# Equitable Graduated Pay Schedules: An Economic Approach

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**An approach for establishing graduated pay schedules that are realistic, equitable, and legally defensible is presented. The method consists of determining the present worth of the extra expense anticipated in the future as a result of work of deficient quality. An appropriate pay schedule is developed on the premise that it would be justifiable to withhold this amount from the contract price. The method is applicable in the case of construction items for which data are available that relate quality to performance. An example is given in which concrete pavement is evaluated in terms of compressive strength.**

In recent years, engineers have begun to recognize that most design parameters are variables and that it is not uncommon (or necessarily undesirable) for a small percentage of test results to fall below some prescribed design value. Even when a greater number of tests fall below this value, experience has shown that the net result may simply be a loss of serviceability. Because of the impracticality of removing and replacing an item that is only slightly deficient, engineers have begun to rely on statistically oriented end-result specifications that use graduated pay schedules to award payment in proportion to the quality received.

Of prime importance in the development of specifications of this type is the establishment of realistic and equitable pay schedules. The approach presented in this paper is an extension of methods suggested in other recent writings (1, 2). In principle, it is as follows: When tests indicate that a construction item is of substandard quality, withhold payment that, when deposited at compound interest, will provide sufficient funds in the future to restore the item to its intended (design) condition. In other words, the amount to be withheld is the present worth of the extra expense anticipated in the future as a result of deficient workmanship.

## EXAMPLE

Suppose it is desired to develop a pay schedule for concrete pavement based on compressive strength. Assuming a design strength of 27.59 MPa (4000 lbf/in$^2$), a coefficient of variation (CV) of 15, and an acceptable quality level (AQL) of 10 percent below design strength, the average strength of AQL concrete will be 34.14 MPa (4950 lbf/in$^2$). Furthermore, based on historical data or engineering judgment or a combination of both, suppose it is decided that the worst quality to be accepted even at reduced payment (the rejectable quality level or RQL) will have 50 percent of the material below design strength. Concrete of this quality will have an average strength of 27.59 MPa (4000 lbf/in$^2$).

Before the expected loss in allowable load repetitions for a shift in quality from AQL to RQL [defined by a shift in compressive strength from 34.14 to 27.59 MPa (4950 to 4000 lbf/in$^2$)] can be calculated, it is first necessary to determine the corresponding loss in flexural strength (modulus of rupture). Data presented by Urquhart (3) can be used to estimate the following relation for concrete that has a compressive strength between 20.69 and 48.28 MPa (3000 and 7000 lbf/in$^2$):

$$y = 1.97 + 0.0709x \qquad (1)$$

where

y = flexural strength (modulus of rupture) (MPa) and
x = compressive strength (MPa).

Then, since the working stress is defined as 75 percent of the modulus of rupture, the following values can be calculated (1 MPa = 145 lbf/in$^2$):

| Quality Level | Compressive Strength (MPa) | Flexural Strength (MPa) | Working Stress (MPa) |
|---|---|---|---|
| AQL | 34.14 | 4.39 | 3.29 |
| RQL | 27.59 | 3.92 | 2.94 |

To determine the reduction in allowable load applications, the American Association of State Highway Officials (AASHO) nomograph for rigid pavements with a terminal serviceability index ($p_t$) of 2.5 (4), shown in Figure 1, will be used. Assuming the pavement was designed to handle 1000 daily 80-kN (18 000-lb) equivalent load applications and that the modulus of subgrade reaction k is 1.21 MPa (175 lbf/in$^2$), the solid line in this figure indicates that this pavement should be 24.1 cm (9.5 in) thick. However, if it is built with this thickness but because of improper materials or workmanship happens to be of RQL quality instead of AQL quality, the dashed line indicates that it will be capable of sustaining only about 700 daily load applications instead of 1000.

Next, this must be converted to time to failure (i.e., time at which an overlay is required). If the traffic volume were constant, the time to failure would be directly proportional to the number of allowable load applications, and the RQL pavement in this case would be expected to last about 70 percent as long as the AQL pavement. However, if there were a tendency for the traffic count to increase over a period of years, fewer of the allowable load applications would occur during the early part of the service life of the pavement and, as a result, it would not reach failure quite as quickly as if the traffic count were constant with time. The following expression for predicted service life can be derived:

$$n = \ln\{1 + (d/D)\,[(1 + R)^N - 1]\}/\ln(1 + R) \qquad (2)$$

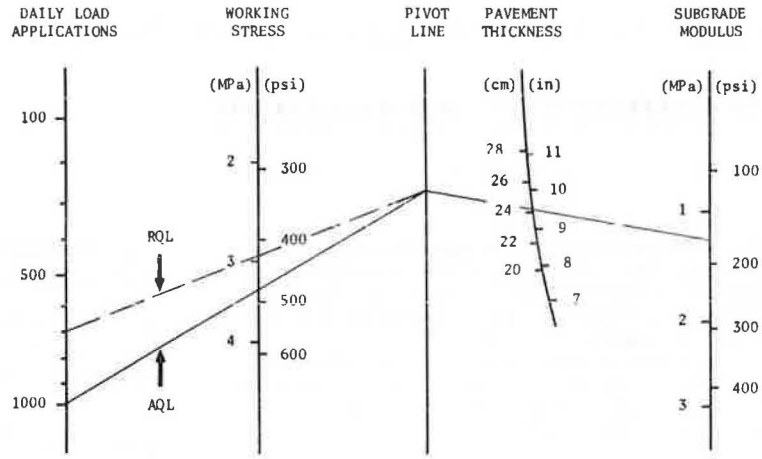
where

n = predicted service life (years);
d = reduced number of daily 80-kN (18 000-lb) load applications determined from AASHO nomograph;
D = design daily 80-kN load applications;
R = yearly traffic count increase expressed as a decimal (although it is not permissible to use R = 0 in this expression, it can be demonstrated that, as $R \to 0$, $n \to dN/D$); and
N = design service life (years).

Although the AASHO method is developed for a 20-year analysis period, suppose local experience has shown that pavements designed by this procedure will last an average of 25 years when properly constructed. Assuming a traffic increase of 2 percent/year (R = 0.02), the following calculation can be made:

$$n = \ln\{1 + (700/1000)\,[(1 + 0.02)^{25} - 1]\}/\ln(1 + 0.02) = 18.7 \qquad (3)$$

Figure 1. AASHO design chart for rigid pavements.




Thus, with an increase in traffic of 2 percent/year, a pavement that has been determined to be capable of sustaining about 70 percent as many load applications by use of the AASHO nomograph is seen to have a service life about 18.7/25 = 75 percent as long as would normally be expected.

In this example, the RQL pavement will require an overlay after 19 years—6 years sooner than the AQL pavement. To determine the present worth of the extra cost of this premature failure, basic engineering-economics formulas (5) are used along with the following data (1 $m^2$ = 1.2 $yd^2$; 1 cm = 0.39 in):

| Item | Amount |
|---|---|
| In-place cost of concrete | $21.52/m$^2$ |
| In-place cost of overlay | $0.54/cm/m$^2$ |
| Interest rate | 5 percent |
| Inflation rate | 4 percent |

In the calculations, the depreciation of an overlay is assumed to be proportional to the length of time it has been in service. For example, if the expected life of an overlay is 10 years, after 7 years its salvage value is considered to be 30 percent of the cost of installing a new overlay at that time.

For this example, it will be assumed that the overlay on the RQL pavement will have to be about 7.6 cm (3 in) thick (because of such factors as cracking and faulting) and that it will have an expected life of 10 years. This overlay will be required 19 years in the future, and at that time its cost will be $7.62 \times \$0.54 \times (1 + 0.04)^{19} = \$8.67/m^2$ ($\$7.27/yd^2$). If the interest rate of 5 percent/year, compounded monthly, is used, the value of this money at the 25th year (6 years later) would be $\$8.67 \times [1 + (0.05/12)]^{12 \times 6} = \$11.70/m^2$ ($\$9.81/yd^2$). At that time, the overlay will have a 40 percent salvage value, which is $0.4 \times 7.6 \times \$0.54 \times (1 + 0.04)^{25} = \$4.38/m^2$ ($\$3.68/yd^2$). The extra cost incurred as a result of deficient quality will be the difference between these last two values, or $\$11.70 - \$4.38 = \$7.32/m^2$ ($\$6.13/yd^2$). To convert this back to present worth, the following expression is used: $\$7.32/[1 + (0.05/12)]^{12 \times 25} = \$2.10/m^2$ ($\$1.76/yd^2$).

Since this is the amount of money that must be invested at compound interest at the time of construction to pay for the future cost of restoring the pavement to its intended (design) condition, it would seem equitable to withhold this amount from the contract price. However, before this result can be used to calculate an appropriate pay schedule, it is necessary to consider the following factors not included in the economic analysis:

1. There will be administrative costs involved in preparing for the premature repair of poor-quality pavements.
2. There will be a cost to the motoring public for earlier and more frequent disruption of traffic to make the necessary repairs.
3. A section of poor-quality pavement will almost certainly make it necessary to overlay a larger section of pavement. For example, if one lane fails, all adjacent lanes will receive an overlay. Similarly, practical considerations will often make it necessary to overlay an entire length of pavement even though only a portion of it has failed.
4. Premature failures, which necessitate additional unanticipated rehabilitation work, could severely restrict the priority-setting capabilities of a highway agency.

Attempts to include item 1, administrative costs, as some fixed percentage of construction costs show this to have little effect on the pay schedule that is ultimately developed. Item 2, the costs associated with inconveniences and delays to the motoring public, is extremely difficult to quantify but does suggest that some increase in expected costs is warranted. Item 3 can be approximately quantified and is seen to have a very significant effect. If a failed section in one lane causes just one adjacent lane to be overlaid, this immediately doubles the cost while providing very little additional benefit. Furthermore, if a failed section (or sections) causes a lengthier section to be overlaid, this cost might easily be doubled again, resulting in a fourfold increase. Finally, if many early failures were to occur, item 4 indicates that some very serious scheduling difficulties might arise. Since fixed appropriations are allotted for maintenance work, the occurrence of several pavement failures might lead to substantial delays in making the necessary repairs. If increased appropriations were not forthcoming, these delays could become prolonged, which would further accelerate the deterioration, cause driving conditions to become more hazardous, and make subsequent repairs even more costly.

Because of the potentially devastating effect of the occurrence of many substandard construction projects, plus the fact that it should be the highway agency's goal to build quality pavements that do not fail prematurely, it is felt that the reduced pay factor for RQL (truly inferior) construction should be set low enough to ensure that the buyer (i.e., the taxpayer) gets his money's worth and that sufficient incentive is provided for the contractor to produce quality workmanship. Since item 3 by itself indicates that the estimated costs of future repairs

should be multiplied by a factor of 2 or more, it is felt that a multiplication factor of at least 3 should be used to account for all unquantified items. The present worth of the cost to repair RQL quality pavement is then estimated to be 3 × \$2.10 = \$6.30/m$^2$ (\$5.28/yd$^2$) and the appropriate percentage payment, based on the bid price of \$21.52/m$^2$ (\$18.00/yd$^2$), is (\$21.52 - \$6.30)/\$21.52 = 70.7 percent, which, for practical purposes, is rounded off to 70 percent.

The next step is to develop an acceptance procedure and a graduated pay schedule that, on the average, will award 70 percent payment for RQL-quality concrete. In an earlier paper (6), it was demonstrated that the average pay factor actually received for RQL-quality concrete will be substantially higher than the minimum value in the pay schedule. This is true because many RQL lots will receive pay factors higher than the minimum value and these, in turn, bring the average up. More recent work by the author has shown that a minimum pay factor of 50 percent will produce an average pay factor between 70 and 80 percent for truly rejectable concrete. Based on this, a minimum pay factor of 50 percent is judged to be appropriate.

Once the minimum pay factor for RQL-quality construction has been established, it remains to develop a series of graduated pay factors that correspond to quality levels between the AQL and the RQL. If one recognizes that the consequences of deficient concrete become much greater as the deficiency increases, it would seem reasonable to graduate the pay schedule in a nonlinear fashion so that concrete that is only slightly below the AQL would receive nearly full payment. One possible pay schedule that uses five steps and an RQL pay factor of 50 percent would be as follows:

| Quality | Pay Factor (%) |
|---|---|
| AQL | 100 |
| | 95 |
| | 85 |
| | 70 |
| RQL | 50 |

In addition to this, most agencies would want to reserve the option to require removal and replacement of any material found to be at or below the RQL.

It is not the purpose of this paper to discuss the development of the acceptance procedure by which the actual quality of a product is estimated. This information may be obtained from many sources (7, 8, 9). When this is completed, it would be wise to use computer simulation (10) or other means to confirm that the expected pay factors for various levels of quality are reasonable and equitable.

## SUMMARY

The intent of this paper is to present by example a rational and logical method for determining the value of an item of substandard quality to provide solid justification for the use of statistically oriented end-result specifications with graduated pay schedules. It is suggested that the present worth of the additional future cost anticipated as a result of construction of deficient quality is a sound basis for the determination of an equitable pay reduction. It is recognized that this method is appropriate only for items for which there are data that relate quality to performance (or expected life), but it is believed that there are a sufficient number of such cases to warrant serious consideration of this approach.

The example presented concerns the development of a pay schedule for concrete pavement based on compressive strength. By using the same AASHO nomograph, it would also be possible to develop a pay schedule based on pavement thickness and, in fact, these two parameters of quality—strength and thickness—could be used jointly. Similarly, a pay schedule based on thickness could be developed for flexible pavements.

It is believed that the information needed to apply this procedure is readily available within most state highway agencies although it is recognized that the choice of specific interest and inflation rates requires the assumption that these rates can be accurately projected some distance into the future. The values used in the example were chosen for purposes of illustration and, as would be expected, slightly different input values will produce slightly different results. Users of this method are cautioned that care should be taken to determine appropriate input values for the agency for whom the specification is being developed.

## ACKNOWLEDGMENT

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