5 percent level of significance.

The second type of lot-sampling plan, attributes sampling, is the type most nearly resembling the present plan. As stated before, each sample unit is judged acceptable or rejectable. If the total number of defective units equals or exceeds a predetermined number, the lot is rejected; if the number of defective units is less than that number, the lot is accepted. An important factor in favor of attributes sampling is that it does not require properties to follow any particular distribution, nor does it require variability data. Even though properties of neoprene joint sealers do not all follow the same distribution, this type of plan would allow one plan for all properties. For these reasons attributes sampling was chosen as the appropriate base for design of a sampling plan for neoprene joint sealer.

Selection of Risks and Quality Levels

To determine number of samples and rejection number, one must choose quality levels and risks. These parameters, referred to earlier in this report, are consumer's risk (β), manufacturer's risk (α), acceptable quality level (AQL), and lot-tolerance fraction defective (LTFD). Consumer and producer risks have historically been set at 5 and 10 percent, respectively (3).

LTFD is chosen by an engineering decision based on product criticality and historical data. If one were to ask a consumer what maximum percent defective he or she could tolerate in a lot of material, one would usually be given low values. Low values are always desirable but sometimes not practical. The quality of the product achievable with the current manufacturing process must also be considered. It has been shown that the present sampling plan is inefficient and takes large risks, yet historical rejection data in Table 2 show high rejection for several properties. Two properties are higher than 10 percent and two others are between 5 and 10 percent. If a more efficient plan had been used, rejections would probably have been greater.

If all properties had proved to be normally distributed, it would have been possible to try to support this with calculations. A simple calculation based on specification limits, means from historical data, and the within-lot variability would have indicated theoretical failure rates. Unfortunately, the properties are not all normally distributed, so the data could not be used in this manner.

First, we believe that the historical rejection rates were conservative, so the LTFD was kept significantly greater than the percentage defective for the highest historical rejection rate. Second, it would have been impractical to require quality infeasible under the present production methods. All the data collected indicate that this is a difficult process to control. In addition, too much sampling would have been required to maintain better quality and lower risks. Product criticality was not worth the extra cost. Thus, the LTFD chosen was 36 percent. Normally the AQL would not have been chosen, but sample size was an important consideration, and several plans were drawn up. The plan that provided the most reasonable combination of sample size, quality levels, and risks was chosen.

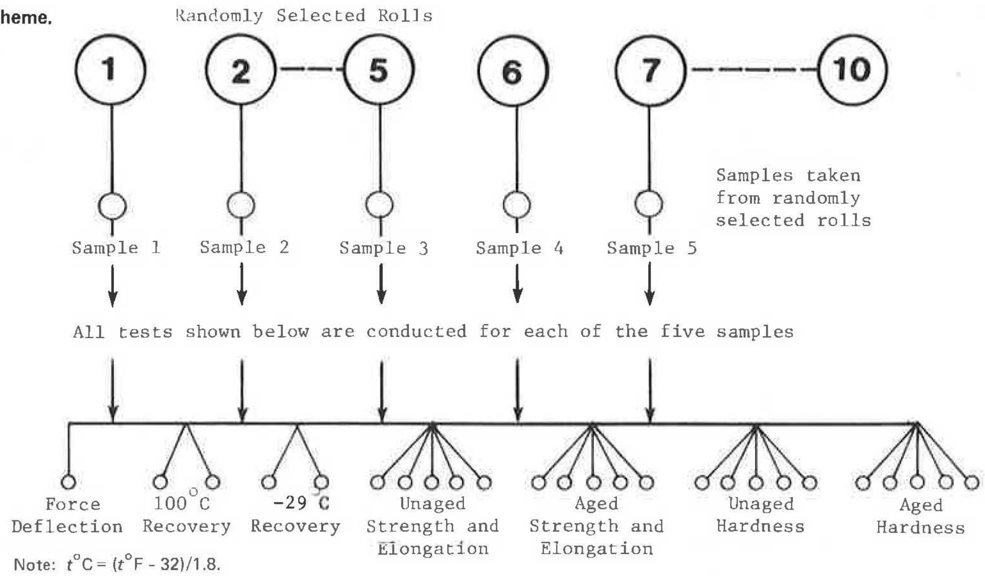
Recommended Plan

An attributes plan with a sample size of five and a rejection number of one is recommended. Each sample can be taken from either the beginning or the end of the roll. If fewer than five rolls are available, the procedure used in the current plan can be followed, and all rolls must be tested. The amount of testing associated with the new plans would be approximately five times greater than is now done.

Sampling and testing for elongation, strength, and hardness would proceed as follows. One sample would be collected from each of five randomly selected rolls. Each sample would be tested five times for strength, elongation, and hardness. From each group of readings a median would be found. If one or more of the five medians calculated for each property failed to comply with specification limits, the lot would be rejected; if all medians were within the limits, the lot would be accepted for those properties.

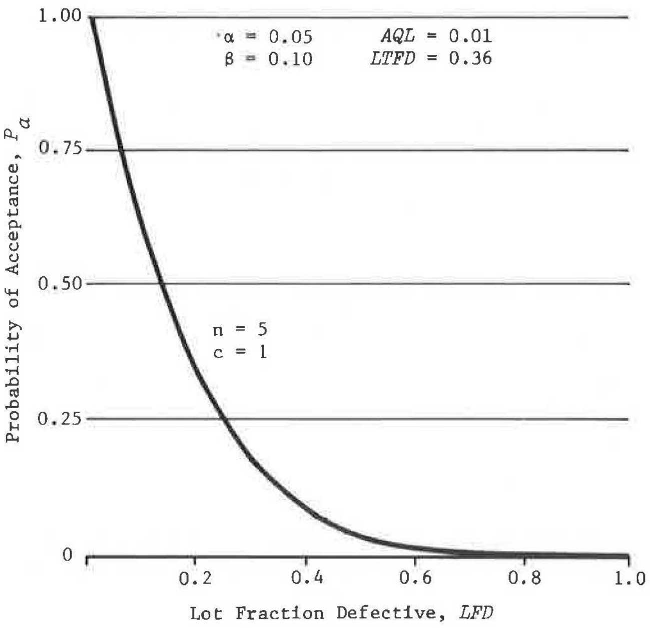
Recovery sampling and testing would follow the same general procedure. Five samples would be taken and two tests run on each sample. Five average readings would be calculated from the two readings on each sample, and, if all complied with specification limits, the lot would be accepted for that property. If one or more of the averages failed to comply, the lot would be rejected.

Figure 7. New sampling scheme.



Note: $t^\circ C = (t^\circ F - 32)/1.8$.

Figure 8. OC curve for proposed sampling plan.



The procedure for force deflection is the same as the current method. Five samples are taken and each is tested. If all five results comply with specification limits, the lot is accepted for that property. If one or more fails to comply, the lot is rejected. An example of the new plan for sampling a lot of 10 rolls is shown in Figure 7.

The parameters of the plan, whose OC curve is shown in Figure 8, are AQL = 0.01, $\alpha = 0.05$, LTFD = 0.36, and $\beta = 0.10$.

The recommended plan is the same as that currently used for force-deflection testing, for which the risks and quality are unaffected but all other properties are significantly affected. For example, the probability of accepting a lot with a 0.30 fraction defective is now 70 percent; with the new plan the probability for a lot of five rolls is 16 percent. Granted, risks increase with smaller lots, but even a lot of two rolls has a 46 percent probability of acceptance for the same fraction defective, which is a 24 percent reduction from the current risk. The risks are greatly reduced and their associated quality levels have been significantly improved.

The recommended plan provides a consistent procedure for accepting material. The risks are known and the desired quality levels are reasonable. A general increase in the quality of accepted material is realized. Also, the new plan can provide historical data that better estimate the property levels of a sealer that is being used on the job. This would provide better performance data for future evaluation of product requirements.

CONCLUSIONS

The variability within one roll or one small section of a roll can be as great as that within the whole lot. Thus, sampling at the beginning or end of a roll provides a representative sample and is adequate as a sampling location. Because χ^2 analysis indicates that not all properties follow the normal distribution, attribute sampling was chosen as the appropriate plan.

Transverse joint sealer had a high rejection rate—25 percent for lots submitted since 1968. The rejection rate is considered conservative because the sampling plan was weak. This gave large risks for most properties. The major causes of rejection were recovery, strength, and force deflection.

ACKNOWLEDGMENT

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Variations in Quality of Treated Materials Arising During Construction

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The statistical variation in quality of cement- and lime-treated materials that arises during construction was studied by comparing the flexural properties of samples recovered from nine contracts with those of samples prepared in a laboratory with the same raw materials. In this way the variations could be replicated and the significance for structural pavement design could be evaluated. The properties examined are bending strength, strain at break, and the elastic modulus. Samples recovered from the contracts indicated that, relative to the evaluated properties, a day's work may be accepted as homogeneous. The differences among sections constructed on different days were extremely significant, even when the sections were constructed with the same materials, by the same contractor, and according to the same specifications. Thus sections constructed on different days could not be regarded as of the same quality and as having the same properties, which varied significantly within a layer. The upper half of the layer seemed to have higher values than the lower half. The difference between field- and laboratory-prepared samples was significant in that the former generally tended to have lower values than the latter, but sufficient information is not available for ascertaining how much lower. It is recommended that a 30 percent reduction in the laboratory values be assumed for the interim.

The properties of materials produced during construction must match those properties assumed by the structural designer. In road construction this correspondence is generally assumed, because it is accepted that the construction controls, such as field density tests, and compliance with the construction methods outlined in the specification are adequate to ensure it. The properties of treated materials are believed to be significantly affected by variations in specifications and differences between construction techniques (mixing, compacting, and curing) of the different construction organizations.

Numerous researchers have extensively studied the effects of all these individual aspects on the different properties of treated materials, but I believe that the combined effects and interaction should be studied under the general heading of construction technique.

The objectives of this paper were therefore (a) to study and quantify the variations in the properties of treated materials constructed in the field and accepted by engineers and (b) to compare the properties of field-constructed materials with those of materials prepared in a laboratory under ideal conditions. The outcome might be useful to the eventual development of a more rational structural pavement design method, because it would indicate to the designer what allowance he or she should make to accommodate the construction process.

LITERATURE REVIEW

One of the first studies on the difference between field strengths and the design values of cement-treated materials was performed by Robinson (1), who attributed the difference largely to an insufficient distribution of the cement through a silty clay. He showed that, if the mixing efficiency could be increased to give a more even distribution of the cement, less cement would achieve the specified strength. This represented approximately a 30 percent reduction in the total stabilizing agent required and could mean significant financial savings on large contracts. This illustrates the importance of efficient mixing in reducing the difference in strength between field- and laboratory-prepared samples.

Mitchell and Freitag (2) reported that British engineers "found that normal construction methods result in a field strength equal to about 60 percent of the laboratory strength for a given cement treatment." The cement content should therefore be the amount needed to obtain a laboratory compressive strength equal to the required field strength divided by 0.6. This implies that, if a compressive strength of 1700 kPa is required, the laboratory strength should be 2800 kPa. The recommendation by Ingles and Metcalf (3) seems to have been based on this work.

Wang (4) performed compressive and bending tests on both field- and laboratory-prepared cement-treated materials. He compared the strengths and elastic moduli; Table 1 summarizes his results. He could not recover beam samples for testing from the materials treated with 6 percent cement until two months after their construction, and no beam samples could be recovered from the 3 percent cement section because the materials were too weak. He did obtain the same densities in the field as in the laboratory; nevertheless both the strength and the elastic modulus of the field samples were only about 50-60 percent of the corresponding laboratory samples. He explained the difference as the result of (a) better mixing in the laboratory than in the field, (b) less effective curing conditions in the field than in the laboratory, and (c) disturbance of field samples during cutting and extraction.

He stated that, "among the possible causes, the effect of low efficiency mixing seems to be a major factor. In addition, the differences in curing condition might be quite significant." This implies that he was not positive of the cause of the differences.

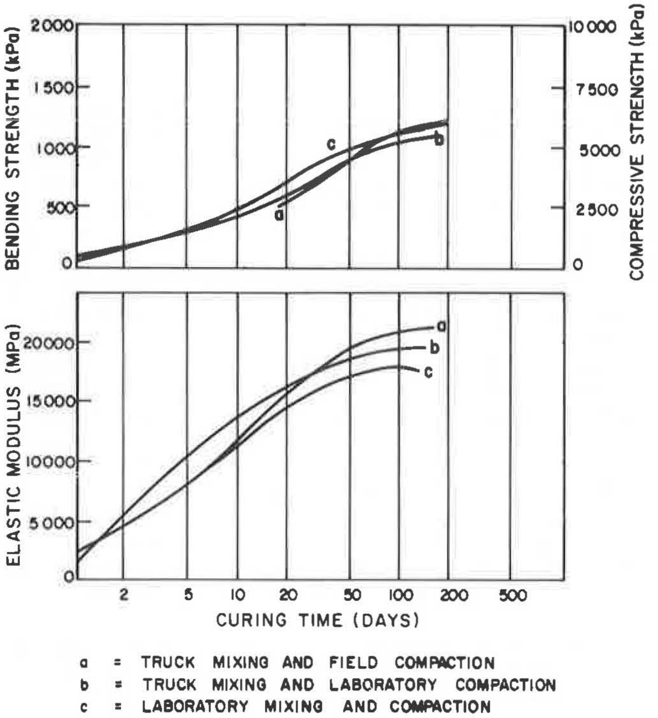
Fossberg (5) recorded the differences between three construction conditions: mixing in a ready-mix concrete truck (called truck mixing) and field compaction, truck mixing and laboratory compaction, and laboratory mixing and compaction. Approximately the same densities were obtained in all three conditions, and the recorded strength and elastic modulus values are shown against curing time in Figure 1. The differences were very small, and he obtained nearly the same strength and elas-

Table 1. Comparison of properties of field- and laboratory-prepared specimens.

	Strength				Elastic Modulus			
	Unconfined Compressive (kPa)		Bending (kPa)		Compressive (MPa)		Bending (MPa)	
Specimen Type	3% Cement	6% Cement	3% Cement	6% Cement	3% Cement	6% Cement	3% Cement	6% Cement
Field prepared	140-340	415-1030	W[a]	W[a]-450	70-66	140-1170	W[a]	W[a]-1720
Laboratory prepared	410-760	760-1720	100-280	380-660	280-1030	100-2200	410-1240	900-3030
Ratio of field prepared to laboratory prepared	0.33-0.45	0.55-0.60	W[a]	W[a]-0.69	0.25-0.64	0.13-0.53	W[a]	W[a]-0.57

[a] W = too weak to be sampled and tested.

Figure 1. Effect of mixing and compaction on elastic properties of a soil-cement.



tic modulus for all three construction conditions. He did, however, observe structural anisotropy in the field-compacted materials; that is, the elastic modulus in the direction of compaction was about 1.5 times lower than in the other two directions, an effect not found in the laboratory-prepared samples.

Structural anisotropy in field-compacted materials was also observed by Otte (6). Measurements on cement-treated crushed-stone samples from six different freeway contracts indicated less anisotropy than that recorded by Fossberg (5). The dynamic elastic moduli in the direction of the compaction (modulus A) and perpendicular to this plane (modulus B) were recorded with an ultrasonic tester. The measurements were taken on soaked and oven-dried samples, and the results are tabulated in Table 2 (6). This table indicates that anisotropy is real and can affect the relationship between field- and laboratory-prepared samples, because the outcome of the comparison between the two methods depends on the direction in which the properties of the field samples were determined.

The results of a previous study (7) indicated a strong possibility that the construction technique has a significant influence on the properties of cement-treated materials. Samples were taken from 14 pavements built by different contractors and supervised by different authorities. Although all the contracts were constructed to the same nominal specification and thus regarded by engineers to be of the same quality, the differences in the material properties were significant. The bending strength varied between approximately 400 and 4400 kPa, that is, by a factor of 10; the strain at break varied between approximately 113 and 251 $\mu\epsilon$, a factor of 2.2; and the elastic modulus varied by a factor of 10.5 between approximately 3700 and 38 900 MPa. These results indicate that cement-treated materials should not be regarded as having the same structural capacities just because they were built to the same specification.

On another contract, two adjoining cement-treated crushed-stone sections were constructed on different days. Although the same materials, specification, and construction team were used on both sections, the amount and extent of cracking differed significantly (Figure 2). The one section (the upper third of Figure 2) had a high elastic modulus and bending strength (8) and was cracked into rectangular blocks of approximately 2×2 m, while the other section (the lower two-thirds of Figure 2) had a low elastic modulus and bending strength and very few cracks reflected through the 25-mm asphalt concrete surfacing. Only construction variations between the two sections could have caused this significant difference in visible cracking and quality of material.

The literature survey seems to indicate that the four main parameters ensuring reasonable agreement between field- and laboratory-prepared samples are cement content and the uniformity of its distribution, density, delay between mixing and compaction, and efficient curing. If good agreement between the field and laboratory conditions can be maintained for these parameters, the material properties also ought to agree.

THE CONTRACTS

The cement- and lime-treated materials evaluated were taken from nine contracts under construction in South Africa between February and June 1976. A description of these contracts, information on the materials treated, and other relevant information are obtainable in other publications (6, 8).

An explanation of contract 1, which was a contract to construct the various sections of a full-scale experiment (9), is considered necessary. For this paper each experimental section 130 m long was considered individually and is referred to by the contract number and a section (S) number. Two different natural materials were treated on these sections—a lateritic soil on sections S7 and S8 and a gridstone on the others—but the percentage of compaction and the stabilizing agent discussed later were less for the lower than for the upper subbase.

The reasons for stabilizing the various materials varied. This explains why the type of stabilizer and specified strength criteria varied among contracts and

Table 2. Structural anisotropy in cement-treated crushed stone recovered from freeway contracts.

		Wet Samples					Dry Samples				
		Modulus A		Modulus B			Modulus A		Modulus B		
Contract	No. of Samples Tested	MPa	CV[a]	MPa	CV	Aniso-tropy	MPa	CV	MPa	CV	Aniso-tropy
A	6	34 600	2.3	37 000	4.6	1.069	25 100	5.3	28 700	3.1	1.143
B	12	30 100	4.0	35 900	4.3	1.192	23 200	14.5	27 800	11.2	1.198
C	12	25 200	6.5	29 200	7.4	1.158	17 300	13.5	19 500	12.0	1.127
D	12	29 700	6.3	31 900	6.6	1.074	20 700	7.7	23 900	11.9	1.154
E	9	27 444	7.2	30 178	5.5	1.099	23 666	7.2	27 266	5.8	1.152
F	10	29 000	5.0	32 200	3.6	1.110	25 000	4.2	30 400	3.3	1.216

[a] CV means the coefficient of variation in percentage.

Figure 2. Two adjoining sections, cracked and uncracked; the cracks sealed with bitumen emulsion.

various materials. Table 3 summarizes the percentage and type of stabilizer used, the use of the treated material in the pavement structure, and the criteria aimed for. Slagment is the South African trade name of commercially produced granulated blast-furnace slag.

On all the contracts, the mix-in-place technique, as generally practiced in South Africa with disc harrows and motor graders mixing the materials, was used. The materials were usually compacted with grid rollers. After compaction, the layers were kept moist for seven days, and if possible the tar prime coat was applied earlier. On contract 1 it was a condition of the contract that the curing membrane be applied immediately after the final compaction or very early the next morning.

OUTLINE OF STUDY

The site was visited and block samples (approximately 600×600 mm) were sawed from the treated pavement layer 7-27 days after construction of the layer, but usually between 20 and 27 days after construction. On one or two contracts it was necessary to remove the blocks relatively early; they were then moistened slightly, sealed in plastic, and stored in a humid room at 20°C. About 27 days after construction, the blocks were sawed into six or seven beam samples (75×75×450 mm), allowed to soak in water for 24 h, and tested in flexure according to a standard procedure (8, 10) to determine the bending strength, strain at break, and elastic modulus. In this paper these samples will be referred to as field-prepared or field samples.

Usually more than one block was removed from a particular section, because the blocks could collapse during subsequent handling. Although it was possible to recover blocks from some sections, it was not possible to saw them into beams because (a) they had fine cracks that only showed up when sawed, (b) the matrix was too weak to hold the larger (+75 mm) stones (and when sawed they pulled out and the beams crumbled), or (c) the material was too soft under wet cutting with a diamond blade. If any of these failures occurred it was not possible to obtain field samples.

During the site visit a 40-kg sample of the untreated soil and a sample of the stabilizing agent actually used by the die contractor were obtained. The relevant soil constants, such as maximum dry density and optimum moisture content, for the material used on the contract were also obtained from the site office.

These soil constants were used throughout the study, and no checks were made on the properties of the particular soil sample. Some variations can of course occur, but this was considered a realistic representation of construction practice. Eight beam samples (75×75×450 mm) were made from each soil sample for each contract. The samples were compacted for 3-4 min on a table vibrating at 50 Hz, but the soil had to be placed in three or four equal layers and tamped in order to work the predetermined mass into the mold. The samples were cured in a room at 100 percent relative humidity and tested at the same age as the corresponding field samples, generally 28 days. These will be referred to as the laboratory-prepared samples.

Throughout the study the goal was to compact the beams to the same average density and percentage compaction as measured by the engineer at the time of approving the construction of the layer. Small differences between the materials on which the soil constants were determined and the sample that was taken to prepare the laboratory specimens and between the specified optimum moisture content and that required by the vibrating compaction technique resulted in lower densities in the laboratory (Table 4).

The averages and coefficients of variation of the six or seven beams sawed from the field samples and of

Table 3. Percentages and types of stabilizer and criteria.

Contract No.	Percentage of Stabilizer	Type of Stabilizer	Layer	Specified Strength Criteria
1	3.75	50-50 mixture of Slagment and	Lower subbase	UCS[a] = 1200 kPa after 7 days
	4.0	portland cement	Upper subbase	UCS = 1725 kPa after 7 days
	5.0		Lower subbase	UCS = 1500 kPa after 7 days (S7 and S8)
2	3.5	Portland blast-furnace cement	Subbase	UCS = 1500 kPa after 7 days
3	4.0	Lime	Subbase	CBR > 70
4	4.0	Lime	Base	CBR > 70
5	4.0	Portland blast-furnace cement	Subbase	UCS = 1500 kPa after 7 days
6	4.0	50-50 mixture of Slagment and portland cement	Base	UCS = 1500 kPa after 7 days
7	3.0	50-50 mixture of Slagment and lime	Lower selected subgrade	Reduction of plasticity index; did not aim for increased strength
8	4.0	50-50 mixture of Slagment and lime	Subbase	CBR > 160; laboratory values around 180 to 200
9	4.0	50-50 mixture of Slagment and lime	Subbase	CBR > 160; laboratory values on 7 samples 174, 167, 201, 163, 154, 191, and 146

[a] UCS is unconfined compressive strength.

Table 4. Difference in field and laboratory densities.

Contract No.	Maximum Dry Density of Material (kg/m³)	Field Samples: Density kg/m³	Field Samples: Density CV[a]	Field Samples: Percentage Relative Compaction	Laboratory Samples: Density kg/m³	Laboratory Samples: Density CV	Laboratory Samples: Percentage Relative Compaction
1	2140	2064	2.2	96.0	1941	1.4	91.0
	2140	2120	2.2	99.0	1954	1.8	91.0
	2160	2083	5.9	96.0	1931	1.8	89.0
2	2020	1968	0.1	97.0	1917	1.1	95.0
3	1935	-[b]			1777	1.8	92.0
4	1965	-		-	1732	2.0	88.0
5	2160	-[b]		-	1960	1.1	91.0
6	1960	2009	4.5	102.5	1803	2.2	92.0
7	2030	-[b]		-	1876	1.0	92.0
8	2200	2114	3.3	96.0	1968	0.8	89.0
9	1865	-[b]		-	1712	1.2	92.0

[a] CV means the coefficient of variation in percentage.
[b] No field samples could be obtained.

Table 5. Variation during a day's work.

Contract No.	Section No.	No. of Beam Samples	Bending Strength kPa	Bending Strength CV[a]	Strain at Break με	Strain at Break CV	Elastic Modulus MPa	Elastic Modulus CV
1	S7	8	785	11.4	129	11.2	7 788	7.7
		7	917	21.4	141	13.2	8 450	8.7
1	S8	5	782	18.4	116	15.4	8 500	4.3
		7	785	26.4	130	12.4	7 992	16.1
2		6	502	13.2[b]	124	16.4[b]	5 900	4.5
		5	345	7.1	92	14.5	5 460	2.1
6		7	464	17.3[b]	237	17.6	2 825	9.6
		7	362	17.1	231	27.4	2 550	17.1
		6	385	31.3	249	22.1	2 608	12.5
8		5	129	35.0	172	27.3	1 810	41.0
		5	192	37.3	196	20.1	2 570	28.5
		6	173	36.5	225	29.1	2 190	25.0
1	S3	6	843	10.1	92	7.2	10 683	9.9
1	S4	7	928	20.0	89	17.3	11 264	11.5
1	S5	5	632	34.1	128	22.1	6 199	27.2[b]
1	S6	7	762	19.2	120	11.4	8 564	12.3
1	S16	8	826	20.9	111	17.3	9 525	15.1
1	S17	8	854	16.3	100	16.0	11 100	18.7

[a] CV means the coefficient of variation in percentage.
[b] Statistically significant difference at the 1 percent level.

Table 6. Variation in quality of work performed on different days.

Contract No.	Section No.	No. of Beam Samples	Bending Strength kPa	Bending Strength CV[a]	Strain at Break με	Strain at Break CV	Elastic Modulus MPa	Elastic Modulus CV
1	S3	6	367	35.7	70	7.5	7 033	24.5
1	S6	9	938	12.5	130	15.0	9 005	7.6
1	S10	10	1035	24.1	99	13.0	11 996	13.3
1	S17	4	762	11.1	102	26.1	9 937	20.0
1	S19	5	1216	24.0	100	17.1	16 240	2.5

[a] CV means the coefficient of variation in percentage.

those prepared in the laboratory were calculated. For each contract the corresponding bending strengths, strains at break, and elastic moduli in bending (8, 10) were compared.

RESULTS

The information obtained from the different contracts allows various interesting observations to be made.

On eight sections it was possible to saw beam samples from at least two different sample blocks. These blocks were constructed on the same day as part of the same section; the variations in their properties will thus indicate the variation during that particular day's work.

The contractor worked some of the adjoining experimental sections (each 130 m long) on contract 1 on the same day and, although they were considered as separate contracts for the purposes of this study, their variations may also be considered as variation during a day's work. Table 5 contains the results, which indicate that there was very little statistical variation during a day's work. The standard deviations are large, and differences at the 1 percent level of statistical significance were therefore only calculated for the bending strength and strain at break on contract 2, the elastic modulus on sections S5 and S6 of contract 1, and the bending strength between two of the three samples on contract 6. This implies that a section constructed on a particular day may be considered homogeneous, although the standard deviations are very large.

Variation in Work Performed on Different Days

Samples were recovered from the lower 150 mm of the cement-treated subbase on five sections of contract 1. These were all constructed with the same material and by the same construction team, but on different days. Table 6 shows the variations in measured properties.

Engineers would normally regard these materials (Table 6) as having the same properties and structural capacity because they were all constructed of the same materials, by the same contractor, and according to the same specifications. A closer study of Table 6 will reveal that this assumption is incorrect, because the bending strength varied by a factor of 3.3, the strain at break by 1.9 times, and the elastic modulus by 2.3 times. Materials exhibiting these orders of variation should not be regarded as being of the same quality.

Variation Within a Layer

On two sections of contract 1 (S20 and S21) it was possible to saw and divide the blocks recovered from the lower 150 mm of the cement-treated subbase in such a way that beams could be sawed from both the upper and the lower 75 mm of the layer. These will be referred to as the upper and lower halves respectively. The results are shown in Table 7.

Student's t-test, at the 1 percent level of significance, showed the difference in bending strength between the upper and lower halves to be significant for both contracts. The differences in the strain at break were not significant. The elastic moduli for contract 1 (S20) were significantly different at the 1 percent level, but on contract 1 (S21) the difference was only significant at the 5 percent level.

One may conclude, then, that on both contracts, although they were constructed on the same day, the upper half had both a higher bending strength and a higher elastic modulus than the lower half of the cement-treated layer.

Motor-grader mixing was used on both these sections. This is a mixing technique that most South African engineers believe produces a uniform vertical distribution of the stabilizing agent in the layer, because the material is bladed and windrowed across the width of the road while special care is exercised to ensure that the full depth of the layer is worked and mixed. There are numerous factors affecting the strength and properties of cement-treated materials, of which the amount of stabilizer is among the most important. These results seem to indicate that, although the mix-in-place technique is generally accepted in South Africa, it may not result in a very uniform vertical distribution of the stabilizing agent.

Variation Between Field- And Laboratory-Prepared Materials

Practical problems that arise in sawing beams from the recovered blocks or in preparing the samples in the laboratory resulted in only five contracts that yielded information usable for comparing field- and laboratory-prepared materials. This information is summarized in Table 8. Contracts 3 and 9 are omitted because no reliable information could be obtained (6, 8).

The table indicates that the properties of the field samples are generally lower than those of the laboratory samples. This does not, however, apply to contract 4, probably because of the low density achieved in the laboratory (Table 4). If generally higher densities could have been obtained in the laboratory, the differences between the field and laboratory samples might have been greater.

It is of interest to compare the results from contracts 6 and 7. The specified and required strength for contract 6 was 1500 kPa, while contract 7 was only treated to reduce the plasticity. This difference was borne out by the field samples, because the quality of the material from contract 6 was better than that from contract 7—it could at least withstand the action of the saw.

Statistically speaking, the quality of the laboratory-prepared samples from the two contracts was the same. This means that the material on contract 7 could have been prepared to obtain a better-quality treated material in the field. The economics of such an improvement depend on the particular site, but I believe that it would have been economical to use the full load-bearing potential of the lime-treated material.

Variation of Compressive Strength

After the bending test was performed, samples 150 mm long were sawed from the ends of a number of the beams and tested in compression. This, however, was not possible for all the field samples, such as for contract 4. The compressive strengths and the ratios between them are given in Table 9. The results indicate a significant difference between the compressive strengths of the field and laboratory samples but give no clear indication of which method produced the highest compressive strength.

DISCUSSION

Although samples recovered from the various contracts indicated little statistical variation across a section constructed on a particular day (Table 5), significant variations were found on sections constructed on different days (Table 6). Thus a specific section, constructed in one operation, can be considered homogeneous. However, different sections of a contract constructed on different days should not be regarded as homogeneous. Neither can a layer be accepted as homogeneous in the vertical direction, since the upper part seems to have better material properties than the lower part.

The study of the difference between field- and laboratory-prepared samples generally indicated better material properties in the laboratory-prepared samples. This was to be expected, because they were prepared under ideal conditions. The lower values for the field samples indicate that, because of the construction technique, the full potential of the materials is not being realized. Some research and development on construction techniques and procedures would therefore prove worthwhile and economical in the long term.

The difference in material properties between the field- and laboratory-prepared materials is an even more important consideration in view of the future application and implementation of the developing pavement structural design procedure. Currently an unconfined compressive strength is specified (as a materials requirement). The construction controls are a method

Table 7. Variation within a layer.

Contract No.	Section No.	Position	No. of Samples	Bending Strength kPa	Bending Strength CV[a]	Strain at Break $\mu\epsilon$	Strain at Break CV	Elastic Modulus MPa	Elastic Modulus CV
1	S20	Upper	6	320	16.0	94	18.3	4925	24.0
		Lower	6	245	17.0	96	16.1	3308	15.3
1	S21	Upper	5	361	13.0	104	23.0	5600	38.5
		Lower	5	162	17.1	120	14.0	2590	44.2

[a] CV means the coefficient of variation in percentage.

Table 8. Variation in field- and laboratory-prepared materials.

Contract No.	Field Prepared: Bending Strength kPa	CV[a]	Strain at Break $\mu\epsilon$	CV	Elastic Modulus MPa	CV	Laboratory Prepared: Bending Strength kPa	CV	Strain at Break $\mu\epsilon$	CV	Elastic Modulus MPa	CV
1[b]							817	13.0	111	11.2	10 625	10.0
							862	15.1	106	7.1	11 475	3.6
							753	22.0	116	23.2	9 417	3.4
2	502	13.2	124	16.4	5900	4.5	443	21.1	97	11.0	7 080	25.0
	345	7.1	92	14.5	5460	2.1						
4	221	49.5	122	22.2	2750	19.1	73	48.0	86	28.0	1 535	13.4
5[c]							481	5.0	101	13.2	9 380	23.1
6	464	17.3	237	17.6	2825	9.6						
	362	17.1	231	27.4	2550	17.1	462	23.3	138	25.0	4 422	21.0
	385	31.3	249	22.1	2608	12.5						
7[d]							619	18.3	189	16.0	4 586	8.0
8	129	35.0	172	27.3	1810	41.0						
	192	37.3	196	20.1	2570	28.5	777	9.1	161	7.6	7 149	6.4
	173	36.5	225	29.1	2190	25.0						

[a] CV means the coefficient of variation in percentage.
[b] The results of the tests of the field-prepared specimens in contract 1 are presented in Tables 5-7.
[c] The field specimens could not be taken because there were so many large stones in the block it could not be sawed.
[d] The field block was too weak to be sawed.

Table 9. Variation in compressive strength of field- and laboratory-prepared materials.

Contract No.	Field Samples kPa	Field Samples CV[a]	Laboratory Samples kPa	Laboratory Samples CV	Ratio
1	4290	33.2	2443	6.7	1.75
	6367	22.0	2340	10.2	2.72
	2128	63.0	4050	13.1	0.52
2	1210	21.4	1830	9.1	0.66
3	-		432	16.0	-
4	-		488	28.2	-
5	-		1353	14.2	-
6	2303	28.3	2195	27.2	1.05
7	282	28.4	2286	12.1	0.12
8	917	42.1	2203	9.2	0.42
9	559	32.1	293	102.5	1.91

[a] CV means the coefficient of variation in percentage.

specification and a check on the specified compressive strength of the mixture and density of the final product. If the contractor complies with these specifications, the materials fit into the original design definitions and the structural pavement design virtually takes care of itself. This is essentially an empirically developed procedure based on successful previous applications of the particular structural layout with the particular type of material.

To best use the produced materials and structural layout, the designer must know the exact quality of the field-prepared materials, or he or she should know the amount by which the laboratory values should be reduced to comply with the field-prepared values. The information in Table 8 is insufficient to reliably indicate the amount of allowable reduction. More study on many more contracts will be required to obtain it. In the meantime it seems that the field bending strength is between 20 and 150 percent of the laboratory bending strength. The corresponding numbers for the strain at break and elastic modulus are between 63 and 180 percent and between 25 and 150 percent, respectively.

At present the quality of cement- and lime-treated materials is controlled by a density determination after final compaction and an unconfined compressive strength test. This test is made on a sample taken after the stabilizing agent, construction water, and material have been mixed, but just before compaction starts. The sample is taken to the laboratory where it is mixed, compacted, cured, and tested under ideal conditions to obtain either the unconfined compressive strength (UCS) or California bearing ratio (CBR), depending on whether it is a cement- or lime-treated layer. The CBR of the material produced by the construction team—i.e., the field-prepared material—may differ significantly because the mixing, compaction, and curing conditions differed significantly. Controlling the strength in this way seems inappropriate, because only the correct amount of stabilizing agent to be added in the field is controlled. Also, only the question of whether the physical and chemical properties that affect the increase in strength and CBR are the same in both materials is asked. This test therefore controls only the strength of the laboratory-prepared materials and not that of the field-prepared materials. Because it is the strength of the latter that controls the future performance of the pavement, I suggest that these be measured and controlled instead. Samples should be recovered from the completed field-prepared materials. It is the bending strength, elastic modulus, and strain at break that should be measured and controlled rather than the UCS or CBR of the laboratory-prepared materials.

CONCLUSIONS

Variation in material properties (i.e., the bending strength, strain at break, and elastic modulus) on a project as a result of the construction process is real and highly significant. Pavement designers should take cognizance of this and allow for it in the structural pavement design.

From the limited number of samples taken on a contract and the limited number of contracts suitable for this study it appears that

1. The variation in material properties in a section constructed during a particular day is not statistically significant, and for pavement design purposes the section may be regarded as homogeneous;
2. The statistical variation in material properties in sections constructed on different occasions or days is significant, and these sections may not be considered the same, even when the same materials, contractor, and specification apply to all the sections;
3. The material properties are not constant throughout the depth of the layer, and the upper half seems to have higher values than the lower half; and
4. The properties of materials constructed on a road by a contractor are significantly poorer than the values obtained on similar materials prepared in a laboratory. From this study it is not possible to indicate the degree of this difference.

Predicting the future behavior of a cement- or lime-treated layer in a pavement from laboratory-prepared samples would appear to be misleading. The extent of the difference between the design properties and the properties of the on-site material is unknown and seems to vary from contract to contract. Nor is the difference constant during the construction period; it varies from day to day. Until these differences have been studied and quantified accurately, for example by controlling the relevant properties or by tightening up the specification on the standard deviation of materials quality, it seems a very difficult task to accurately predict the long-term behavior of a pavement containing cement- and lime-treated materials.

RECOMMENDATIONS

From practical observations and until more specific recommendations become available, it is recommended that the values of the properties of field-prepared cement- and lime-treated materials be taken as 70 percent of those of laboratory-prepared materials. A 30 percent reduction in the laboratory values is thus recommended. Research along the lines indicated in the paper should be continued.

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Demonstration Project 42: Highway Quality Assurance

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The purpose of the Federal Highway Administration's demonstration project on highway quality assurance was to develop a short course for government and private administrative personnel in the highway industry to demonstrate the benefits of using statistical methods in quality assurance programs. The two-and-a-half-day course was divided into two essential parts: the first devoted to the development of basic statistical methods, the second to the application of these methods in acceptance plans. This paper discusses briefly the statistical methods covered and several of the areas in which they are applied. A limited discussion of the response to the 31 courses presented and comments on possible future programs of this type are included.

Federal Highway Administration (FHWA) Demonstration Project 42—Highway Quality Assurance, sponsored and funded by FHWA region 15, developed a short course for presentation to federal, state, and local highway and transportation administrative personnel and administrative personnel from the construction and materials production industry. The course presented statistical quality control and acceptance techniques designed to instruct course participants in judging the benefits of using statistical quality assurance programs.

The course lasted two and a half days. The first day was devoted to the development of basic methods used in statistical quality assurance and the second day to the application of these methods in acceptance plans. Control procedures such as control charts were covered only briefly, but the implications of statistical acceptance plans for the contractor or producer were discussed. For instance, the required average strength of concrete with a given variability was indicated for various acceptance plans. An additional half day was alloted for contractor and producer comments on statistical quality assurance, for a description of computer simulations of acceptance plans, and for discussions of rapid testing procedures and testing methodology.

COURSE CONTENT

The two-day portion of the course covering statistical concepts and applications was developed by C. S. Hughes, M. C. Anday, K. H. McGhee, and me, all from the Virginia Highway and Transportation Research Council and acting as consultants for FHWA region 15. The course outline was as shown below, and the course manual followed the same outline.

Session No.	Topic
1	Need for statistical methods
2	Introduction to distribution of measurements
3	Characteristics of normal curve
4	Calculation of standard deviation
5	Variability of highway products
6	Relationship of means and individuals
7	Relationship of statistics to specifications
8	Development of several statistical specifications
9	Implications of several statistical specifications
10	Summary

In the outline, sessions 1-7 covered the basic concepts of statistical quality assurance as developed in the project, and sessions 8 and 9 illustrated the applications developed by several states and the FHWA.

Basic Concepts

In the initial session the instructor indicated that statistics is simply the science that deals with the treatment and analysis of numerical data; it is no more than a tool that can be used to put acceptance and control plans on a quantifiable, rational basis. He stressed that the use of statistics does not eliminate the need for proper and often difficult engineering decisions such as which product characteristics should be tested and what the acceptable levels of the chosen characteristics are. In fact, statistical quality assurance was defined as a two-component process of making sure the quality of a product is what it should be. The two components are "making sure the quality of a product is," which involves control and acceptance and can benefit from statistical procedures, and "what it should be," which involves making proper engineering decisions.

It was also indicated in session 1 that highway materials and processes are not perfect, but that variability does exist, and that statistical methods can be useful in defining the amount of this variability. In this regard, the importance to private enterprise of its involvement in the whole statistical quality assurance issue was discussed. Appropriate acceptance plans, including specification limits, can be accomplished only after the reasonable production variabilities have been identified.

In session 2 the concepts of population and samples were discussed. In a chip-sampling class exercise from a known population, about 40 samples were drawn and used to illustrate that sampling tends to miss extreme values in the population. Plotting the sample also results in a histogram that tends to form a bell-shaped distribution similar to the known population distribution. By averaging each four consecutive sample results and plotting the averages it was shown that sample averages vary less than individual sample results and form a similar but narrower distribution.

The concepts discussed in session 2 were reemphasized in session 3, first by showing histograms of several types of highway-related sampling data and then by discussing the characteristics of the normal curve. The concepts of average (μ), standard deviation (σ), and areas under the normal curve represented by $\mu \pm z\sigma$ were presented, and several class problems were used to illustrate them. It should be mentioned that throughout the remainder of the course all concepts were presented on the basis of the normal distribution, essentially because of time limitations in presenting concepts; that is, sampling distributions and, in particular, the t distribution were not introduced in the course. But it was and is believed that, for presenting general concepts, the use of the normal distribution only is sufficient.

Session 4 dealt with the method of calculating the standard deviation and the relationship of the standard deviation and the range for various sample sizes. Most of session 5 was devoted to presenting typical variabilities found in highway products and processes from various data sources. One new concept was presented in session 5: the components of variance. It was explained that in statistical control or acceptance plans the square root of the total variance (σ^2) is the value of interest but that this value is the square root of the sum of both testing variance (σ_t^2) and materials variance (σ_μ^2). Thus, changes in either sampling and testing practices or in production practices could influence σ.

The use of sample averages initially discussed in session 2 was discussed in detail in session 6. The concept of the standard error of the mean ($\sigma_{\bar{X}}$) was introduced and its relationship to the standard deviation (σ) was discussed ($\sigma_{\bar{X}} = \sigma/\sqrt{N}$, where N is the number of samples averaged). It was indicated that areas under the curve are determined in the same way with $\sigma_{\bar{X}}$ as with σ and that clearly the ability to estimate the true population mean value (μ) improves as N increases. The importance of considering sample size when setting specification limits was stressed through the use of illustrations and class problems.

For session 7 the concepts presented in the previous six sessions were used to illustrate how statistical methods relate to the development of acceptance or control plans. The concepts of producer and consumer risks and how they influence sample size and acceptance limits were discussed, as were lot size and random sampling. Again, it was stressed that in developing acceptance or control plans extremely important engineering decisions must be made on what is acceptable and what is unacceptable in a product and that statistical methods allow specification limits to be set so that the probability of rejecting an acceptable product or accepting an unacceptable product is known. Both variability-known and variability-unknown approaches to specification development, as well as some limited discussion of control charts, were included in session 7.

Applications

As already indicated, the second day of the course (sessions 8 and 9) was devoted to the application of statistical methods in acceptance plans. The thought process used in developing some statistical specifications was covered in session 8, and the implications of several additional

Figure 1. States where Project 42 classes were held.

specifications for the producer and for the accepting agency were covered in session 9. The specifications covered in the two sessions included

1. A strip method for controlling and accepting compaction,
2. A specification for the acceptance of the cement content of pug-mill-mixed aggregates,
3. Specifications for the acceptance of gradation and asphalt content of bituminous concrete,
4. Specifications for the acceptance of gradation and liquid limit of pug-mill-mixed base and subbase materials,
5. The American Concrete Institute (ACI) building code, part 3 (portland cement concrete),
6. The FHWA Demonstration Project Guide Specification for portland cement concrete, and
7. The Georgia and West Virginia specifications for the thickness of concrete pavement.

This list includes both variability-known and variability-unknown types of specifications.

COURSE PRESENTATIONS AND RESPONSE

The pilot course was held in August 1976 in Washington, D.C. Participants included members of the Technical Advisory Committee and several FHWA region 15 personnel. Several constructive criticisms voiced at the initial course were incorporated, particularly those on session 7 about risk and variability-unknown specifications.

Originally, 10 regional courses were planned to follow the pilot course. However, because of the very good response, the courses shown as asterisks in Figure 1 were given. One course (a), that at Kansas City, Missouri, was a regional course covering FHWA region 7. All other courses were conducted essentially for the requesting state, and two courses were held for several states (Alaska, Washington, Illinois, Ohio, and New Jersey).

Generally, attendance at each of the courses was between 35 and 45 representatives from state and other local agencies, the FHWA, and, to a lesser extent, contractors and producers. Usually the statistical quality assurance concepts and methods covered were well accepted. In fact, in several courses the contractor and producer personnel, who had exhibited a negative attitude at the beginning of the course, became particularly enthusiastic about the potential of this approach.

There were three areas in which problems recurred. The concept of risk always confused several people. The idea of determining what an unacceptable product is and deciding what a reasonable chance of accepting this product is can seem somewhat unusual. Second, the course participants frequently confused testing methods and technology with statistical procedures. A final problem was that in several of the courses participants held positions too low in the administrative structures of their agencies to be among those who decide if statistical methods are desirable and should be used. Thus, although the response was good, the course may not have been as effective in promoting the implementation of statistical procedures as had been hoped, because top management people were not involved in the courses.

DESIRABLE FUTURE ACTIVITIES

While I feel that Demonstration Project 42 was very successful, I also feel that additional educational activities are desirable. Already some courses for presenting statistical methods and procedures to technical personnel and technicians are under way. In addition to this effort, other possible activities could include

1. A very concise, one-day course for top-level management that would cover the essential concepts of statistical quality assurance, including the concept of risk and the definitions of an acceptable product and an unacceptable product from an engineering standpoint;
2. A workshop course of two or three days designed to develop greater expertise in the states for developing statistical acceptance procedures (some actual specifications based on the needs and characteristics of particular states) would be developed in a general form; and
3. The development of some model specifications in an attempt to standardize to some extent the efforts of various states.

It is not necessarily intended that all or several states adopt the same specification for any given production items. Conditions, requirements, and values vary from state to state. However, some consistency in approach is desirable, and a flexible guideline specification could help develop consistency.

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