SUMMARY

The complete development of a PWL type of acceptance plan is founded on complex statistical theory. It is not necessary to understand the theory to use a PWL acceptance plan since estimation tables can easily be modified from Military Standard 414. However, if flexibility in adapting the standard to highway construction specifications is desired, a knowledge of the underlying theory is certainly helpful. Although one adaptation of Military Standard 414 plans—the range method—has gained a foothold in statistically based highway construction specifications, we believe that PWL plans are not being used to their fullest potential. It is hoped that the summary presented in this paper of the basic theory that underlies PWL acceptance plans will better equip highway agencies to develop acceptance plans specifically suited to their needs.

ACKNOWLEDGMENT

The contents of this paper reflect our views, and we are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Pennsylvania Department of Transportation or the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

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Contractor Control of Asphalt Pavement Quality

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Warren Brothers Company builds asphalt pavements in seven states that use statistically based end-result specifications that require contractor control of quality. Company experiences with these seven different specifications are described, and control systems developed to comply with the specifications are explained. Problems and their solutions are discussed, and contractor costs and benefits are tallied. On balance, company experience with end-result specifications has been favorable. It is shown that end-result specifications can be workable for contractors, and improvements that would be beneficial to both contractors and agencies are suggested.

Over approximately the past 10 years, several state highway agencies have adopted end-result specifications for asphalt paving that encourage, if not require, contractor control of quality (1). All of these specifications are statistically oriented to some degree. There has been a high degree of interest in statistically oriented end-result specifications for about 20 years, but in spite of that interest implementation has been slow. One reason cited for the slow pace of implementation has been contractor resistance to change (1). This paper is concerned with the experiences and practices of one contractor—Warren Brothers Company, a division of Ashland Oil—with modern end-result specifications and quality control systems for asphalt paving.

HISTORICAL PERSPECTIVE

Contractor control of quality is not a new concept. In fact, early pioneers in bituminous paving such as Abbott, DeSmedt, and the Barber Asphalt Paving Company had their own quality control systems 100 years ago (2, 3). They had to have their own systems because nobody else knew how, but they had learned that control was necessary in order to duplicate successes.

Warren Brothers is no newcomer to quality control.

When Warren Brothers began building patented pavements in 1901, a quality control system was developed (4). This system was used successfully for over 40 years wherever Warren pavements were built.

Although contractors had control systems, paving specifications that required certain controls were in use before 1900 (2). By 1920, control by specification rather than by contractor was preferred (5).

Today, Warren Brothers Company operates 175 asphalt plants in 21 states and places pavements in 25 states. Annual production is about 13 000 000 Mg (14 000 000 tons) of asphalt concrete. Of these, 44 plants operate in seven states that use end-result specifications. A few plants located near state lines operate under both end-result and specification control. More than 10 years ago, the company began to participate in trials in these and other states. Overall company experience with modern end-result specifications is broad and varied, and it is from this multifaceted perspective that modern experiences are viewed.

MODERN END-RESULT SPECIFICATIONS

Acceptance Systems

Agencies in the seven states that use end-result specifications use seven different acceptance systems. The differences among the systems are significant and do not allow generalization. The requirements specified by these agencies are given below:

Requirement	Number of Agencies
Aggregate gradation	7
Number of sieves (typical surface mix)	
8	1
7	4
4	1
3	1
Asphalt content	7
Mix temperature	7
Marshall stability	4
Marshall flow	2
Air voids	1
Roadway density	5
Smoothness	4
Thickness	2

All seven agencies specify aggregate gradation, asphalt content, and mix temperature. One or more agencies specify up to six additional requirements. Agencies that do not specify density and smoothness have requirements for these items that are not included in their end-result specifications.

In addition to the number of requirements, the requirements themselves differ among agencies. The table above indicates that aggregate gradation is accepted on the basis of various numbers of sieves. More difference among grading requirements is illustrated below by a tabulation of requirements for one sieve:

Agency	Number of Tests per Lot	Tolerance for Average Result
1	5	±2.2
2	4	±4.3
3	2	±6.0
4	Unspecified	±3.0
5	5	±2.5
6	5	±4.7
7	4	±4.5

Similar differences are found for other sieves, asphalt contents, and requirements.

Acceptance is based on the lot—a specified unit of production—and a specified frequency of testing. Lot size can be one day's production (three cases), various amounts of material (three cases), or unspecified (one case). In some cases, provision is made to handle unusually large or small lots. The frequency of testing is shown in the table above where the indicated frequency is applicable to other requirements also. In some cases, mixture production lots and testing frequency are distinct from roadway lots and testing frequency.

Although it is not strictly a part of acceptance requirements, the job mix formula is an important consideration because it is the target that forms the basis of acceptance. In all seven cases, the contractor is required to submit a job mix formula that must then be approved by the agency. Approval involves duplicate testing in some cases and accepting the contractor's documentation in others.

Control Systems

One concept that has encouraged the adoption of end-result specifications is that, if end results are specified, control requirements can be eliminated entirely. This dream has not yet been realized. Many provisions of previous construction specifications have been retained and acceptance requirements simply added. This practice is correct because the previous specifications did not include explicit acceptance requirements. However, when new controls accompany the acceptance requirements, the net effect is an increase in control requirements.

Among the seven state agencies, the most elaborate new control system provides that the contractor furnish an agency-certified technician to perform all acceptance testing. Facilities and equipment for sampling and testing are specified. Acceptance tests are the basis of control. Altogether, test results for 10 mixture and pavement characteristics are reported on each sublot. All test results are recorded and plotted on control charts. Another agency has similar requirements for control but performs acceptance testing itself. Evidence of satisfactory control is, however, required.

Some controls are recommendations rather than requirements. One agency performs its own acceptance testing and recommends a control system for the contractor's consideration. Various random sampling plans are recommended for both acceptance and control, but none is specified. In general, it has appeared prudent for contractors to follow these recommendations as if they were requirements.

In some cases, no new control requirements are used. The contractor is free to do whatever he or she wants to ensure that the process is under control.

Complicating Factors

When end-result specifications are implemented, contractors are faced with a new acceptance system and must at least consider establishing a new control system. Frequently, there are additional considerations.

New acceptance systems are often accompanied by new requirements. For example, master ranges of aggregate gradation and asphalt content have been changed enough so that satisfactory mixtures that had been produced for many years would no longer be acceptable. Other examples of new requirements include Marshall stability and related criteria, density, and smoothness, all of which have been either new or applied in new ways with end-result specifications.

When considering a new control system, a contractor must also consider local aggregates. The control sys-

tem at an asphalt plant to control aggregate gradation may range from almost nothing where aggregate producers have good control systems to a very intensive testing program where aggregate producers have poor control systems.

Local markets must also be considered. In addition to the local state agency, paving contractors also work for other government agencies, various authorities, private customers, and other contractors who purchase mixtures FOB. Some plants produce more than 20 job mixes and work with up to 10 aggregate sizes to comply with the various specifications. The contractor must make an end-result specification with new acceptance and control requirements compatible with the remainder of his or her operation or vice versa.

CONTRACTOR CONTROL SYSTEMS

Contractor control systems for end-result specifications begin with the specified controls. This includes many of the plant and construction controls from previous specifications and may include additional control tests. The next step is to establish whatever other controls may be needed to satisfy particular local conditions and still comply with the new acceptance requirements.

With Specified Controls

When additional control tests have been specified, test results for from 8 to 11 mixture and pavement characteristics are required on each sublot. Usually, there are four or five sublots per day. Test results are recorded and plotted on control charts as required.

This much work is a full-time job for one very good technician at one plant. Where required, the technician is agency certified. Because the technician's time is fully occupied with specified control testing, he or she does not perform other control work and is not expected to. The technician's job is to sample, test, and report as required—in other words, to produce the required evidence of control.

Evidence of control may be all that is needed to control the process. Minor adjustments of batch weights, cold-feed settings, burner temperature, and roller patterns, for example, can be accomplished on this basis before the process gets out of control.

Although this much evidence of control is certainly not too little, sometimes it is too late. In that case, additional personnel must be assigned to perform other control work to supplement but not duplicate the required control testing. Supplemental control testing concentrates on problem areas at a particular plant and should always occur at a point earlier in the process than the required control testing. Aggregates present the most frequent need for supplemental testing and may be tested at hot bins, cold feed, or the source as circumstances require.

Personnel requirements for supplemental control work vary, but someone must spend at least part time on it when it is needed. Sometimes supervisory personnel can perform the necessary work, but more often it has to be assigned to a technician who can concentrate on it. Rarely, however, does supplementary control work require a full-time technician when a plant already has a technician who works on required control tests.

Without Specified Controls

When contractor control testing and procedures are not specified, agency acceptance testing becomes the basis for control. There can be no other basis because it would be useless (even though possible) for a contractor to establish a control system that is incompatible with the acceptance system. In other words, if the control system indicates good control, the acceptance system should indicate an acceptable product.

Although control testing and procedures are not specified, an agency-certified technician usually is. Whether specified and certified or not, competent contractor personnel should be assigned to perform necessary control work. Full cooperation with the inspection personnel of the agency is perhaps the most essential aspect of the control technician's duties.

In addition to being the basis of control, agency acceptance testing can also serve as control testing. In these cases, control personnel do not have to do anything beyond monitoring test results and adjusting processes. However, more effective use of these personnel can be made, often depending on agency preferences. In some cases, inspection and control personnel work together on all aspects of the acceptance system. When sampling locations are selected by random numbers or some other device, both are present and both know that there is no bias. They obtain samples together and, if possible, each tests specimens of the same sample or in some way checks the other's testing. Test results are recorded, and control charts are plotted together. Discrepancies are investigated and corrected. In this way, both know with certainty that test results, whether good or bad, are correct. The duplication that characterizes this system may be wasteful, but it provides a very high degree of confidence for both parties and practically eliminates any possibility of dispute. Duplication can be advantageous: One of the two people performing the job—the contractor's technician—can find time for supplemental control work and thereby reduce or eliminate personnel requirements for this purpose.

In other cases, the agency prefers to work alone on acceptance, and the contractor's control is an entirely separate operation. Acceptance and control personnel work closely together, but control personnel are free to concentrate on the most troublesome areas. The control system is established to satisfy the demands of the local situation and may include duplication of the acceptance system, supplemental control tests, or some combination of the two. In practice, supplemental control tests have received the most attention because they allow concentrated effort where it is needed. Frequently, random sampling plans, standard test methods, control charts, and other necessary aspects of statistical quality control are not used because they do not help to solve the problem that the control testing is trying to overcome.

A situation in which agency acceptance testing was not useful in some way for control purposes has not been encountered. Some agency acceptance testing is more useful than others, and the contractor's control system must be established accordingly.

When no control system is specified, whatever system is established must be well documented. Sample locations must be pinpointed, and all test results—good and bad—must be recorded. Control charts can be useful and should be used when appropriate data are obtained. Control technicians do not find control charts to be particularly valuable because the technician knows the control situation when he or she obtains the test result; however, the charts are valuable to contractor supervisory personnel and agency personnel. All control records and charts and other control information, such as plant recordation, must be open and available to agency personnel at all times. The need for complete and open documentation of control cannot be overemphasized because these documents form the basis for appeal when acceptance testing indicates an inferior product. Erroneous acceptance testing has been discovered and cor-

rected in this way. This feature of control documentation is to the contractor's advantage because it has always been used to correct indications of inferior products and never to correct indications of acceptable products.

PROBLEM AREAS

A great variety of problems have been encountered through the years with the several systems. Ultimately, the major problems revolve around acceptance testing identifying inferior products.

Difficult Requirements

Compliance with certain acceptance requirements has been difficult, if not impossible, in some cases. These experiences suggest that the acceptance requirements may not be realistic. For example, a table given previously reveals different tolerances for one mixture characteristic. Even when allowance is made for the number of tests, it is difficult to avoid the conclusion that all tolerances cannot be right and some may be unrealistic. An unrealistic tolerance could be either too small or too large. Too small results in frequent noncompliance and is the difficult requirement. Too large is not difficult but results in acceptance of inferior products, an unfavorable situation for both agency and contractor.

Most difficult requirements are in some way new requirements that had to be established based at least partly on engineering judgment. Aggregate gradation, which the table on tolerances illustrates, is a time-honored, traditional basis for control and acceptance, but the use of random sampling and statistical procedures is new. Thus, tolerances for this and for other traditional characteristics as well required judgment. Experience suggests that many of these tolerances may be realistic for major paving operations in which continuous operation is possible but unrealistic for bridge approaches, intersections, and other irregular areas that are a part of nearly all paving contracts and require stop-and-go, low-production operation. Experience also suggests that tolerances that appear to be realistic for surfaces are unrealistic for bases, but one set of tolerances is applicable to both.

New, difficult requirements have also been encountered with respect to pavement smoothness, thickness, and density. In the past, these items were controlled mostly by method requirements rather than result. Experience shows that full compliance with these new requirements has not been possible in some cases when the old methods were used and in other cases no matter what methods were used. A majority of paving contracts involve leveling or base courses or both, but the new acceptance requirements appear to be reasonably applicable only to surface courses and then only if the contract provides enough leveling so that a smooth, dense surface can be built.

Feedback

It has already been noted that acceptance requirements are the basis for control and that acceptance testing can be used for control. Either way, prompt reporting of acceptance test results to the contractor is essential. Otherwise, the contractor does not know where he or she stands no matter what quality control system is used because acceptance tests are the bottom line. Delay appears to serve no useful purpose, and it does prolong undesirable situations that could be corrected. Prompt and timely reporting of acceptance test results is the practice in many cases. No overwhelming reason is known for not practicing it in all cases.

Number of Requirements

Most agencies use approximately 10 acceptance requirements, and some require an equal number of controls. If the probability of acceptance of one requirement is 0.99, most statisticians would agree that the process is under very good control with respect to that requirement. When there are 10 such requirements, the probability that their combination is acceptable is 0.99^{10} or 0.90. If the requirements are not mutually exclusive, which is usually the case with paving requirements, the probability is less than that. Even though there is ample evidence that actual processes are under good control, the number of requirements makes full compliance with all requirements all of the time unlikely. Yet, a process under good control should be able to comply.

Reproducibility

Two or more laboratories are often involved in mix design, control, and acceptance. The reproducibility of the results of most of this testing is judged to be poor. Discrepancies between laboratories in excess of specified tolerances is expected. Mix designs that cannot be produced have been required, and mix designs that another laboratory could not duplicate and therefore accept when produced have been required.

When control testing is specified, the problem is not reproducibility because the laboratories test different materials. However, some sort of agreement between laboratories is required and is often unattainable within specified tolerances. When control testing is not specified, the problem does not exist even though laboratories do not agree because the objective of control testing is control rather than agreement.

Judgment

In theory, statistically based end-result specifications require no judgment in application because all decisions were made when the specifications were written. In practice, experience shows that judgment is needed. Because of the variety of circumstances encountered in pavement construction, it is unlikely that all situations can be anticipated. Decisions made in the field are necessary and often advantageous to all parties.

EVALUATION OF CONTROL AND ACCEPTANCE SYSTEMS

Contractor Costs

In every case in which responsibility for quality control has passed from the agency to the contractor, there has been an increase in contractor costs. These costs vary with circumstances and stem from several sources. Whatever they add up to, these costs must be included in bids.

Qualified personnel must be made available. In a few cases, qualified quality control personnel were already present and only needed to assume new duties. The work that they had been doing still needed to be done and had to be assigned to others but with a minimum of new hiring. In most cases, additional quality control personnel must be hired. One technician per plant is not always required. Multiplant operations can be handled by a team of technicians who concentrate their efforts where needed.

Training of personnel is an additional cost. Because an agency-certified technician is required in most cases, training is not optional. Where agency certification is

required, more training than necessary appears to be desirable even though expensive. Supervisors and plant foremen have been trained so that the required presence of a certified technician is ensured. Additional training by the contractor usually follows depending on the experience and background of the personnel.

Laboratory facilities and equipment represent another cost. In some cases, this has amounted to practically nothing because suitable laboratories were already present. Minor repair and replacement costs have been incurred. In other cases, new equipment and buildings have been necessary. Although these costs are high, they are depreciated over several years, which results in substantial but not excessive annual costs.

The final cost item is the penalties that are part of every statistically based end-result specification. Although alarming penalties have occasionally been assessed, generally penalties have not been excessive. Where penalties have been large, the cause has been found and corrected. More often than not, the cause was the specification. Today, penalties amount to a small fraction of 1 percent of contract prices, which is regarded as about as good as possible. Bids must bear the cost of penalties, but a separate item for penalties is not included in cost estimates.

There are also hidden costs of penalties. When a penalty is assessed, it would be folly not to investigate it. This may involve supervisors, plant and street crews, and estimators in addition to control personnel. Although such an investigation may pay significant dividends either immediately or in the future, it does cost time and effort.

The most significant cost of penalties is poor psychology. One supervisor reported that he was not dealing with an end-result system but a penalty system. Another stated that penalties were very rare but too often too close for comfort. Both were working to avoid penalties and could do a better job working toward incentives. Penalties, even though only occasional and small, must be explained by quality control personnel. With an incentive system, the same personnel would occasionally be praised and would not have to explain anything.

Contractor Benefits

Although there are costs associated with contractor control of quality, there are also benefits that at least partly offset the costs.

All end-result specifications require contractors to submit mix designs. Contractor mix designs are often more economical and easier to produce than agency mix designs because the contractor's knowledge of materials is different from the agency's knowledge of the same materials. If the same mixture can be used by other customers, significant cost reductions are possible.

Control personnel are not fully occupied all of the time on control of agency jobs. Their free time can be devoted to mix design, concentrated effort on problem areas, helping other customers with quality control, and a variety of related work. Experience shows that control personnel can always be used effectively even though required agency work may occupy less than half of their time.

Other personnel, such as plant and laydown crews, can be used more effectively to control quality. They can make minor, previously prohibited adjustments. Any adjustment must be reported to control personnel, but it can be made when it is needed. Timely, minor adjustments can eliminate problems before they become serious. When personnel can make such minor adjustments, they develop an improved attitude toward quality.

In most cases, cooperation between contractor and agency has improved. Lines of authority and responsibility are more distinct and logical. Adversary relationships that sometimes existed have disappeared. A side benefit is improved relations with other customers who have been ready and willing to accept contractor control even though their specifications do not provide for it.

Most benefits of contractor control are intangibles that are not readily reduced to bookkeeping entries. Whether or not the costs outweigh the benefits cannot be determined. However, even if costs exceed benefits, contractor control appears to be worth the cost in most cases.

FUTURE IMPLEMENTATION

On balance, company experience with modern end-result specifications and contractor control of quality has been favorable. Major difficulties have been corrected either internally or through agency cooperation. Accordingly, further implementation can be expected in the future.

Future end-result specifications can be improved if quality can be ensured by more realistic requirements and procedures. The areas to be considered include tolerances, number of requirements, reproducibility, feedback, and penalties. Of these, realistic tolerances and fewer requirements will probably be the most difficult to achieve. Penalties can be replaced by incentives. Reproducibility and feedback problems are not present in some existing systems and could probably be eliminated from all.

Even more improvement could be expected if, instead of one end-result specification per agency, there were just one end-result specification. A standard end-result specification used by all would be easier for everyone to understand. Contractors, who have been accused of resisting the adoption of end-result specifications, would resist less and perhaps not at all if they were faced with a specification that contained realistic, understandable requirements. Agencies could communicate with each other better and learn more from each other's experiences. The machinery for developing such a standard already exists in the American Society for Testing and Materials. That machinery can be used to everyone's benefit.

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