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Experience in statistical quality control for road construction in South Africa

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Synopsis

For some time road engineers have been concerned that the variability inherent in road construction materials and their sampling and testing has not been logically and consistently catered for in the road construction process or in construction control. Over the last few years various process and acceptance control plans for road construction, based on stochastic procedure, have been developed, both in South Africa and abroad. In this paper the first large-scale South African application of statistically oriented acceptance control procedures to a major road construction project is examined and it is concluded that such procedures promise to be of benefit to both the client and the contractor.

Samevatting

Padingenieurs is geruime tyd reeds besorg oor die feit dat daar in proses- en konstruksiebeheer by padbou nie logies en konsekwent voorsiening gemaak word vir die varieerbaarheid inherent in padboumateriaal en in die bemonstering of toetsing daarvan nie. Gedurende die afgelope paar jaar is verskeie proses- en aanvaardingsbeheerplanne vir padbou, gebaseer op stogastiese prosedures, in sowel Suid-Afrika as oorsee ontwikkel. In hierdie referaat word die eerste grootskaalse toepassing in Suid-Afrika van statisties georiënteerde aanvaardingsbeheerprosedures by 'n groot padbouprojek ondersoek. Die gevolgtrekking is dat sulke prosedures belofte van voordeel vir sowel die klant as die kontrakteur inhou.

Introduction

Road authorities in South Africa have for several years been concerned about the quality of some of the construction work which is carried out, particularly about the application of uniform standards of judgement in the acceptance or rejection of work.

The Division of National Roads of the Department of Transport was aware that all materials, construction processes and contractors exhibited different degrees of variability and that supervisory engineers often applied different judgement criteria to work which did not strictly conform to specifications. Accordingly, in 1972, the Division decided to initiate the incorporation of statistical principles into certain road contracts in order to define in a rational manner the properties of engineering materials and to assist in providing uniform judgement criteria for making decisions on acceptance or rejection.

The primary motives behind this decision were an endeavour to give economic encouragement to contractors who delivered uniform construction work and to reduce as far as possible the element of risk of having basically acceptable work rejected.

Description of acceptance schemes

The acceptance control plans adopted for use by the Division of National Roads are fully described in the paper *The Department of Transport's acceptance control plans for road construction* presented at the 1974 CAPSA Conference[1]. In conjunction with the Natal Roads Department, the Division decided that the first major contract on which statistically oriented acceptance control procedures would be utilized for the judgement of certain parameters would be Contract 90/NR 2/25 encompassing a portion of National Route 2 on the Durban Outer Ring Road.

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Background to acceptance control

This decision did not originally meet with enthusiasm from all the road engineers involved in the project. This is not surprising as this has been the case in nearly every initial application since statistical methods were first introduced to any industry. Yet statistical methods have made major contributions to, and are firmly established in, many of the industries in which they have been applied. We believe that statistical methods will not only prove helpful in solving problems of quality control and acceptance of completed work in road engineering, provided they are properly applied, but also that contractors will come to realize that they are a definite improvement on the methods used in the past and that they will become standard practice for quality control.

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In the early stages of the development of road construction many of the present specifications and tests were developed on an empirical basis, both to guide contractors and to provide quality acceptance parameters. One of the major functions of a specification was to convey technical instructions to both the contractor and the resident engineer.

With the improvement of technology in the contracting industry it is hoped that it will soon be possible to specify only the significant characteristics of the end product in terms of measurable parameters and to accept the work when test results indicate that the desirable characteristics have been attained. Before this goal can be reached many problems must be overcome, the most important of which is changing the practice of joint and ill-defined control of both processes and acceptance by both contractor and engineer, to the separate control of processes by the contractor and of acceptance by the engineer.

It must be emphasized that the statistical procedures now being introduced into the South African road construction industry are not new concepts but that similar procedures have been successfully applied in road construction in North America for many years.[2] The South African procedures do of course incorporate values for the factors which have reflected construction quality in the Republic over the past few years.

Despite a difficult transition period in which a large amount of *education* was required, it is gathered that contractors in the USA have now generally accepted statistically based acceptance control procedures. The better contractors, recognizing the advantages accruing to them from the production of uniform quality work, are now amongst the procedures' main advocates and many are employing *quality control* engineers on their construction staff.

Abbreviated rationale of plan

Since there are no materials and construction processes that are absolutely homogeneous, ie they all vary according to some type of distribution (usually approximating a *normal distribution*), 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 which can be drawn from a population. To complicate matters even further there is a possibility that the test results may belong to a population which is either acceptable or unacceptable in terms of the specification (see Fig 1).

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 which 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 (see Fig 2).

From Fig 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 per cent of being wrongly rejected because there is still a probability of α per cent 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 per cent of accepting an unacceptable product because there still is a probability of β per cent 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 towards making these two values as low as possible, at the same time maintaining practical limits for the quality of the work.

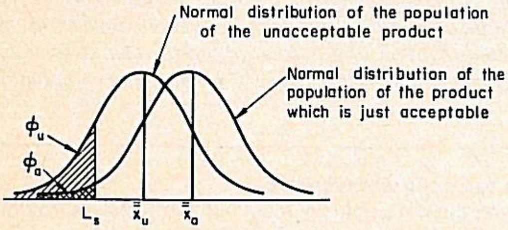

Fig 1: **Normal distributions of populations with a lower specification limit (see *Key to notation* at end of paper)**

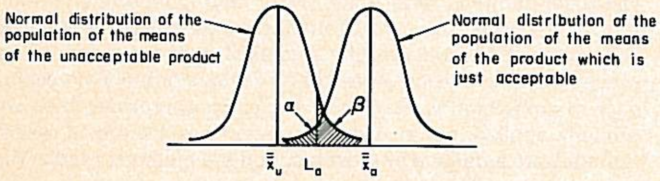

Fig 2: **Normal distributions of the populations of the means**

Furthermore, if the value of $\bar{x}_n$ is lower than L_a and tends towards $\bar{\bar{x}}_u$, it is clear that the contractor's risk α of being wrongly rejected decreases but that the client's risk β of accepting an unacceptable product increases. It is therefore considered equitable that lower payment should be made for this material if it is accepted by the client, as was the case with some of the premix material on this contract.

The values for ϕ_a have been calculated from past 'as-constructed' data in order to ensure that the standard of construction remains relatively stable in terms of previous specifications. Furthermore the contractor's risk α is fixed at five per cent at the acceptance limit which means that he runs a risk of one in twenty of having a product of borderline quality rejected. For a higher quality material the risk at the acceptance limit will be lower and for a lower quality material, higher.

The same principles apply to material properties with upper specification limits or double specification limits. However, in the case of properties with double specification limits the value of ϕ_a, used in deriving the acceptance limit, is limited to 50 per cent of the total percentage allowed to be outside the double specification limits.

For the test results to represent the true population of the material property as accurately as possible it is imperative that the samples should be randomly obtained, in other words 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 in that it eliminates the subjective element which would otherwise be involved.

The distinction between the *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, while process control, on the basis of selected sampling *during the actual production process,* indicates adjustments required to be made by the producer to maintain the process within the prescribed limits.

Contract administration

Contract 90/NR 2/25 was administered by the resident engineer, using the specified statistical method of control for the acceptance of certain portions of the work. Each section of the pavement layer under review was subjected to acceptance control with seven randomly selected samples generally being taken from the lot or day's work. The lot would be accepted if the mean of the sample results was greater than L_s (or for some parameters, eg per cent passing the 0,075 mm sieve, less than L'_s) plus (or minus) the range (difference between the highest and lowest test results) multiplied by a prespecified factor. (For future contracts the standard deviation will be used instead of its simplified approximation, ie the range.)

In the sub-base layers the density, lime content and percentage passing the 0,075 mm sieve were subjected to statistical acceptance control. The bitumen-bound base was controlled by an assessment of the aggregate gradings, filler and bitumen content, and density. Payment penalties were imposed on the bitumen layers for material which failed to meet the requirements of the specification, with a maximum allowable penalty of 30 per cent reduction in payment. If the parameters tested resulted in a payment reduction of more than 30 per cent the lot would be rejected and would have to be removed from the works.

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

Visual inspection of the processed sub-base 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 his processing of the sub-base, with consequent good results in the material processed.

The results of the tests done on samples of the bitumen-bound base material indicated a wide variability in the product, due mainly to the variability of the fine-sand fraction of the aggregates. Penalties were invoked and the contractor suffered financially. However, the penalties which were imposed were less onerous when judged on a statistical basis than when judged by the older type of specification. The accompanying Table shows the comparison between the new and original specifications in the assessments of some of the test results for the bitumen-bound base material which was judged defective. Similar information is available for all materials and properties subjected to statistical acceptance control on this contract.

A portion of the bitumen-bound base was rejected completely because it failed to comply with any of the specified parameters, especially that for the bitumen content. The contractor was required to remove it from the site of the works. This material constituted 0,06 per cent of the total tonnage 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 he could reduce the amount of stabilizing agent. The standard deviation of the test result was fairly consistent at a figure of 0,65, indicating a reasonable amount of control over the processing operation, which was the client's objective.

Bitumen-bound basecourse

Bitumen 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 per cent reduction in payment for work done was imposed. The acceptance limits were directly connected to the range of the test results. A large range produces a small difference between the upper and lower acceptance limits. Such a range indicates poor production control and a poor product. The trend charts which were compiled for the test results did not show any particular trend, since the product was not consistent.

Filler content: The variation of the filler content (the –0,075 mm fraction) in the basecourse was largely responsible for the penalty which the contractor suffered. A comparison between the actual range and the standard deviation and those specified clearly showed the variability of the filler content. If it had been judged on the standard deviation specification a large percentage of the premix would have been unconditionally rejected. Instead, using the range as an indication of variability, the financial penalty was imposed as required by the specification.

Comparison of assessments: The Table gives 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 this table that material which is marginally acceptable is not penalized as heavily under the new statistical acceptance control scheme. It appears that under this specification scheme the client's risk is higher than under the original specification scheme, especially when a contractor is not capable of producing a consistent product.

Comparison of statistical acceptance control scheme with 'engineering judgement' procedure

Before the application of statistical principles to quality control, *engineering judgement* was applied in a rational manner to the acceptance control of work. This judgement was based on an analysis of the test results. Different resident engineers might have been interpreting the specifications with varying degrees of harshness. It was decided therefore to compare all acceptance control test results for this contract with the assessments of five experienced road construction engineers.

When the premix 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:

Table

Comparison of payment deductions for bitumen-bound base under new and original specification schemes

Statistical specification									*Original specification rigidly enforced*				
Date	*Lot*	*Grading*		*Filler*	*Bitumen*	*Total Penalty*	*Scheduled payment*	*Penalty deduction*	*Grading*		*Filler*	*Bitu-men*	*Penalty deduction*
		Coarse Agg	*Fine Agg*						*Coarse Agg*	*Fine Agg*			
	Tonnes	*% Tests*	*% Tests*	*% Tests*		*Cumulative %*	*Rand*	*Rand*	*Based on 1 test per 100 t production*				*Rand*
		(a)	(a)	(a)	(a)		(b)	(c)	(d)	(d)	(d)	(d)	(e)
4.12.74	486,06	5 $^{7}/_{7}$	5 $^{7}/_{7}$	–	–	10	4 392,83	439,28	$^{4}/_{4}$	$^{4}/_{4}$	–	–	4 392.83
5.12.74	611,87	5 $^{4}/_{7}$	–	10 $^{5}/_{7}$	–	15	5 529,80	829,47	$^{4}/_{6}$	–	$^{4}/_{6}$	–	3 949,86
13.12.74	603,70	5 $^{5}/_{7}$	5 $^{7}/_{7}$	10 $^{5}/_{7}$	10 $^{2}/_{7}$	30	5 405,11	1 621,53	$^{5}/_{6}$	$^{6}/_{6}$	$^{6}/_{6}$	$^{1}/_{6}$	5 405,11
14.01.75	523,38	–	–	10 $^{2}/_{7}$	10 $^{1}/_{7}$	20	4 729,98	946,00	–	–	$^{3}/_{5}$	–	1 351,42
21.01.75	535,44	–	–	10 $^{4}/_{7}$	10 $^{3}/_{7}$	20	4 838,97	967,79	–	–	–	$^{3}/_{5}$	2 765,13
25.01.75	82,14	5 $^{1}/_{2}$	5 $^{1}/_{2}$	–	10 $^{1}/_{2}$	20	742,38	148,48	–	–	–	$^{1}/_{2}$	371,19
7.02.75	600,79	– $^{1}/_{7}$	5 $^{1}/_{7}$	10 $^{4}/_{7}$	10 $^{3}/_{7}$	25	5 405,35	1 351,34	$^{1}/_{5}$	$^{1}/_{5}$	$^{3}/_{5}$	$^{3}/_{5}$	3 088,77
27.03.75	241,16	–	–	–	10 $^{2}/_{3}$	10	2 139,01	213,90	–	–	–	$^{2}/_{3}$	1 426,01
08.04.75	609,03	5 $^{2}/_{7}$	–	10 $^{5}/_{7}$	10 $^{4}/_{7}$	25	5 453,15	1 363,29	$^{2}/_{7}$	–	$^{5}/_{7}$	$^{4}/_{7}$	3 895,11
15.04.75	223,33	5 $^{3}/_{4}$	5	10 $^{4}/_{4}$	– $^{1}/_{4}$	20	2 018,23	403,64	$^{3}/_{4}$	–	$^{4}/_{4}$	$^{1}/_{4}$	2 018,23
							40 654,81	8 284,72					28 663,66

Notes

Column (a) represents percentage deduction (eg 5%) and number of tests failing to meet specification (eg $^{7}/_{7}$ – seven fail in seven tests)
Column (b) represents the value of premix without penalty deduction
Column (c) represents the monetary value deducted from the day's work
Column (d) represents tests per 100 t not conforming to specification
Column (e) represents the monetary value of deductions for premix judged under original specification

1. For the individual properties the engineers' assessments agreed, on average, 77 per cent of the time with the statistical assessments. (The agreement varied from 81 per cent to 73 per cent for the different properties.)
2. Amongst themselves the engineers agreed, on average, 95 per cent of the time in their assessments of individual properties. (This varied between 98 per cent and 92 per cent for the different properties.)
3. In the overall assessment of the lots submitted for assessment the engineers agreed 82 per cent amongst themselves.
4. The mean payment factor according to the engineers' assessments (employing the payment system used on the contract) was 0,89. (This ranged from 0,91 to 0,87 amongst the engineers.)
5. If the old specification had been rigidly applied the mean payment factor for all the premix work according to the engineers' judgement would have been 0,54. (This ranged from 0,64 to 0,44 amongst the engineers.) (Rigid application means no payment for a rejected lot.)
   The mean payment factor for all premix test results according to the statistical method was 0,79.

Because the quality of the premix on this contract was extremely variable, test results from another premix project, constructed by the same paving contractor with the same plant but with a better quality premix, were assessed in exactly the same manner as the premix results on this contract. To avoid any bias in the engineers' assessment this set of results was separated from the first and denoted Section 2, the first set of results being called Section 1. In the assessment of Section 2 the following was found:

1. For the individual properties the engineers' assessments agreed, on average, 92 per cent of the time with the statistical assessments.
2. Amongst themselves the engineers agreed, on average, 99 per cent of the time in their assessment of individual properties.
3. The mean payment factor according to the engineers' assessments (employing the payment system used on the contract) was 0,99.
4. If the old specification had been rigidly applied, the mean payment factor according to the engineers' judgement would have been 0,97.
5. The mean payment factor for Section 2, according to the statistical method was 0,96 (when employing the system used on the contract).

When the sub-base test results for contract 90/NR 2/25 were assessed according to the statistical method and this assessment was compared with that of the five engineers, the results were as follows:

1. For the individual properties the engineers' assessments agreed, on average, 95 per cent of the time with the statistical assessments.
2. Amongst themselves the engineers agreed, on average, 98 per cent of the time on their assessment of individual properties.
3. In the overall assessment of the lots, the engineers agreed 91 per cent of the time amongst themselves.

Discussion of assessments

From a comparison of the assessments of premix Sections 1 and 2, it appears that as the quality of the material decreases, so the correlation in the assessments of the material decreases. This clearly points to the subjective element involved when work is judged purely on engineering judgement. It is also evident that borderline material provides greater assessment problems in arriving at a balanced decision; this is borne out by the sub-base results.

One can only conclude from these results that the use of the statistical method leads to more consistent interpretations of the results than when acceptance control is left to engineering judgement.

Some of the engineers involved in the assessment were asked to carry out another assessment of the project after a substantial period had elapsed, without referring to their initial assessments. For the sub-base the reassessments of individual properties agreed, on average, 97 per cent of the time with the initial assessments. For the overall assessments of the sub-base the correlation was 95 per cent.

In the case of the premix test results for Section 1, the reassessments of individual properties agreed, on average, 94 per cent of the time with the initial assessments. However, in the overall reassessment of the premix the correlation dropped to about 80 per cent. In the case of the premix for Section 2, the reassessments of individual properties agreed, on average, 99 per cent of the time with the initial assessments. In the overall reassessment of the premix this correlation dropped to about 95 per cent.

From these results it is clear that even though engineers were able to reassess individual test results with a fair degree of repeatability, the overall reassessments of the lots, combining more than one acceptance parameter, were not as accurate, which clearly points to the subjective element involved when engineering judgement is used. If the statistical approach had been used the correlation in all cases would have been 100 per cent because the material is judged according to certain criteria whose influence on the assessment remains stable, irrespective of the mood of the engineer involved in the assessment.

Conclusion

A study of the test results showed clearly that where the 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 premix can only lead to trouble and the use of the statistical acceptance plan provides the client with an adequate means of judging the product.

The statistical acceptance control scheme should not, however, be seen as another 'big stick' with which the engineer may beat the contractor. It should be seen as a scientific assessment of the contractor's capability to produce a uniform product. Ad hoc or biased judgements of the product are obviated and on-site arguments between the contractor and 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 which accrue to both contractor and client must eventually accrue to the construction industry as a whole.

The continued use of statistical acceptance control on roadwork projects is therefore recommended. The ultimate aim of the major clients connected with the road construction industry is to develop a standard, statistical, acceptance control specification based on the several specifications which are presently being implemented throughout the country.

Acknowledgements

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Key to notation

ϕ = percentage of the population of the material lying outside the specification limit
L_a = acceptance limit
L_s = lower specification limit
L'_s = upper specification limit
$\bar{x}_n$ = mean test result value
$\bar{\bar{x}}_a$ = population mean of a product which is just acceptable in terms of the specification
$\bar{\bar{x}}_u$ = population mean of a product which is totally unacceptable in terms of the specification
ϕ_a = percentage of the material below L_s for a product which is just acceptable
ϕ_u = percentage of the material below L_s for a product which is unacceptable