10. J. B. DiCocco. Quality Assurance for Portland Cement Concrete. Federal Highway Administration, Sept. 1973.
11. Quality Assurance in Highway Construction. Public Roads, Vol. 35, No. 6 to 11, Feb.-Dec. 1969.

Publication of this paper sponsored by Committee on Quality Assurance and Acceptance Procedures.

Statistical Quality Assurance in Highway Engineering in South Africa

M. F. Mitchell, South Africa Department of Transport
C. J. Semmelink, National Institute for Transport and Road Research, South Africa
A. L. McQueen, A. A. Loudon and Partners, South Africa

This paper examines the first large-scale application of process and acceptance control plans to a major road construction project in South Africa. The acceptance control scheme used and its background are outlined, and certain controversial features of the scheme are discussed. The variability of typical South African construction materials and processes is indicated. Some economic consequences of the use of the plan are also reported. Because the average quality of the work was well above the minimum standard required, a fully conclusive assessment of the financial advantages or disadvantages of the scheme is not possible. Because of this, a comparison was made between the acceptance decisions of the specific scheme discussed, and those of the engineering judgment approach. It is concluded that the use of the statistical method leads to more consistent interpretation of results, and the continued use of this scheme on highway projects is recommended.

Highway authorities in South Africa, like authorities in other countries, have for several years been concerned about the quality of construction work, particularly about the application of uniform standards of judgment to the acceptance or rejection of such work. The Division of National Roads of the South Africa Department of Transport—aware that differences existed in materials, construction processes, and contractors and that supervisory engineers often applied different criteria to work that did not strictly conform to specifications—decided in 1972 to incorporate statistical principles into certain road contracts. This was done so that the properties of engineering materials could be rationally defined and to assist in providing uniform criteria of judgment for acceptance or rejection decisions. The department primarily wanted to give economic encouragement to contractors who delivered uniform construction work and to reduce as far as possible the risk of having basically acceptable work rejected.

The theory and the design of the acceptance control plans adopted for use by the Division of National Roads are fully described by Kühn, Mitchell, and Smith (1). A document that explains the system and the method of implementation and also contains a typical specification is available (2). In conjunction with the Natal Roads Department, the division decided that the first major contract on which statistically oriented acceptance control procedures would be used in judging certain parameters would be a contract encompassing a portion of National Route 2 on the Durban Outer Ring Road. This $8 million contract consisted of the construction of 4.8 km of six-lane double carriageway freeway including 1.3 million m^3 of earthworks, 66 Gg of asphaltic concrete, and 121 000 m^3 of base and subbase layers.

ACCEPTANCE CONTROL IN SOUTH AFRICA

The decision to use a statistically oriented acceptance control procedure for the National Route 2 contract did not originally meet with enthusiasm from all the road engineers involved in the project. This was not surprising for two reasons: (a) Nearly every change in existing quality control procedures in road construction had met with the same reaction, and (b) most engineers do not possess an in-depth knowledge of the principles of statistics. Statistical methods are helpful, however, in solving problems of quality control and acceptance of completed work in road engineering, provided they are properly applied. It is anticipated that such procedures will come to be recognized as a definite improvement on past methods and that they will become standard practice for quality control.

In the early stages of the development of road construction in South Africa, many of the current specifications and tests were developed on an empirical basis and were largely method-type procedures both to guide contractors and to provide parameters for quality acceptance. One of the major functions of a specification was to convey technical instructions to both the contractor and the resident engineer.

It is hoped that, because of the accent on technological improvements in the contracting industry, it will soon be possible to specify only the significant characteristics of the end product in terms of measurable parameters and use a rational acceptance control procedure for the acceptance of the work. Before this goal can be reached many problems must be overcome, the most important of which is changing the practice of ill-defined joint control of both processes and acceptance by contractor and engineer to separate control of processes by the contractor and control of acceptance by the engineer.

The statistical procedures now being introduced into the South African road construction industry are not new concepts; similar procedures have been successfully applied in road construction in North America for many

Figure 1. Normal distributions of populations with a lower specification limit.

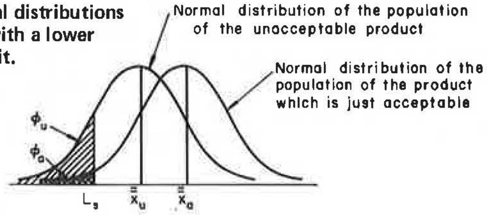
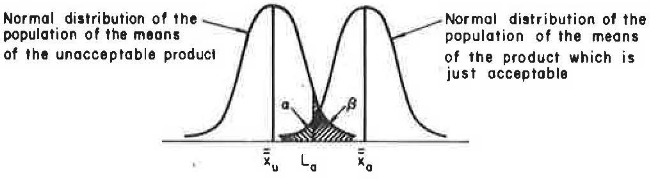


Figure 2. Normal distributions of populations of the means.



years. To quote from DeYoung (3),

> The first application of statistical quality control in American industry was made by Dr. Walter Shewhart of the Bell Telephone Laboratories during the 1920's. The development of this new methodology and its acceptance by other industries in the United States was very slow until the advent of World War II.
>
> About this time a new concept, statistical decision, was introduced. The Department of Defense, which was faced with a massive procurement program, recognized the utility of this technology and pioneered the general development and application of statistical-based process control and acceptance concepts to industrial products. This effort stimulated its application to a great variety of industrial products.
>
> The rather startling experiences with construction control at the AASHO Road Test and the institution by the Bureau of Public Roads and state highway departments of a "record sampling program" are considered to have generated the first real active effort by highway engineers to explore the use of statistical concepts as a tool for the solutions of many quality assurance problems. Dr. Robert G. Baker, former Director of the Office of Research and Development of the Bureau of Public Roads, is cited as one of those who recognized its power and aggressively promoted its use. He believed this development should contribute as much to our ability as engineers as did the advancement of the elastic theory in the 19th century and the use of computers and new construction equipment in the 20th century.

The South African procedures, of course, incorporate values for factors that have reflected construction quality in that country over the past few years.

RATIONALE OF ACCEPTANCE CONTROL PLAN

No materials and construction processes are absolutely homogeneous; i.e., they all vary according to some type of distribution (usually approximating a normal distribution). Therefore, it must be accepted that a limited number of sample test results will yield a mean and a standard deviation, which may differ from the true population mean and standard deviation. In addition, it is obviously impractical to test all possible samples that can be drawn from a population. To complicate matters even further, the test results may possibly belong to a population that is either acceptable or unacceptable in terms of the specification. The normal distributions of product populations with a lower specification limit are shown in Figure 1. In the figure,

L_s = specification limit,
ϕ_a = percentage of the material below L_s for a product that is just acceptable,
ϕ_u = percentage of the material below L_s for a product that is unacceptable,
$\bar{\bar{x}}_a$ = population mean of a product that is just acceptable in terms of the specification, and
$\bar{\bar{x}}_u$ = population mean of a product that is totally unacceptable in terms of the specification.

Because the mean value of the test results ($\bar{x}_n$) is used to assess the material, this value should be compared with the population of the means of both the acceptable and unacceptable products that have a standard deviation equal to ($\sigma/\sqrt{n}$), where σ is the true standard deviation of the population and n is the number of samples. In practice the value of the sample standard deviation (S) is used for σ because it is the best available estimated value (Figure 2).

From Figure 2 it is evident that, if the mean test result ($\bar{x}_n$) is compared with an acceptance limit (L_a) and the product is rejected because $\bar{x}_n$ is just smaller than L_a, the contractor runs a risk of α percent of being wrongly rejected because there is still an α percent probability that the true mean of the population is equal to $\bar{\bar{x}}_a$. On the other hand, if the product is accepted because the value of $\bar{x}_n$ is exactly equal to L_a, the client runs a risk of β percent of accepting an unacceptable product because there is still a β percent probability that the true mean of the population is equal to $\bar{\bar{x}}_u$. A perfect acceptance plan would be one in which these two risks, α and β, were zero. From a practical point of view this is impossible, and effort is best directed toward making these two values as low as possible and at the same time maintaining practical limits for the quality of the work.

Furthermore, if the value of $\bar{x}_n$ is lower than L_a and tends toward $\bar{\bar{x}}_u$, it is clear that the contractor's risk (α) of being wrongly rejected decreases but the client's risk (β) of accepting an unacceptable product increases. It is considered equitable, therefore, that lower payment should be made for this material if it is accepted by the client; this was the case with some of the asphaltic concrete material in the road construction contract discussed here.

The values for ϕ_a have been calculated from past as-constructed data to ensure that the standard of construction remains relatively stable in terms of previous specifications (1). Substantial information on the variability of material and construction is available from overseas investigations, particularly those conducted in the United States. Some information on this has also resulted from analyses of road construction data in South Africa. This information was verified and extended by analyzing data from some recently completed South African road construction projects. This was only a limited investigation, however, and it is imperative that much more information be analyzed if the parameters involved are to be adequately quantified.

For each of the chosen product properties and structural layers involved in a particular contract, a lot consisting of between 20 and 110 test values was analyzed and the mean, the standard deviation, and the coefficient of variation were determined. These determinations were repeated for different lots from various contracts throughout South Africa (Tables 1, 2, and 3); the number of lots (n) varied between 3 and 34.

The following quantities were among those finally obtained for each property: overall mean specification value (x_s), overall mean achieved ($\bar{x}$), standard deviation ($\sigma_{\bar{x}}$) and coefficient of variation ($v_{\bar{x}}$) for all n groups, and standard error of all standard deviations (σ_σ) and coefficients of variation (σ_v). In addition, the 50th and 70th percentiles of both the standard deviation and the coefficient of variation (σ_{50}, σ_{70}, V_{50}, and V_{70}) were calculated as well as the percentage defective (ϕ) of the achieved mean ($\bar{x}$) relative to the specified mean (x_s) by using the 70th percentile of the coefficient of variation (V_{70}). V_{70} was used because it was considered to be generally achievable under present conditions.

In the scheme used, the contractor's risk (α) is fixed at 5 percent at the acceptance limit, which means that the contractor runs a 1-in-20 risk of having a product of borderline quality rejected. The risk at the acceptance limit will be lower for a higher quality material and higher for a lower quality material.

The same principles apply to material properties with upper specification limits or double specification limits. But, in the case of properties with double

Table 1. Variability of bituminous materials.

Parameter	Number of Lots (n)	Overall Mean ($\bar{\bar{x}}$)	Coefficient of Variation of Lot Means ($V_{\bar{x}}$ percent)	50th Percentile Coefficient of Variation (V_{50} percent)	Percentage Defective From Current Specifications (ϕ based on σ_{70})
Continuously graded material					
Flow	10	2.34	15.11	14.50	33.05
Stability	10	9.87	19.32	13.00	0.21
Voids	10	4.94	19.58	16.78	37.51
Bitumen content	10	5.42	8.17	2.40	7.29
Passing sieves					
13.2 mm	10	98.51	1.69	0.90	0.27
4.75 mm	10	53.99	6.74	6.40	31.30
2.36 mm	10	36.42	8.88	8.00	40.02
0.30 mm	9	14.71	8.06	11.08	10.60
0.075 mm	10	7.07	9.35	11.00	1.76
Percentage compaction	10	96.19	0.60	1.12	16.11
Gap-graded material					
Flow	17	4.68	80.54	15.00	48.16
Stability	17	7.14	15.75	17.25	5.11
Voids	17	5.29	17.99	16.75	21.58
Sieve analysis (0.075 mm < x < 2.36 mm)	17	43.11	18.12	6.76	62.06

Table 2. Variability of unstabilized materials.

Parameter	Number of Lots (n)	Overall Mean ($\bar{\bar{x}}$)	Coefficient of Variation of Lot Means ($V_{\bar{x}}$ percent)	50th Percentile Coefficient of Variation (V_{50} percent)	Percentage Defective From Current Specifications (ϕ based on σ_{70})
Compaction of fill	16	96.63	1.99	2.88	4.05
Selected subgrade					
Compaction	14	98.20	2.69	3.25	9.73
California Bearing Ratio	8	42.68	26.07	34.50	1.58
Plasticity index	14	4.27	54.22	80.00	3.03
Liquid limit	12	15.63	36.96	62.00	36.94
Subbase					
Compaction	16	99.37	2.14	2.38	6.11
California Bearing Ratio	12	59.44	57.60	21.67	13.35
Plasticity index	13	3.50	67.25	65.00	0.32
Liquid limit	13	12.09	65.28	81.00	40.87
Compaction of base course (natural gravel)	6	99.59	0.27	1.30	20.39
Crusher-run base course					
Compaction	12	97.46	6.92	2.20	11.86
Layer thickness	34	130.71	15.31	8.30	41.10
Plasticity index	7	3.04	18.75	43.75	4.56
Liquid limit	7	17.61	13.73	36.50	13.31
Passing sieves					
2 mm	11	26.50	11.60	14.85	14.54
0.425 mm	12	14.07	24.16	17.00	10.51
0.075 mm	10	5.73	47.91	21.00	32.56

Table 3. Variability of stabilized materials.

Parameter	Number of Lots (n)	Overall Mean ($\bar{\bar{x}}$)	Coefficient of Variation of Lot Means ($V_{\bar{x}}$ percent)	50th Percentile Coefficient of Variation (V_{50} percent)	Percentage Defective From Current Specifications (ϕ based on σ_{70})
Compaction of stabilized subgrade	5	96.75	1.51	2.56	7.70
Stabilized subbase					
Compaction	19	98.18	1.57	2.15	12.81
Layer thickness	17	134.03	11.21	6.25	46.22
California Bearing Ratio	6	215.50	35.43	37.50	11.55
Plasticity index	5	5.85	79.34	23.50	9.70
Liquid limit	5	19.69	48.53	9.33	—
Stabilized natural gravel base course					
Compaction	34	99.96	2.33	2.00	12.19
California Bearing Ratio	26	306.74	24.76	30.83	9.48
Plasticity index	3	3.86	113.76	67.00	10.53
Liquid limit	4	15.97	55.15	128.00	17.06
Stabilized crusher-run base course					
Compaction	27	100.69	1.48	1.93	11.40
Layer thickness	19	113.84	15.28	9.56	10.82
Plasticity index	10	2.94	33.45	32.50	1.17
Liquid limit	10	17.12	30.18	13.00	13.03
Passing sieves					
2 mm	27	31.92	22.38	12.38	4.75
0.425 mm	28	16.39	22.46	15.00	2.35

Table 4. β risks of the client.

Property	n	ϕ_a	ϕ_u	Client's Risk (%) β_a (α = 5 percent)	β_r (α = 1 percent)	β_r (α = 0.1 percent)
Relative density of fill	4	5	20	51.54	76.43	93.11
Relative density of selected subgrade	4	10	40	34.02	60.63	84.93
Subbase						
Relative density	6	10	40	19.10	42.36	71.61
Lime or cement content (if stabilized)	20	10	40	0.16	1.15	6.57
Crusher-run base						
Relative density	6	15	60	6.49	20.24	47.24
Grading						
Percentage < 19 mm	6	10	40	19.10	42.36	71.61
Percentage < 2.36 mm	6	10	40	19.10	42.36	71.61
Percentage < 0.425 mm	6	10	40	19.10	42.36	71.61
Percentage < 0.075 mm	6	10	40	19.10	42.36	71.61
Asphalt surfacing						
Relative density	6	15	60	6.49	20.24	47.24
Asphalt content	8	10	40	10.32	28.02	57.21
Grading						
Percentage < 13.2 mm	6	10	40	19.10	42.36	71.61
Percentage < 2.36 mm	6	10	40	19.10	42.36	71.61
Percentage < 0.300 mm	6	10	40	19.10	42.36	71.61
Percentage < 0.075 mm	6	10	40	19.10	42.36	71.61

specification limits, the value of ϕ_a, which is used in deriving the acceptance limit, is limited to 50 percent of the total percentage allowed to be outside the double specification limits.

If the test results are to represent the true population of the material property as accurately as possible, the samples must be randomly obtained (i.e., every position or portion of the material should have an equal chance of being selected for sampling). This leads to a more balanced assessment of the material by eliminating the subjective element that would otherwise be involved.

The distinction between acceptance control and process control procedures should be noted: Acceptance control indicates the inherent quality of the finished population from which the sample was drawn, and process control, which is based on selected sampling during the actual production process, indicates adjustments required of the producer to maintain the process within the prescribed limits.

FEATURES OF ACCEPTANCE CONTROL PLAN

Contractor's Risk

Implicit in the acceptance control plan of the South Africa Department of Transport (1) is the fact that both the contractor and the client at all times run the risk that the wrong conclusion will be drawn from the test results. These are the commonly known α and β risks. The relation between the α and β risks is as follows:

$$(k_\alpha + k_\beta) = \sqrt{n}(k_{\phi_a} - k_{\phi_u}) \qquad (1)$$

where

k_α = normal distribution constant, related to the contractor's risk of α percent;
k_β = normal distribution constant, related to the client's risk of β percent;
k_{ϕ_a} = normal distribution constant, related to the percentage ϕ_a; and
k_{ϕ_u} = normal distribution constant, related to the percentage ϕ_u.

Both ϕ_a and ϕ_u are, of necessity, dependent variables because they must conform to specified engineering requirements in the definition of acceptable and unacceptable products. n may be an independent variable, but for the immediate future at least it should conform as far as possible to currently used sample sizes. At this stage, therefore, n is a dependent variable. In the case of the remaining parameters, α and β, either one could be an independent variable but the other must be a dependent variable. For the control of an unacceptable product, β is fixed to limit the client's risk; for the control of an acceptable product, α is fixed to limit the contractor's risk.

In South African practice, it is currently deemed advisable to control the acceptable product—in other words, to fix α—because α is the only unknown parameter whereas, in the control of the unacceptable product, decisions would have to be taken on both ϕ_u and β. It is also felt that the fixing of α at a reasonably low level will provide the essential assurance to the contractor—through the introduction of rational quality assurance—of fair judgment under all circumstances.

The contractor's risk at the acceptance limit (α_a) was set at a reasonable level of 5 percent. A second limit with an even lower risk, known as the rejection limit, was introduced. Initially, the contractor's risk at the rejection limit (α_r) was set as low as 0.1 percent. However, as the contractor's risk of having an acceptable product wrongly assessed decreases, the client's risk of accepting an unacceptable product increases (Figure 2).

Table 4 shows the β risks of the client for some of the properties that have already been incorporated into the system for the proposed sample sizes; α risks equal to 5.0, 1.0, and 0.1 percent; and ϕ_u equal to four times ϕ_a. Data given in Table 4 clearly indicate that the client assumes a much greater risk than the contractor does. For this reason, the contractor's risk was set at 1 percent at the rejection limit, which leads to a substantial decrease in the client's risk.

Effect of Using Sample Standard Deviation

Although the assumption has been made that the true standard deviation (σ) of the population as a whole is equal to the sample standard deviation (S), this is not quite correct. However, S has a normal distribution with a mean $[\sqrt{(2n-3)/(2n-2)} \cdot \sigma]$ and a standard deviation $(\sigma/\sqrt{2n-2})$. A product is judged by comparing the mean test result ($\bar{x}_n$) with the acceptance limit (L_a or L_a') or the rejection limit (L_r or L_r'). By taking the properties of S into account, it is possible to calculate the true α risk (the contractor's risk of being wrongly

Table 5. True α risks of the contractor.

Property	Sample Size	Contractor's Risk		
		α_{at}	α_{rt}	ϕ_a
Relative density of fill	4	6.88	1.24	5
Relative density of selected subgrade	4	5.31	0.97	10
Subbase				
Relative density	6	5.98	1.09	10
Lime or cement content (if stabilized)	20	7.84	1.90	10
Crusher-run base				
Relative density	6	5.19	0.98	15
Grading				
Percentage < 19 mm	6	5.98	1.09	10[a]
Percentage < 2.36 mm	6	5.98	1.09	10[a]
Percentage < 0.425 mm	6	5.98	1.09	10[a]
Percentage < 0.075 mm	6	5.98	1.09	10[a]
Asphalt surfacing				
Relative density	6	5.19	0.98	15
Asphalt content	8	6.46	1.25	10[a]
Grading				
Percentage < 13.2 mm	6	5.98	1.09	10[a]
Percentage < 2.36 mm	6	5.98	1.09	10[a]
Percentage < 0.300 mm	6	5.98	1.09	10[a]
Percentage < 0.075 mm	6	5.98	1.09	10[a]

[a] In the case of properties with double specification limits, ϕ_a is equal to 0.5 ϕ_a.

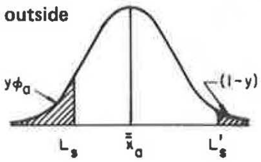


Figure 3. Parts of the population outside the specification limits.

assessed) in comparison with the theoretical α risks of 5 percent (α_a) and 1 percent α_r.

The risk at the acceptance limit is the probability that $\bar{x}_n$ will be smaller than L_a and can be shown to be equal to the following for a lower specification limit:

$$\alpha_a = F\left\{[K_{\phi_a} - K_a\sqrt{(2n-3)/(2n-2)}] \div \sqrt{(1/n) + [K_a^2/(2n-2)]}\right\} \quad (2)$$

where $k_a = k_{\phi_a} - (k\alpha_a/\sqrt{n}) = F(K_{\alpha_{rt}})$ where α_{at} is equal to the true α_a risk. Likewise, the risk at the rejection limit can be shown to be equal to the following:

$$\alpha_r = F\left\{[K_{\phi_a} - K_r\sqrt{(2n-3)/(2n-2)}] \div \sqrt{(1/n) + [K_r^2/(2n-2)]}\right\} \quad (3)$$

where $K_r = K_{\phi_a} - (K\alpha_r/\sqrt{n}) = F(K_{\alpha_{rt}})$ where α_{rt} is equal to the true α_r risk. There are similar relations for upper specification limits.

It is quite clear from these terms that true α risks are independent of L_s or S but are dependent on K_a or K_r, K_{ϕ_a}, and n.

Table 5 gives some of the properties that have been incorporated into the system, together with the recommended sample size, as well as the true α risks at the theoretical acceptance limit (α_a = 5 percent) and theoretical rejection limit (α_r = 1 percent). Table 5 clearly indicates that the assumption that the true standard deviation (σ) of the material as a whole is equal to the sample standard deviation (S) does lead to slightly higher α risks for the contractor. But Table 4 clearly indicates that the client's risk of accepting an unacceptable product with ϕ_u equal to four times ϕ_a is far greater than the contractor's risk of being wrongly assessed. For this reason, it seems quite equitable that the true standard deviation of the material as a whole should be accepted as equal to the sample standard deviation (σ = S).

ϕ_a for Double Specification Limits

In the case of properties with double specification limits, there may be a certain amount of material beyond both the upper and lower specification limits, as shown in Figure 3. The total allowable percentage of material outside the specification limits is expressed as follows:

$$\phi_a = y\phi_a + (1-y)\phi_a \quad (4)$$

The initial problem was to decide what value the fraction (y) should have. By using different values for y and drawing operating characteristic curves for these different values, the influence the value of y has on the assessment of a set of test results can be determined.

It was found that the closer y, or 1 - y, was to unity, the greater would be the probability of accepting an unacceptable product. For this reason it was decided to fix the value of y at 0.5. In other words, the maximum amount of material allowed to be outside either the upper or lower specification limit is limited to 50 percent of the total amount of material allowed outside the specification limits, based on past experience.

CONTRACT ADMINISTRATION

The contract was administered by the resident engineer, and the specified statistical method of control was used for the acceptance of certain portions of the work. Each section of the pavement layer under review was subjected to acceptance control; generally, seven randomly selected samples were taken from a lot (or a day's work). The lot would be accepted if the mean of the sample results was greater than L_s (or, for some parameters, e.g., percentage passing the 0.075-mm sieve, less than L_s') plus (or minus) the range (the difference between the highest and lowest test results) multiplied by a prespecified factor. (In future contracts the standard deviation will be used instead of its simplified approximation, i.e., the range.)

In the subbase layers, density, lime content, and percentage passing the 0.075-mm sieve were subjected to statistical acceptance control. The asphaltic concrete base was controlled by an assessment of aggregate gradings, filler and asphalt content, and density. Payment penalties were imposed on the bitumen layers for material that failed to meet the requirements of the specification; the maximum allowable penalty was a 30 percent reduction in payment. If the parameters tested resulted in a payment reduction of more than 30 percent, the lot would be rejected and would have to be removed.

The subbase layers on the contract consisted of three 150-mm-thick lime-stabilized layers; the bottom layers were natural shale material excavated from the road prism, and the upper layer was an imported tillite crusher-run with a specified plasticity index of 4 to 12. All the layers were mixed on site by means of graders and a mechanical mixer-leveler unit.

Visual inspection of the processed subbase showed the mixture to be consistent and homogeneous. Control testing of the material confirmed the visual inspection, and few sections were rejected by the statistical assessment of the results. On this contract, the contractor made a great effort to maintain a high standard in the processing of the subbase, and the processed material showed good results.

The results of the tests done on samples of the asphaltic concrete base material indicated a wide variability in the product that was mainly caused by the variability of the fine-sand fraction of the aggregates. Penalties were invoked, and the contractor suffered

Table 6. Payment deductions for apshaltic concrete under new specifications.

	Grading										
	Coarse Aggregate		Fine Aggregate		Filler		Asphalt				
Lot (Mg)	Payment Deduction (%)	Number of Test Failures	Payment Deduction (%)	Number of Test Failures	Payment Deduction (%)	Number of Test Failures	Payment Deduction (%)	Number of Test Failures	Total Penalty (cumulative percentage)	Scheduled Payment[a] (R)	Penalty Deduction[b] (R)
486.06	5	7 out of 7	5	7 out of 7	—	—	—	—	10	4 392.83	439.28
611.87	5	4 out of 7	—	—	10	5 out of 7	—	—	15	5 529.80	829.47
603.70	5	5 out of 7	5	5 out of 7	10	5 out of 7	10	2 out of 7	30	5 405.11	1 621.53
523.38	—	—	—	—	10	2 out of 7	10	1 out of 7	20	4 729.98	946.00
535.44	—	—	—	—	10	4 out of 7	10	3 out of 7	20	4 838.97	967.79
82.14	5	1 out of 2	5	1 out of 2	—	—	10	1 out of 2	20	742.38	148.48
600.79	—	1 out of 7	5	1 out of 7	10	4 out of 7	10	3 out of 7	25	5 405.35	1 351.34
241.16	—	—	—	—	—	—	10	2 out of 3	10	2 139.01	213.90
609.03	5	2 out of 7	—	—	10	5 out of 7	10	4 out of 7	25	5 453.15	1 363.29
223.33	5	3 out of 4	5	5	10	4 out of 7	—	1 out of 4	20	2 018.23	403.64
Total										40 654.81	8 284.72

Note: 1 R = $1.15.

[a] Value of asphaltic concrete without penalty deduction.

[b] Monetary value deducted from day's work.

Table 7. Payment deductions for asphaltic concrete under original specifications.

	Number of Test Failures[a]						
	Grading						
Lot (Mg)	Coarse Aggregate[b]	Fine Aggregate[b]	Filler[b]	Asphalt	Total Penalty (%)	Scheduled Payment[c] (R)	Penalty Deduction[d] (R)
486.06	4 out of 4	4 out of 4	—	—	100	4 392.83	4 392.28
611.87	4 out of 6	—	4 out of 6	—	71	5 529.80	3 949.86
603.70	5 out of 6	6 out of 6	6 out of 6	1 out of 6	100	5 405.11	5 405.11
523.38	—	—	3 out of 5	—	29	4 729.98	1 351.42
535.44	—	—	—	3 out of 5	57	4 838.97	2 765.13
82.14	—	—	—	1 out of 2	50	742.38	371.19
600.79	1 out of 5	1 out of 5	3 out of 5	3 out of 5	57	5 405.35	3 088.77
241.16	—	—	—	2 out of 3	67	2 139.01	1 426.01
609.03	2 out of 7	—	5 out of 7	4 out of 7	71	5 453.15	3 895.11
223.33	3 out of 4	—	4 out of 4	1 out of 4	100	2 018.23	2 018.23
Total						40 654.81	28 663.11

Note: 1 R = $1.15.

[a] Tests per 100 Mg not conforming to specification.

[b] Based on one test per 100 Mg production.

[c] Value of asphaltic concrete without penalty deduction.

[d] Monetary value of deductions for asphaltic concrete judged under original specification.

financially. However, the penalties imposed were less onerous when judged on a statistical basis than when judged by the older type of specification. Tables 6 and 7 provide a comparison between new and original specifications in the assessments of some of the test results for the asphaltic concrete base material that was judged defective [data were taken from lots (a day's work) from December 1974 through April 1975]. Similar information is available for all materials and properties subjected to statistical acceptance control on this contract.

A portion of the asphaltic concrete base was rejected completely because it failed to comply with any of the specified parameters, especially that for asphalt content. The contractor was required to remove it from the work site. This material constituted 0.06 percent of the total lot of material laid down in the contract.

DISCUSSION OF RESULTS

Lime-Stabilized Layers

The results of tests on material taken from the lime-stabilized layers showed that the contractor had decided to play it safe and not take advantage of a uniform processing operation whereby the amount of stabilizing agent could be reduced.

The standard deviation of the test results was fairly consistent at a figure of 0.65 and indicated a reasonable amount of control over the processing operation, which was the client's objective.

Asphaltic Concrete Base Course

Asphalt Content

The specification in operation on the contract clearly defined the upper and lower acceptance limits. When the mean of seven test results fell outside the acceptance limits, a penalty of 10 percent payment reduction was imposed for work done. The acceptance limits were directly connected to the range of the test results. A large range produces a small difference between upper and lower acceptance limits. Such a range indicates poor production control and a poor product. Because the product was not consistent, the trend charts compiled for the test results did not show any particular trend.

Filler Content

The variation of the filler content (the -0.075-mm fraction) in the base mix was largely responsible for the penalty the contractor suffered.

A comparison between actual and specified range and standard deviation clearly showed the variability of the filler content. If it had been judged on the standard deviation specification, a large percentage of the asphaltic concrete would have been unconditionally rejected. Instead, by using the range as an indication of variability, the financial penalty was imposed as required by the specification.

Comparison of Assessments

Tables 6 and 7 give a comparison, based on test results selected at random, between material judged on the statistical acceptance scheme and on the old, or original, type of specification. It is apparent from the tables that marginally acceptable material is not penalized as heavily under the new statistical acceptance control scheme. Under this specification scheme, the client's risk appears to be higher than it was under the original specification scheme, especially when a contractor is not capable of producing a consistent product. However, because the quality of the work was generally well above the minimum standard required, a fully conclusive assessment of the financial implications of using the acceptance control scheme was not possible.

COMPARISON OF STATISTICAL ACCEPTANCE CONTROL WITH ENGINEERING JUDGMENT PROCEDURE

Before statistical principles were applied to quality control, engineering judgment based on an analysis of the test results was applied in a rational manner to the acceptance control of work. Because different resident engineers might have interpreted the specifications with varying degrees of harshness, it was decided to compare all acceptance control test results for this contract with the assessments of five experienced road construction engineers.

When the asphaltic concrete test results were assessed according to the statistical method, and this assessment was compared with that of all the engineers, the results were as follows:

1. The engineers' assessments of the individual properties agreed with the statistical assessments, on average, 77 percent of the time. Agreement varied from 81 to 73 percent for the different properties.
2. On average, the engineers agreed among themselves 95 percent of the time in their assessments of individual properties. This agreement varied between 98 and 92 percent for the different properties.
3. In an overall assessment of the lots submitted for assessment, the engineers agreed among themselves 82 percent.
4. The mean payment factor according to the engineers' assessments (using the payment system used on the contract) was 0.89. Among the engineers this factor ranged from 0.91 to 0.87.
5. The engineers' judgment was that, if the old specification had been rigidly applied, the mean payment factor for all the work would have been 0.54. Among the engineers this factor ranged from 0.64 to 0.44. (Rigid application means no payment for a rejected lot.) The mean payment factor for all the work, according to the statistical method, was 0.79.

Because the quality of the asphaltic concrete on this contract was extremely variable, test results from another asphaltic concrete project—constructed by the same paving contractor with the same plant but with a better quality asphaltic concrete—were assessed in exactly the same way as were the results on this contract. To avoid any bias in the engineers' assessment, this set of results, called section 2, was separated from the first set of results, called section 1. The following findings resulted from the assessment of section 2:

1. The engineers' assessments of the individual properties agreed with the statistical assessments, on average, 92 percent of the time.
2. On average, the engineers agreed among themselves 99 percent of the time in their assessment of individual properties.
3. The mean payment factor according to the engineers' assessments (using the payment system used on the contract) was 0.99.
4. The engineers' judgment was that, if the old specification had been rigidly applied, the mean payment factor would have been 0.97.
5. The mean payment factor for section 2, according to the statistical method, was 0.96 (when the engineers used the system used on the contract).

When the subbase test results for the contract were assessed according to the statistical method and this assessment was compared with that of the five engineers, the results were as follows:

1. The engineers' assessments of the individual properties agreed with the statistical assessments, on average, 95 percent of the time.
2. On average, the engineers agreed among themselves 98 percent of the time in their assessment of individual properties.
3. In the overall assessment of the lots, the engineers agreed among themselves 91 percent of the time.

A comparison of the assessments of the asphaltic concrete of sections 1 and 2 reveals that, as the quality of the material decreases, the correlation in the assessments of the material decreases. This is clearly a result of the subjective element involved when work is assessed purely on the basis of engineering judgment. In addition, greater assessment problems are involved in arriving at a balanced decision about borderline material (this is borne out by the subbase results). It can be concluded from these results that the use of the statistical method leads to more consistent interpretations of results than does the judgmental approach to acceptance control.

Some of the engineers involved in the assessment were asked to make another assessment of the project after a substantial time period had elapsed without referring to their original assessments. The reassessments of individual properties of the subbase agreed with the original assessments, on average, 97 percent of the time. For the overall assessments of the subbase, the correlation was 95 percent.

The reassessments of the individual properties of section 1 asphaltic concrete agreed with the initial assessments, on average, 94 percent of the time. However, in the overall reassessment of the asphaltic concrete, the correlation dropped to about 80 percent. The reassessments of the individual properties of section 2 asphaltic concrete agreed with the initial assessments, on average, 99 percent of the time. In the overall reassessment of the asphaltic concrete, this correlation dropped to about 95 percent.

It is clear from these results that, although engineers were able to reassess individual test results with a fair degree of repeatability, the overall reassessments of the lots, which combined more than one acceptance parameter, were not as accurate, which clearly points to the subjective element involved when engineering judgment is used. If the statistical approach had been used, the correlation in all cases would have been 100 percent because the material would have been judged according to certain criteria whose influence on the assessment remained stable irrespective of the subjective approach of the engineer involved.

CONCLUSIONS

Although the project described in this paper was the first application of this scheme to a road project in South Africa, approximately $200 million of work incorporating the use of this or similar acceptance control schemes has since been let to contract. Unfortunately, however, it is not possible to gauge accurately the feelings of contractors about the scheme. Certain contractors—generally the more technologically advanced organizations—appear to welcome the approach, but others have expressed their doubts about it. The more dubious contractors generally do not appear to understand the principles involved nor to be able to explain their misgivings clearly.

A great deal of education in statistical principles thus appears to be required. This education, the collecting and processing of more and reliable information about the variability associated with construction control testing, and the relative variabilities contributed by the sampling and testing processes are regarded as the most important phases of this work to be done in the immediate future. It is hoped that the introduction of a quality assurance subsystem into the computerized data management system currently being implemented by the South Africa Department of Transport will help to some extent in obtaining more information about variability in materials and processes.

A study of the results of tests on asphaltic concrete showed clearly that, when a contractor makes a definite effort to produce a homogeneous or consistent product, there is no difficulty in fulfilling the requirements of the specification. The use of inconsistent material in the production of asphaltic concrete can only lead to trouble. Use of the statistical acceptance plan provides a client with an adequate means of judging the product.

The statistical acceptance control scheme should not be seen as another "big stick" with which the engineer may beat the contractor but as a scientific assessment of the contractor's capability to produce a uniform product. Ad hoc or biased judgments of the product are eliminated, and on-site arguments between the contractor and the resident engineer are reduced to a minimum. The contractor is encouraged to produce a uniform product, which is what the client desires, and the benefits that accrue to both contractor and client must eventually accrue to the construction industry as a whole.

The continued use of statistical acceptance control on road-work projects is therefore recommended. The ultimate aim of the major clients connected with the road construction industry in South Africa is to develop a standard statistical acceptance control specification based on the several specifications that are now being implemented throughout the country.

ACKNOWLEDGMENTS

We wish to express our appreciation to the Secretary for Transport and the Director of the National Institute for Transport and Road Research for their permission to publish this paper.

REFERENCES

1. S. H. Kühn, M. F. Mitchell, and R. A. F. Smith. The Department of Transport's Acceptance Control Plans for Road Construction. Proc., 2nd Conference on Asphalt Pavements for Southern Africa, Durban, Council for Scientific and Industrial Research, 1974, RR 175, pp. 5-83.
2. Statistical Concepts of Quality Assurance and Their Application in Road Construction. National Institute for Transport and Road Research, Pretoria, Technical Recommendations for Highways 5, 1977.
3. C. E. DeYoung. Construction Practices. HRB, Special Rept. 118, 1971, pp. 11-12.

Publication of this paper sponsored by Committee on Quality Assurance and Acceptance Procedures.

Quality Criteria for Maintenance and Reinforcement of Pavements in the Netherlands

P. M. W. Elsenaar and C. van de Fliert, State Road Laboratory, Delft

In the next 10 years, population and traffic density will reach a maximum in the Netherlands and other industrial countries of Western Europe. The need for an adequate policy for spending the available (and decreasing) funds for roads necessitates the development and application of objective criteria for maintenance and reconstruction of the existing road network. These criteria deal mainly with road-surface characteristics (safety and riding comfort), bearing capacity (strength) and durability of the pavement, and traffic safety. Quality criteria relating to road-surface characteristics and the condition of the pavement as a bearing layer are examined. In the Netherlands, such criteria are gradually being more systematically applied in judging priorities and making decisions on maintenance and strengthening of pavements. These criteria have been developed on the basis of measurements and research on the national road system carried out by the State Road Laboratory, especially during the past 25 years. An explanation is given of the methods of measurement, the interpretation of the results of testing and visual inspection of roads, and the way the data are used in developing and applying a system of rational pavement management practice.

In a number of Western European countries, and particularly in the densely populated Netherlands, the planned road networks required to provide an effective infrastructure are nearing completion. Figure 1 shows the 1968 state highway plan for the Netherlands; after some