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ROLLING REQUIREMENTS TO IMPROVE COMPACTION OF DENSE ROADBASE AND BASECOURSE MACADAM

by

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Ownership of the Transport Research Laboratory was transferred from the Department of Transport to a subsidiary of the Transport Research Foundation on 1st April 1996.

ROLLING REQUIREMENTS TO IMPROVE COMPACTION OF DENSE ROADBASE AND BASECOURSE MACADAM

ABSTRACT

There is potential for improving the compaction of dense roadbase and basecourse macadam in the critical wheel-path zones which determine the structural performance of pavements. The Report considers the effect of cooling of bituminous layers on compaction and describes a procedure which should expedite the rolling process and ensure that adequate compactive effort is applied before the material has cooled excessively. Proposals are made for an improved method specification. It is hoped that reductions in the design thickness of dense coated macadams can be made when improvement in compaction in the wheel-paths has been demonstrated at several sites.

1. THE CURRENT SPECIFICATION FOR COMPACTION

In general, compaction of dense bitumen-macadam roadbases and basecourses has been considered satisfactory and poor performance of pavements has rarely been ascribed to inadequate compaction. However, recent evidence[1] has indicated there is potential for increasing the density of material in the critical wheel-path zones, which determine the structural performance of pavements, by about 3 per cent. Studies[2] have furthermore shown that such an increase in compaction would produce substantial benefits in terms of improved performance.

The present specification[3] for compaction of bituminous materials in the United Kingdom defines the type and overall weight of roller, limiting values of thickness of the compacted layers, and temperature limits for materials both at delivery on site and at the start of rolling. Neither the number of rollers nor the number of passes is specified but materials must be compacted to a specified thickness and, in the case of surfacing layers, to an acceptable surface regularity. Much however is left to the discretion of the roller driver.

The cost of compaction in the United Kingdom is only about one or two per cent of the total cost of laid material and there is considerable scope for improving the control of compaction at little or no extra cost, by modifying the compaction procedures. Given the prospect of cost savings arising from improved performance of better compacted materials, it is worthwhile investigating ways of achieving improved compaction in the field.

2. THE COOLING OF BITUMINOUS MATERIAL DURING COMPACTION

The temperature of bituminous material is a major factor in determining the viscosity of the binder and several laboratory experiments[4] have shown that it has an important effect on compaction. In pavement construction a substantial drop in temperature normally occurs while material is being rolled and the temperatures of rolling usually quoted are those at commencement of rolling. Results of studies at three sites are shown in Fig 1 and these confirm the importance of temperature in determining the level of compaction achieved with a given number of roller passes. Dense bitumen-macadam rolled at an initial temperature of 85°C is far more difficult to compact than that initially at 130°C; after 20 roller passes the void content of the mineral aggregate (VMA) of the cooler material is approximately 5 per cent higher than that of the hotter material. At a fourth site the VMA of a slag tarmacadam (54° e.v.t. tar) was reduced by nearly eight per cent when the temperature at commencement of rolling was increased from 60°C to 80°C. Evidence obtained at many sites shows that, over the permitted range of rolling temperature, the compaction of dense coated macadam containing crushed rock or slag is facilitated if its temperature at commencement of rolling is increased.

Although these results indicate the trends to be expected when materials are compacted at different temperatures, they cannot be used in any particular instances to predict accurately the compaction level obtained after a given number of roller passes; the intermittent nature of rolling and the rate of cooling subsequent to commencement of rolling are also important influences on the results achieved. Fig 2 shows the variation of temperature with time measured at 2 sites and also indicates the timing of roller passes applied in the nearside wheel-path which was taken to be 0.9m from the edge of the laid width. The material at both sites was dense bitumen-macadam mixed with 100 pen bitumen. The rate of cooling of the macadam laid at a low temperature (the temperature at commencement of rolling was just above the minimum specified) was almost as great as that of the material laid at high temperature because ambient conditions at these two sites were very different; at the first the material was laid in cold, windy conditions whereas at the second site the weather was warm and calm. Although rolling was carried out at roughly the same rate on both sites, 12 passes were applied at temperatures above 80°C at the first site compared with only three at the second. The result in terms of compaction was that the hotter material was compacted to a VMA of 13.5 per cent whereas the corresponding value for the colder material was 18.4 per cent.

The foregoing results obtained in site trials indicate there is scope for improving compaction by increasing the number of roller passes at higher temperatures. A study was therefore made of rates of cooling for different site conditions and of procedures currently executed by contractors, as a preliminary to developing an improved compaction procedure.

3. PREDICTED RATES OF COOLING

A sketch showing the flow of the heat to and from newly-laid bituminous material is shown in Fig 3. Heat is lost to the supporting layer by conduction and to the atmosphere by convection and radiation. Account must also be taken of radiant energy absorbed from the sun. The net heat loss depends on the temperature of the material when it is laid, its thickness, and ambient conditions such as the initial temperature of the supporting layer, air temperature, wind speed and solar flux. Information on cooling rates over a wide range of site conditions can be gathered experimentally but would involve a protracted programme of work. A theoretical model of the heat transfer process is therefore desirable to predict rates of cooling of bituminous layers for the wide range of conditions encountered in practice and to identify the factors that have greatest influence on the cooling rate.

At any depth x in the bituminous layer and at time t the flow of heat by conduction is given by

$$\frac{\delta T}{\delta t} = \frac{k}{\rho c} \times \frac{\delta^2 T}{\delta x^2}$$

where T is the temperature, k the thermal conductivity of the material, ρ its density and c the specific heat. A numerical solution based on dividing the laid material and its supporting layer into finite elements has been developed and calculated rates of cooling have been found to be in good agreement with those determined experimentally[5]. A computer program was used to facilitate the determination of the variation of temperature with time and depth within layers.

The predicted distribution of temperature through a bituminous layer 30 minutes after laying is shown in Fig 4 for average conditions and also for material laid in a relatively cool condition (but within specification) on a cold and windy day. Both curves illustrate the large variation of temperature with depth and highlight the necessity of stipulating the position at which temperature is measured in the layer. Temperatures quoted in this Report and those determined in practice are taken at the middle of layers. Comparison of the two curves shows that the mid-depth temperature 30 minutes after laying under normal conditions would be 95°C whereas that of material laid cold in wintry conditions would be 60°C.

Figure 5 shows the effect of layer thickness, initial temperature of the laid material, ambient temperature and wind speed on the mid-depth temperature 30 minutes after laying. The temperature of the supporting layer at the time of laying has been assumed equal to the ambient temperature. Factors which have greatest effect on cooling are seen to be the thickness and initial temperature of the material; ambient temperature has less effect and, over the relevant ranges of the factors, wind speed is least important. Broadly similar conclusions have been obtained for other periods of cooling. The greater heat retention of thick layers was demonstrated in an experiment[6] constructed by the Laboratory at Sevenoaks By-pass on A21 where layers 175mm and 240mm thick retained heat for a very extended period and had, in consequence, to be rolled at temperatures above the maximum limit specified.

Computed cooling rates have been used abroad to develop "cessation requirements" that permit paving when sufficient time is available for satisfactory compaction to be achieved[7]. These requirements were proposed to replace a specification based on single minimum air temperature, which applies in several States in the USA. Before using this approach, knowledge is required of the temperature below which significant further compaction cannot be obtained. The minimum temperature for the completion of rolling has generally been taken[8,9] to be that mid-depth temperature corresponding to a binder viscosity of 10^3 poise. The grade of binder will of course determine the minimum compaction temperature; for 100 pen bitumen, the most common binder in dense roadbase and basecourse macadams used in the construction of heavily trafficked roads, the temperature corresponding to a binder viscosity of 10^3 poise is 60°C. The time taken for the temperature of a bituminous layer to fall to this minimum level will vary considerably with ambient temperature, layer thickness and its temperature when laid, and a specification for compaction incorporating these variables would be too complicated for implementation in normal practice.

A more realistic approach is to base the specification for compaction on time available for effective compaction under the most adverse conditions encountered when poor compaction is most likely to occur. The minimum thickness of dense coated macadam used in the construction of heavily trafficked roads is normally 60 to 65mm[10] and the minimum ambient temperature, 2°C. The minimum specified delivery temperature for dense bitumen-macadam containing 100 pen bitumen is 105°C and it is therefore to be expected that the minimum laying temperature will be about 95–100°C. Figure 5 shows that under these conditions the period in which effective compaction can take place is about 30 minutes. Dense coated macadam materials containing other binder grades would have different temperatures for delivery and for cessation of rolling, and in Fig 6 the predicted rates of cooling indicate that the time available for compaction under the most adverse conditions varies from less than 20 minutes for 200 pen bitumen to 30 minutes for 100 pen bitumen, the two tars requiring times in between these figures. In Fig 7 rates of cooling under more favourable and more typical ambient conditions (ambient temperatures of 5°C and 10°C) show that the time available for compacting tarmacadam (laid 65mm thick) is slightly greater (about 30 minutes) whereas the corresponding time for material containing 200 pen bitumen remains considerably less, about 22 minutes.

The most common grade of binder used in dense roadbase and basecourse macadams for heavily trafficked roads is 100 pen bitumen for which 30 minutes is available for effective compaction even under adverse conditions. Tarmacadams are not extensively used and 200 pen bitumen may be used only for pavements designed for less than 2.5×10^6 standard axles. With the exception of dense bitumen-macadam containing 200 pen bitumen there are at least 30 minutes available for effective compaction under most site conditions. Material containing 200 pen bitumen however must be delivered at temperatures at least 10°C higher than the minimum specified of 80°C to ensure that the time available for compaction is 30 minutes or more.

It is proposed to base the specification for compaction of all dense roadbase and basecourse macadam on a 30-minute period because this period is a good estimate of the time available for compaction under adverse conditions. It remains to specify a minimum number of roller passages in this period; this has been determined from a theoretical model of the rolling process and studies of normal rolling procedures at sites.

4. THEORETICAL MODEL OF THE ROLLING PROCESS

A model of a simple uniform rolling process enables the important factors to be identified. When one roller is used, the model is based on the following criteria.

a) The paving machine advances continuously at a uniform speed (S_p).

b) The roller moves continuously at a uniform speed (S_R) reversing when it reaches a fixed distance D from the paver and again when it reaches the paver.

c) The fixed maximum distance D of the roller from the paver is such that rolling continues for as long as effective compaction is possible but no longer.

This implies that the area being rolled advances at an average rate equal to the paver speed and that therefore the time available for rolling (T) at a particular position along the road is the time taken by the paver to advance a distance equal to the average length D of roller passages so that $T = D/S_P$. The number of roller passages (defined in Appendix) completed by one roller in this period T is given approximately by

$$N = \frac{S_R}{S_P} \qquad \dots\dots\dots\dots\dots \quad 1$$

A small correction is necessary for large values of N to allow for the delay time involved in reversals of rolling direction. In practice the delay time is typically 5 seconds and the appropriate correction has been applied to calculate the number of roller passages shown in Figs 8 and 9 for different speeds of both roller and paver and a rolling period of 30 minutes. If more than one roller is employed the number of roller passages given by Equation (1) is multiplied by the corresponding number of rollers.

The mean paver speed at sites is normally less than 6m/min, typically 2 or 3m/min, whereas the roller speed is about 100m/min. Figs 8 and 9 show that these values of roller and paver speed enable more than 30 passages to be completed in 30 minutes using the 2 rollers that are normally available on site; indeed, in many practical situations, one roller would be sufficient to complete 30 passages in this period.

In the model it is assumed that rolling is distributed over the whole of the period in which effective compaction can take place, that is 30 minutes. The period in which rolling is completed is shortened however if the roller-passage length is made less than $D = 30.S_P$; the total number of passages is unaltered but they are completed in a shorter time. Figure 10 shows how the number of roller passages completed within 30 minutes varies with both roller passage length and paver speed. If the roller passage length is extended beyond $D = 30.S_P$ then the number of passages completed in 30 minutes will be correspondingly reduced.

The model predicts that there should be no difficulty, generally, in completing 30 passages in 30 minutes but, if less than 30 passages are completed in this time, one or more of the following adjustments may be made:

a) reduce the length of roller passages

b) increase roller speed

c) reduce paver speed

d) increase number of rollers used.

5. SITE STUDIES OF ROLLING PROCEDURES

Productivity studies at several motorway sites have produced a large amount of data on the compaction procedures normally employed; in this work the roller passages were recorded at several reference points along lengths of carriageway of 100 to 500m. Definitions of 'roller passage' and 'roller pass' are given in the Appendix.

Typical results obtained for a laid width of material of about 4m are presented graphically in Figs 11 and 12; the number of passages completed in 30 minutes at locations regularly spaced along the carriageway and the contribution made by each of the two three-wheel rollers is shown. Both figures show that rolling begins within 6 minutes of laying and that the speed of rolling is sufficient for the completion, on the average, of over 30 passages in 30 minutes. There is however considerable variation in the number of passages completed in the first 30 minutes; the number ranges from 21 to 46 in Figure 11 and from 28 to 45 in Figure 12. In both figures the furthermost reference point along the carriageway represents the end of one section of paving and it is a common feature that fewer passages are made by the second roller as it approaches this point. This is a consequence of the second roller working far back from the paver initially and gradually moving closer to the paver during the period of paving.

The data reveal that compaction procedures vary considerably not only from day to day on a given contract but continuously during each day's work. In Fig 13 the second roller begins to roll too late and continues to work too far behind the paver; few passages were made in the first 30 minutes and some areas were being rolled 2 hours after the material was laid. The second roller did not start rolling at one reference point until 65 minutes after laying and was then almost 300m behind the paver.

The results show that in general best use is not being made of the compaction plant available at sites and there is considerable variability in the rolling procedures. There is therefore a need to ensure that compaction procedures in general are brought up to the best standards being achieved at the present time. The results confirm that for paving speeds of up to about 6m/min it is easy to achieve 30 passages in 30 minutes with the use of two rollers.

6. PROPOSED COMPACTION REQUIREMENTS

Previous road trials[11] have shown that conventional rolling results in a variation of compaction across the laid width and that 30 passages over a laid width of 4m should result in about 7 roller passes in the wheel-path zones. Modified rolling, in which half the total number of roller passages are made by one roller concentrating on rolling the edges, would increase the number of passes made in the wheel-path. If this roller were a tandem, about 11 passes would be completed in the wheel-paths after a total of 30 passages had been made whereas 8 or possibly 9 passes would be achieved if a three-wheel roller were used for this purpose. Of course, the rolling capacity on site frequently enables considerably more than 30 passages to be completed within 30 minutes of laying. Consideration of the foregoing results has led to the following proposals.

a) For a laid width of 4m a minimum of 30 roller passages should be completed within 30 minutes of the material being laid. The number of passages made is not of course limited to 30; if the rolling capacity available at site is more than adequate, additional passes should be made within the 30 minute period or later. When the laid width is other than 4m the minimum number of roller passages should be adjusted in direct proportion with the laid width.

b) Half of the roller passages should be carried out with the nearest edge of the roller within about 300 mm of the edge of the laid material. This could usually be achieved by using one of the two rollers normally available at sites, to concentrate on rolling the edges. Greater improvements in compaction at the wheel-path zones can be realized if this second roller is a tandem.

c) The minimum delivery temperature should be increased from 80°C to at least 90°C when 200 pen bitumen is used.

The compaction time of 30 minutes specified in Proposal a) is the time available for effective compaction under adverse conditions when poor compaction is most likely to occur. Effective compaction can of course still continue for longer than 30 minutes when conditions are more favourable but requirements which take all conditions into account would be too complicated for normal operation.

If these proposals were adopted and existing delivery temperatures were unaltered except for 200 pen bitumen, the specification of a minimum compaction temperature would be unnecessary. Rolling temperatures would be controlled by the specified delivery temperature and the required rate at which rolling is carried out. Reference has already been made to the difficulty of making accurate measurement of the temperature of laid material and it would be a distinct advantage if this measurement were not necessary in a modified specification.

The proposed requirements (a) and (b) for compacting dense roadbase and basecourse macadams should expedite the rolling process, ensuring that more passes are made at relatively high temperatures and that the proportion of passes made in the wheel-path zones is increased.

7. PERFORMANCE BENEFITS

Previous work[1] has shown there is scope for improving compaction in the wheel-paths by about 3 per cent. Furthermore, the relation between the performance and compaction of dense coated macadam studied in an associated programme of pilot-scale and laboratory tests[2] has shown that worthwhile performance benefits would be derived if density were increased by about 3 per cent. The increased performance of better compacted material would probably be exploited in the form of reduction of pavement thickness rather than as an extension in pavement life and in this case 3 per cent improvement in compaction of dense coated macadam should permit about an 8 per cent reduction in design thickness. It is hoped that reductions of this order can be made when improved compaction has been demonstrated at several sites where the proposals have been implemented.

8. ACKNOWLEDGEMENTS

The work described in this report was carried out in Pavement Design Division (Head of Division: Mr N W Lister) of the Highways Department of TRRL and it forms part of the programme of co-operative research between the Asphalt and Coated Macadam Association and TRRL. The assistance of the Operational Research Section of Construction and Maintenance Division in providing site data of conventional rolling procedures is gratefully acknowledged.

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10. APPENDIX

DEFINITION OF 'ROLLER PASS' AND 'ROLLER PASSAGE'

In the context of this Report, any point on the laid material is said to be subjected to a roller coverage if some part of a roll comes into contact with it. Although the rear rolls of a three-wheel roller have a greater mass per unit width than the front roll, the pressure applied by the rear rolls is reduced in relation to its mass per unit width because of the greater roll diameter and hence larger contact area. Accurate knowledge of the effect of roll diameter on the compaction achieved is, however, not available. It has therefore been assumed that front- and rear-roll coverages of a three-wheel roller produce equal amounts of compaction; the number of roller passes may then be defined as half the sum of the number of front- and rear-roll coverages. A comparison of the results of a pilot-scale trial using a 8.5 Mg three-wheel roller with those obtained in a similar trial with a 9.5 Mg tandem roller suggest that the present simple definition of roller passes is not unreasonable.

If a roller while compacting the material completely passes a reference line across the laid width, then a roller passage is said to have been executed at the line. Roller passages are a convenient measure of rolling but if the amount of compactive effort is required at a point then the exact lateral position and dimensions of the roller have to be taken into account to calculate 'passes' as defined above.

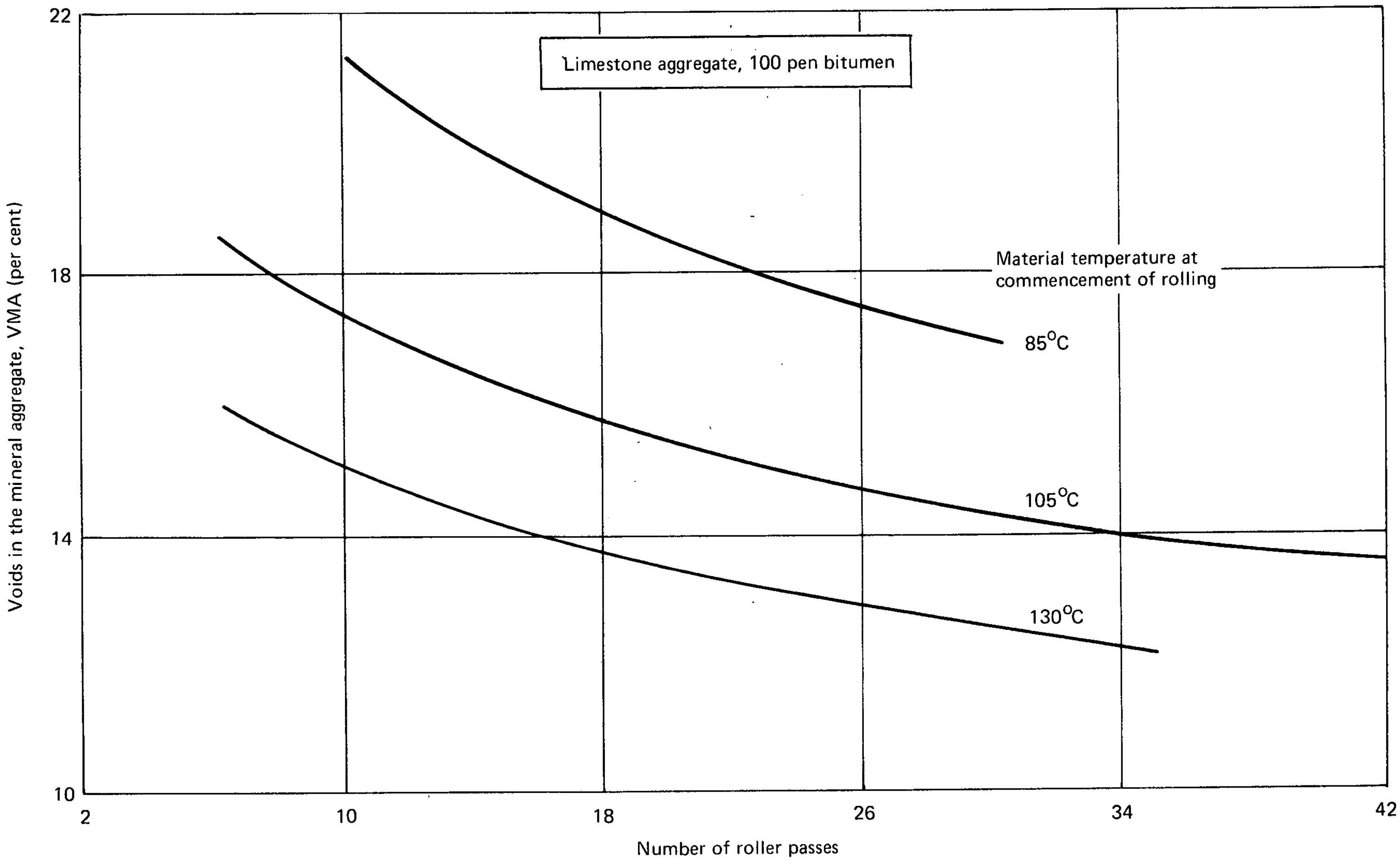


Fig. 1. VARIATION OF VOIDS IN THE MINERAL AGGREGATE WITH ROLLER PASSES FOR DENSE BITUMEN MACADAM

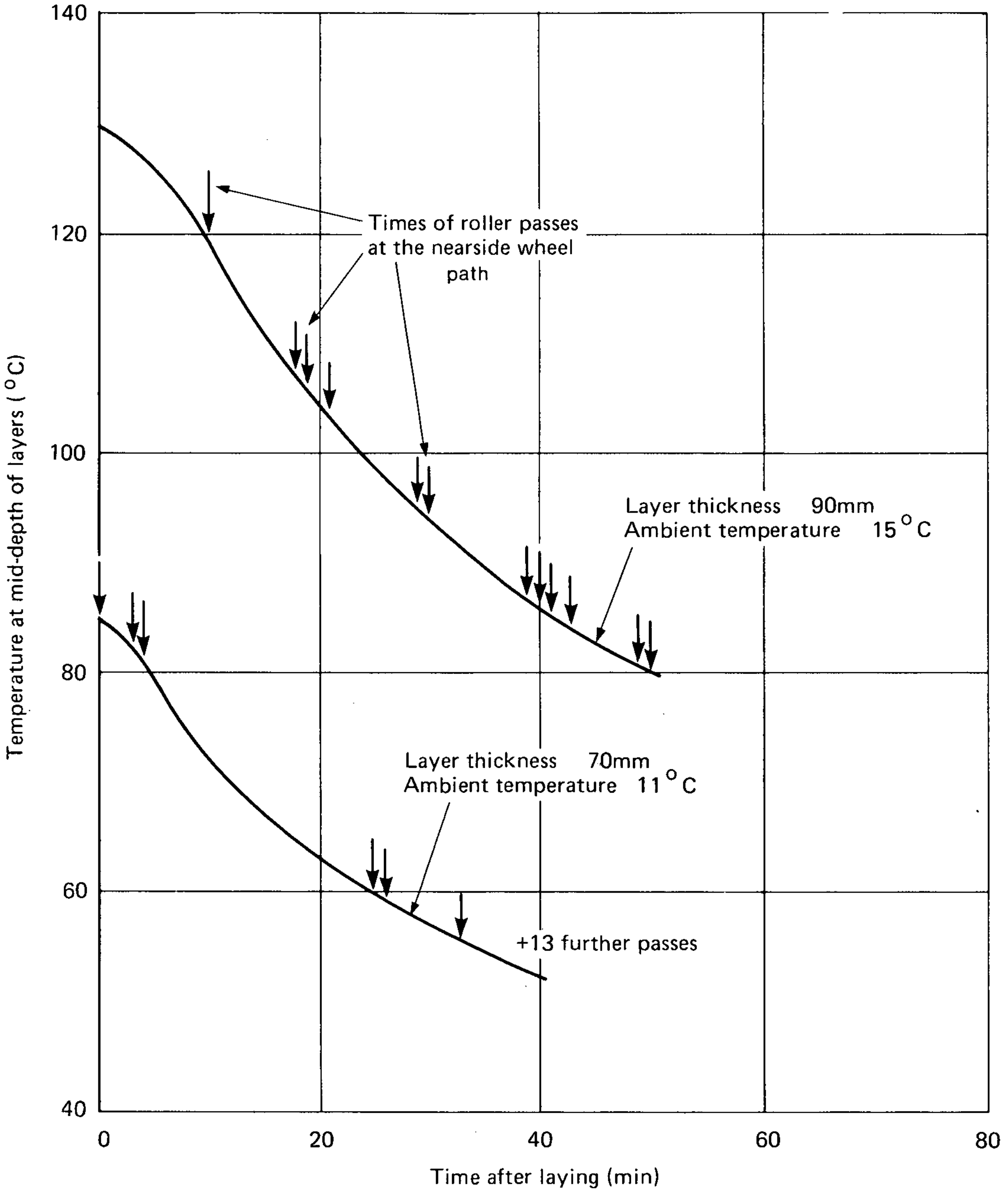


Fig. 2. VARIATION OF TEMPERATURE OF DENSE BITUMEN MACADAM LAYERS WITH TIME RELATED TO PASSES OF A ROLLER IN THE WHEEL PATH POSITION

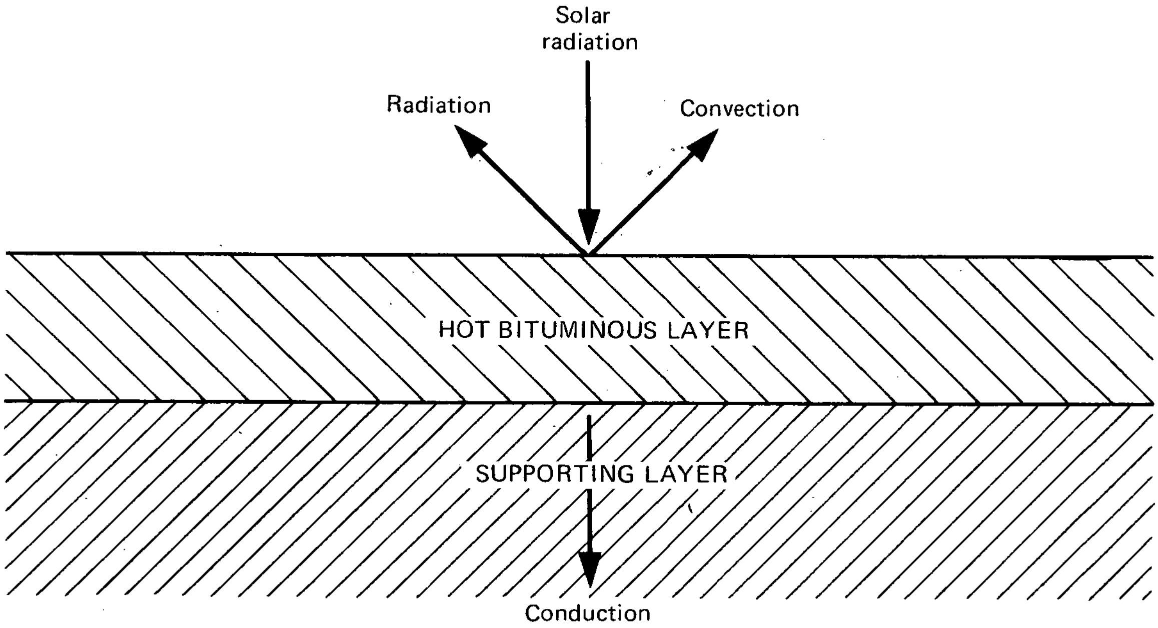


Fig. 3. COMPONENTS OF HEAT TRANSFER FOR NEWLY-LAID HOT BITUMINOUS MATERIAL

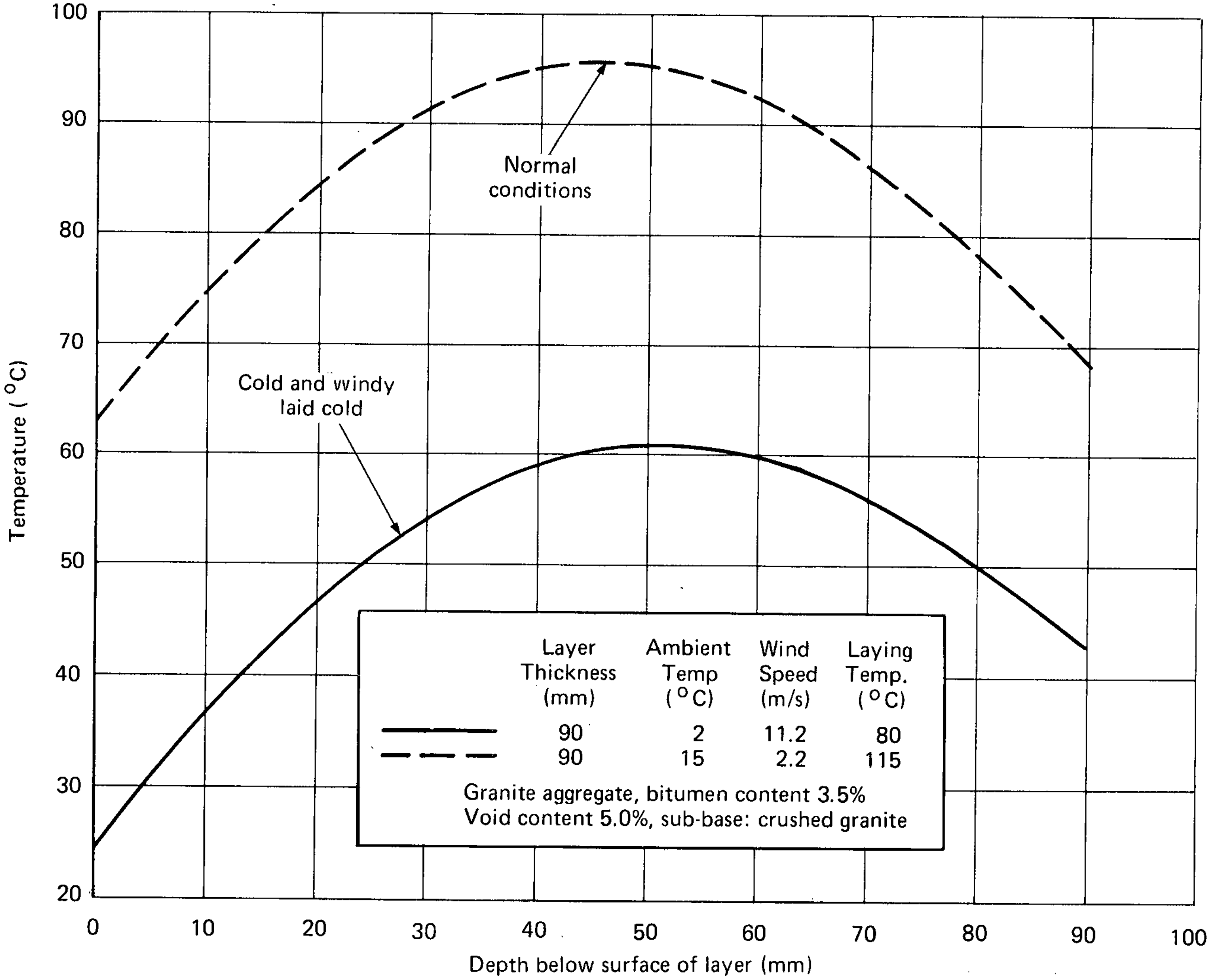


Fig. 4. VARIATION OF TEMPERATURE WITH DEPTH WITHIN A BITUMINOUS LAYER 30 MINUTES AFTER LAYING

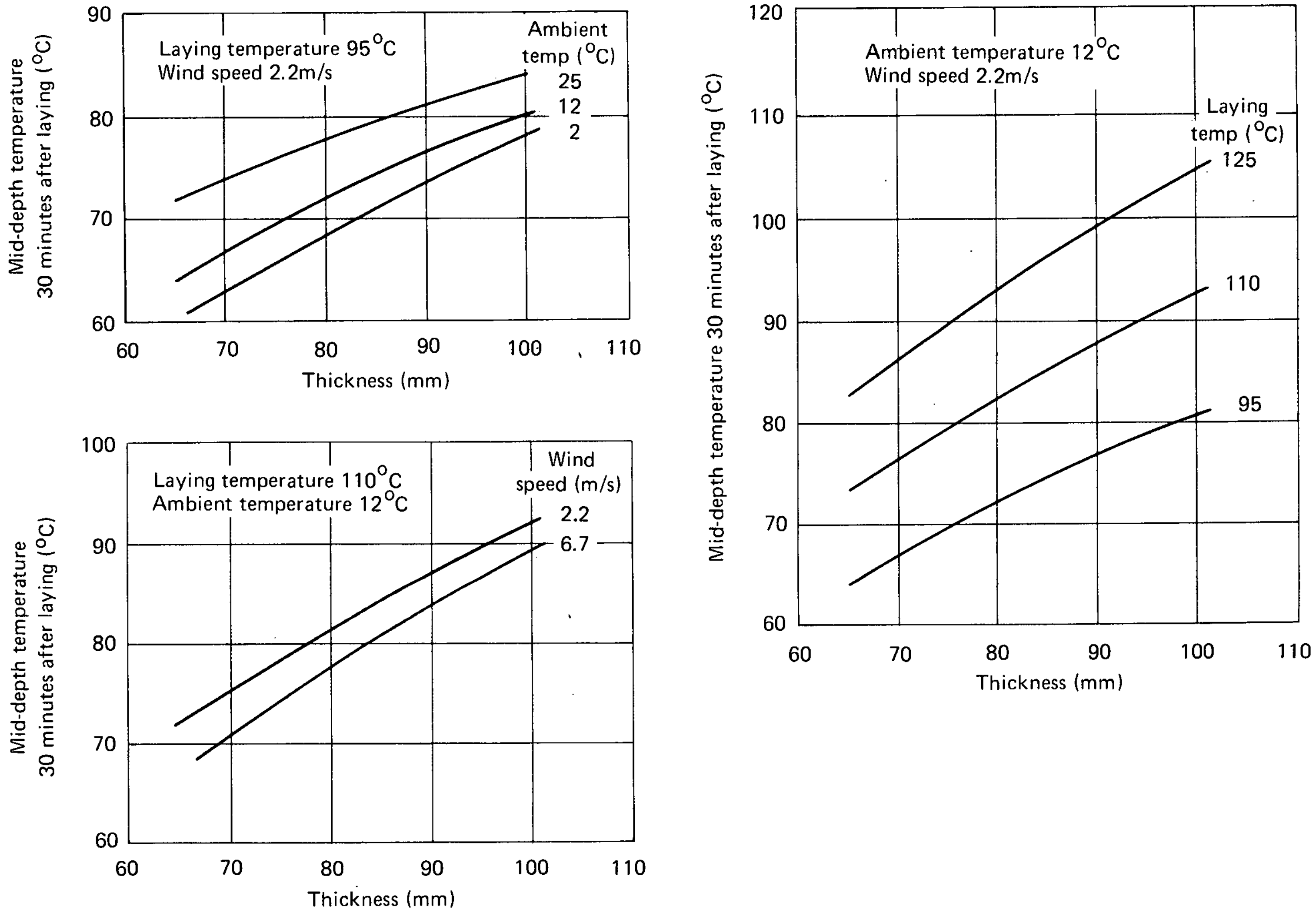


Fig. 5. EFFECT OF LAYER THICKNESS, INITIAL TEMPERATURE OF THE MATERIAL, AMBIENT TEMPERATURE AND WIND SPEED ON MID-DEPTH TEMPERATURE 30 MINUTES AFTER LAYING

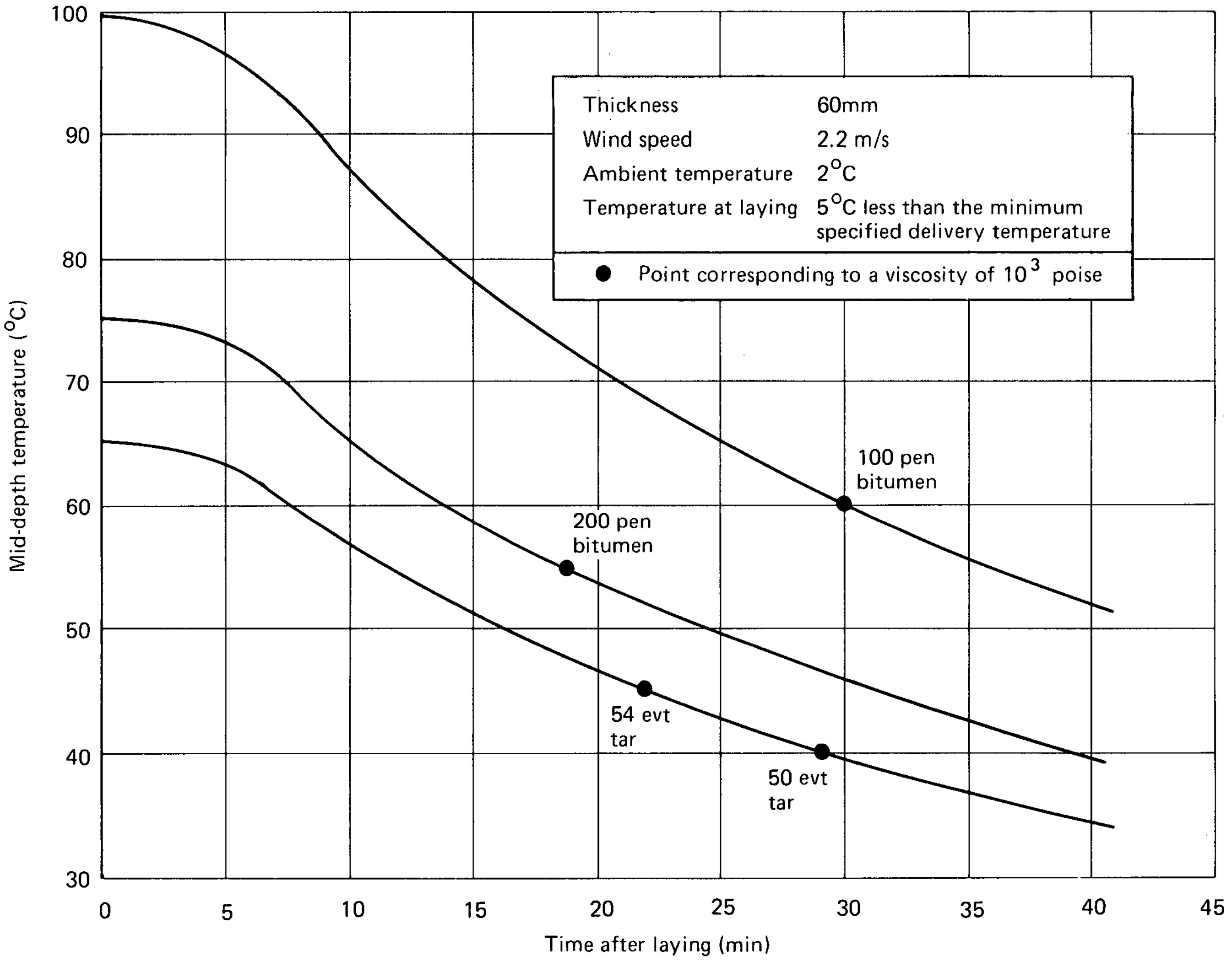


Fig. 6. RATES OF COOLING OF DENSE ROADBASE MACADAM CONTAINING DIFFERENT GRADES OF BINDER, UNDER ADVERSE SITE CONDITIONS

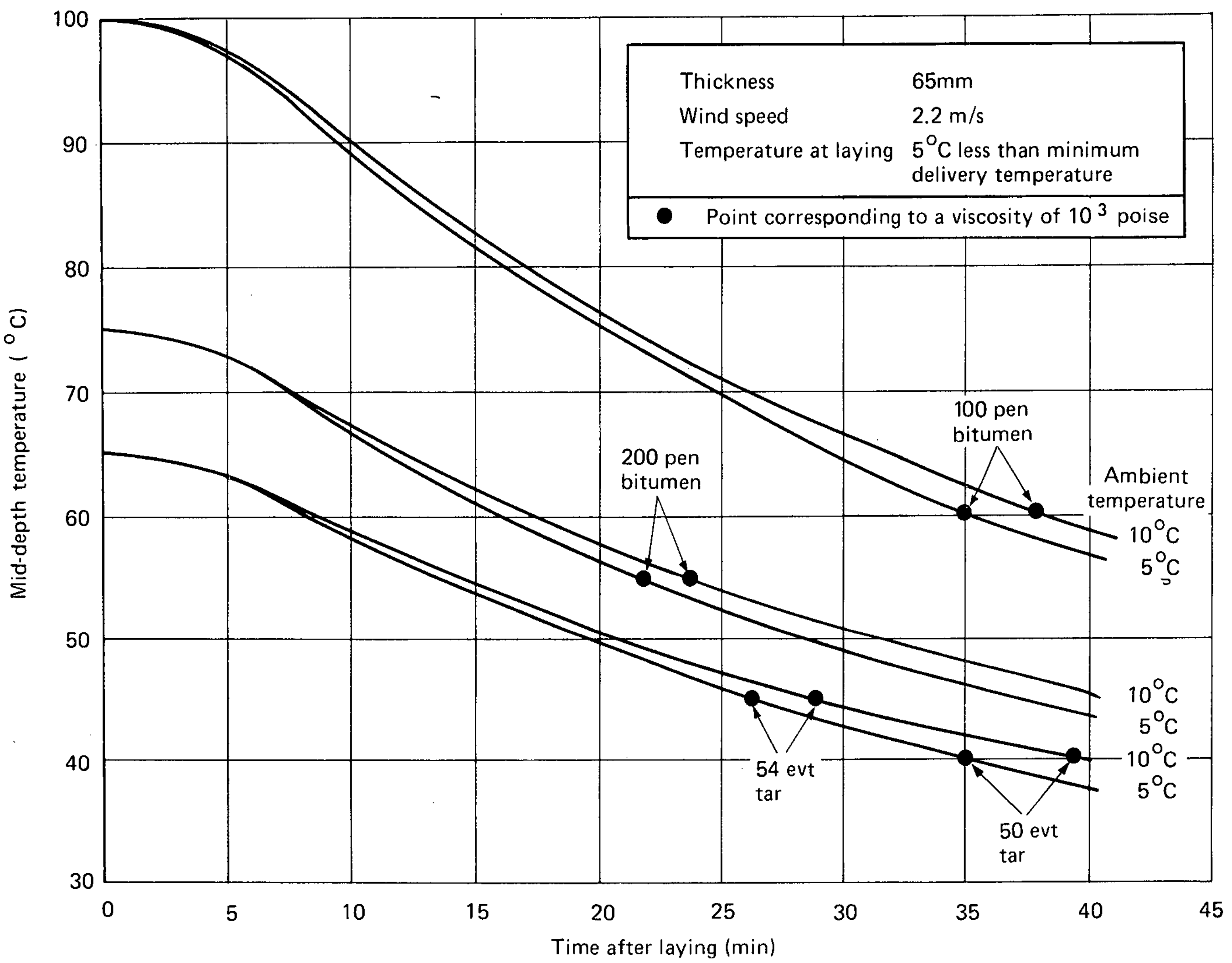


Fig. 7. RATES OF COOLING OF DENSE ROADBASE MACADAM CONTAINING DIFFERENT GRADES OF BINDER, UNDER DIFFERENT AMBIENT CONDITIONS

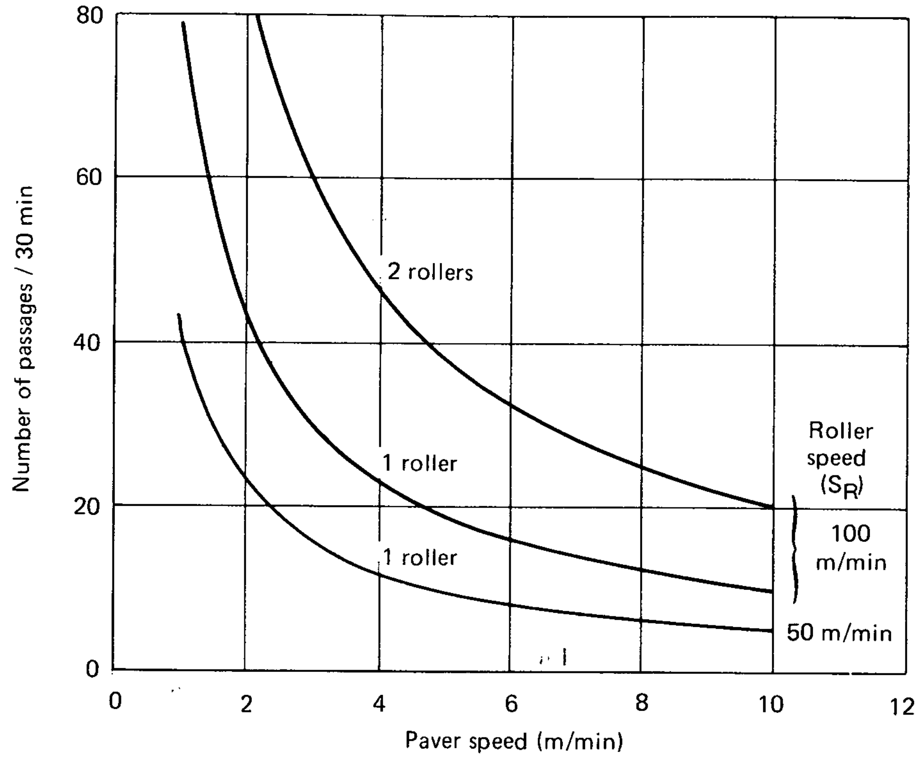


Fig. 8. EFFECT OF PAVER SPEED ON NUMBER OF ROLLER PASSAGES COMPLETED IN 30 MINUTES

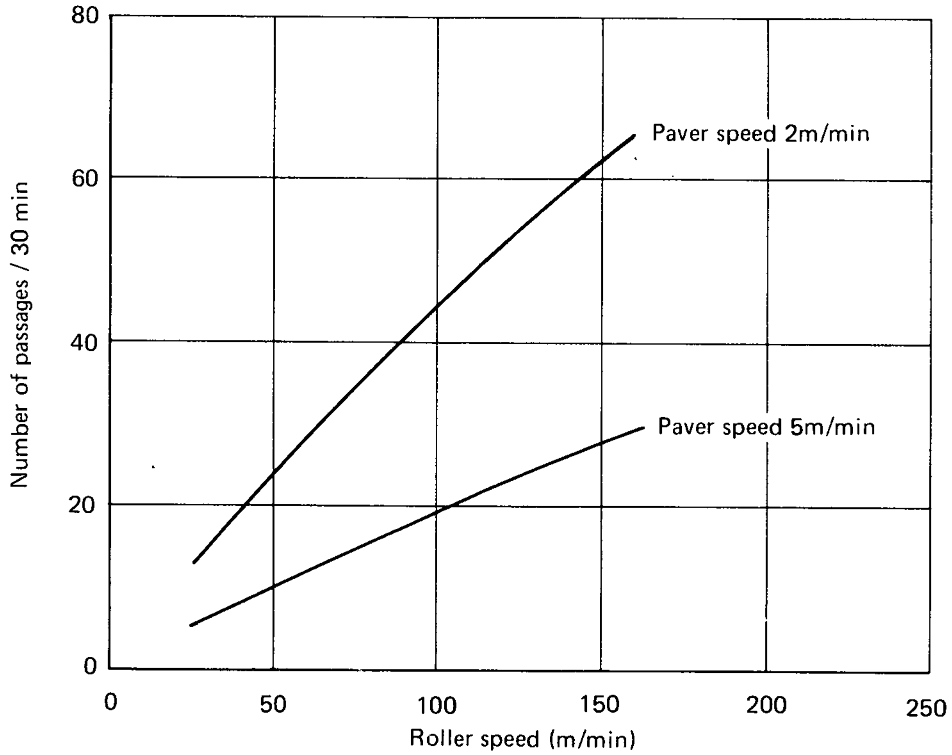


Fig. 9. EFFECT OF ROLLER SPEED ON NUMBER OF PASSAGES COMPLETED BY ONE ROLLER IN 30 MINUTES

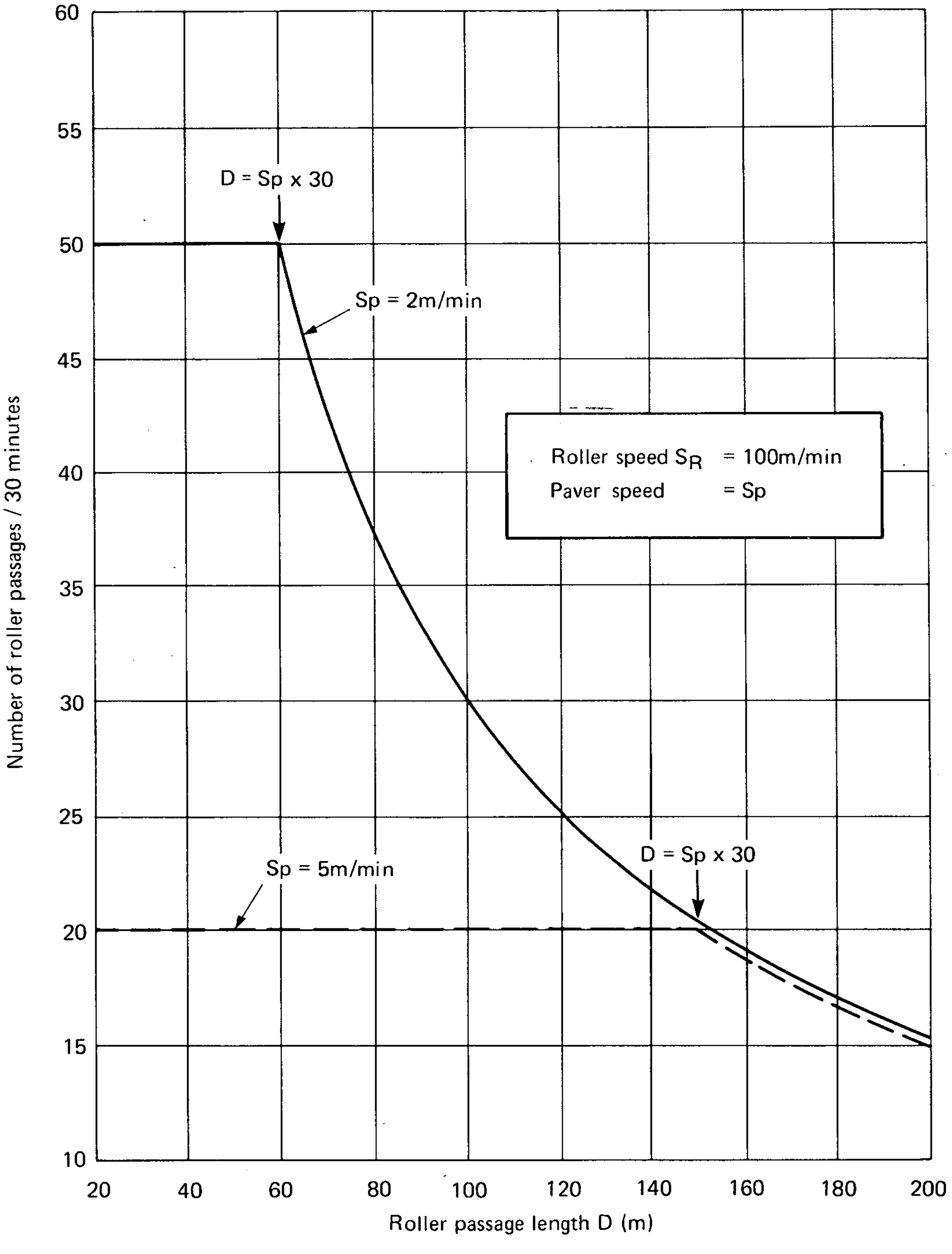


Fig. 10 EFFECT OF ROLLER PASSAGE LENGTH ON PASSAGES COMPLETED IN 30 MINUTES FOR DIFFERENT PAVER SPEEDS

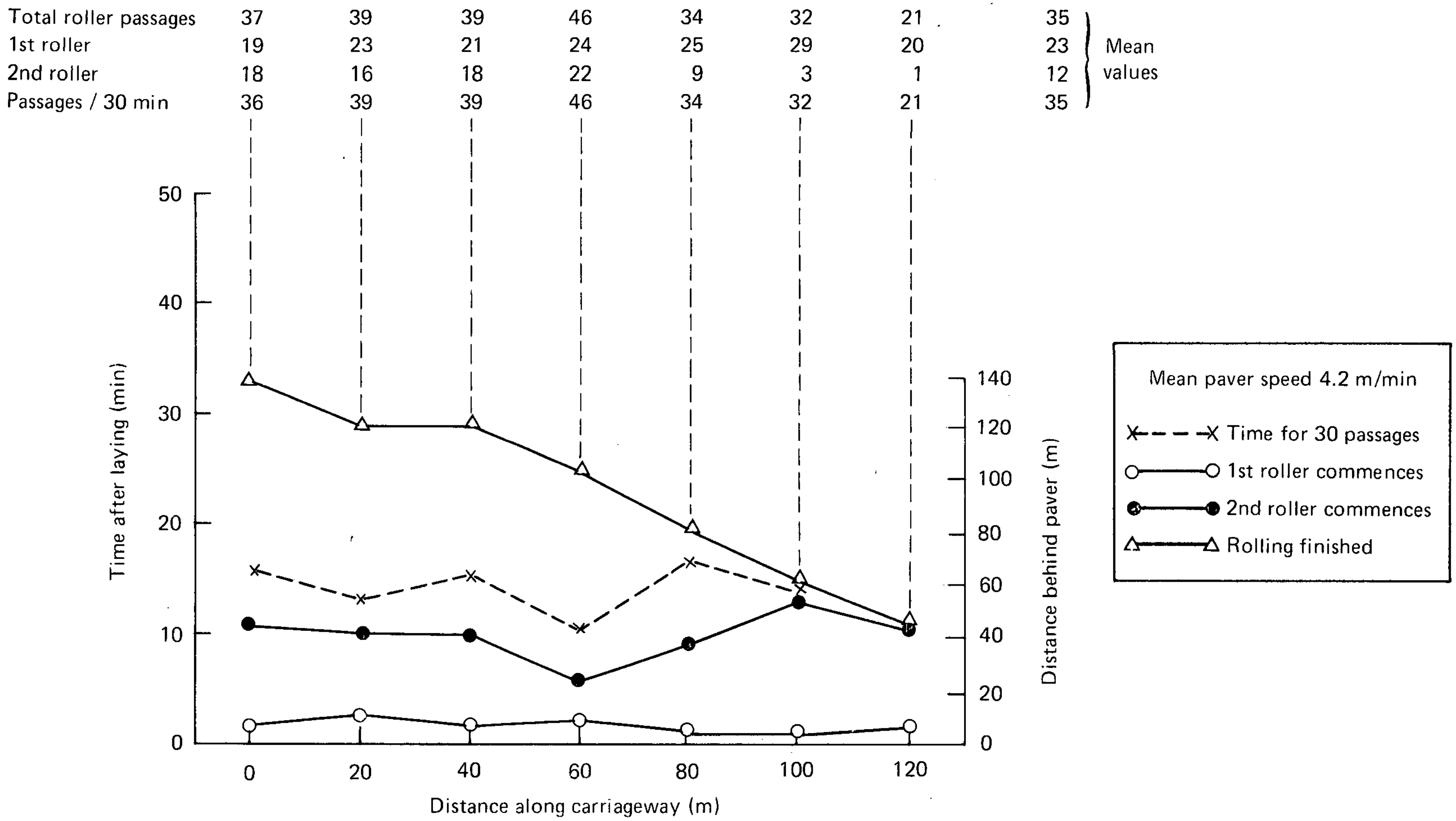


Fig. 11. TIME TAKEN TO COMPLETE THE DIFFERENT STAGES OF ROLLING – TYPICAL RESULT

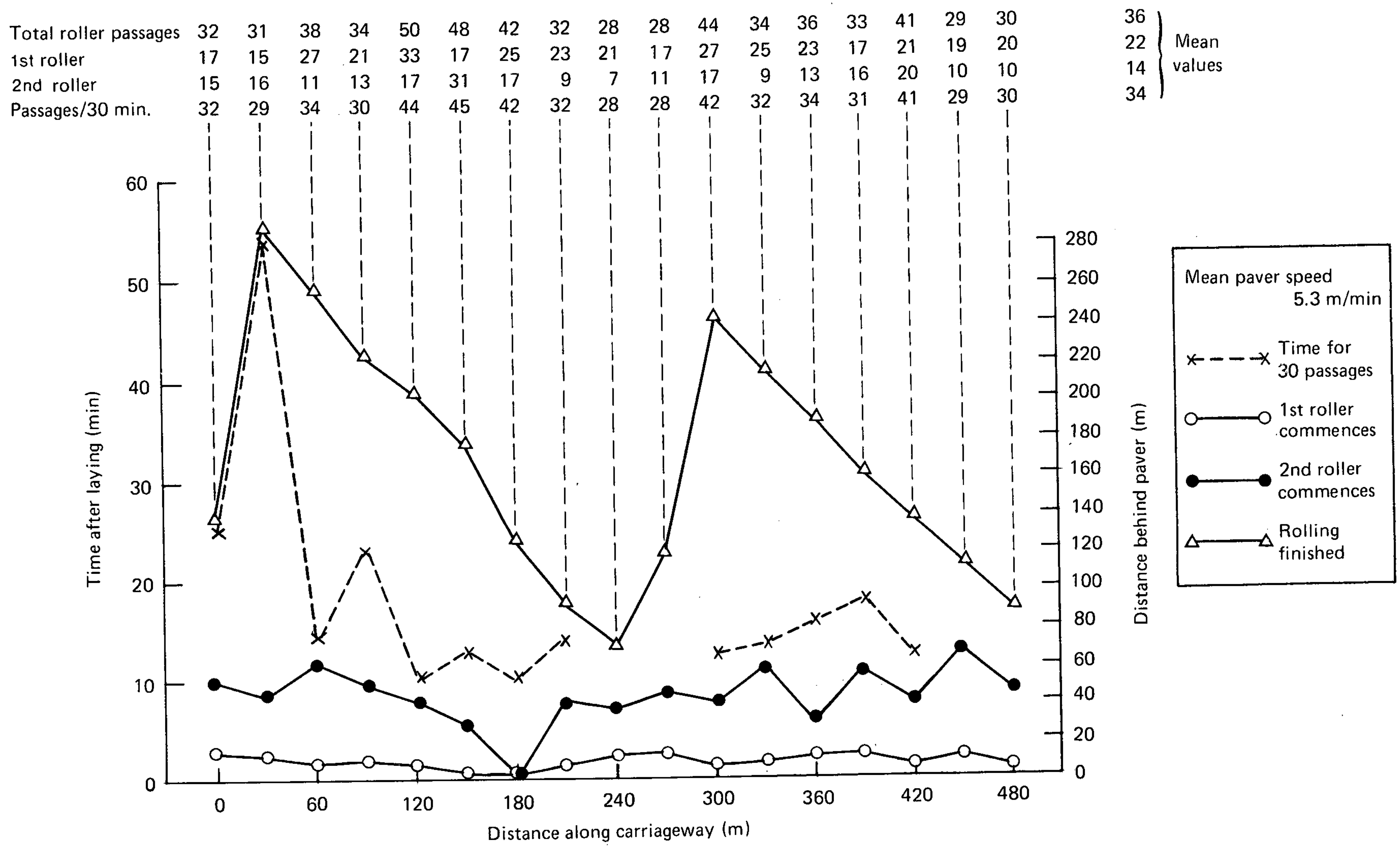
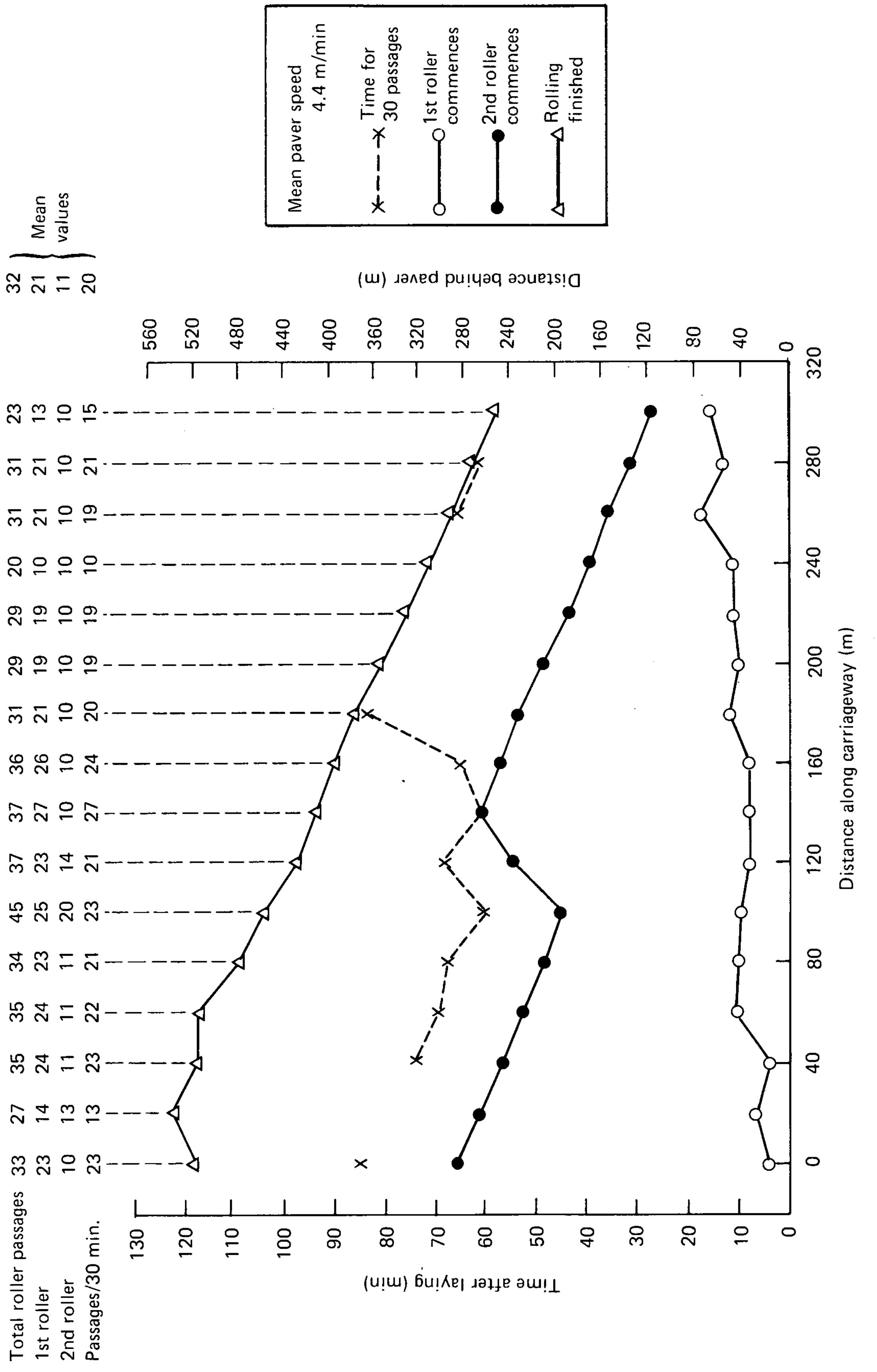


Fig. 12. TIME TAKEN TO COMPLETE THE DIFFERENT STAGES OF ROLLING – TYPICAL RESULT



Distance along carriageway (m)	0	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300	Mean values
Total roller passages	33	27	35	35	34	45	37	37	36	31	29	29	20	31	31	23	32
1st roller	23	14	24	24	23	25	23	27	26	21	19	19	10	21	21	13	21
2nd roller	10	13	11	11	11	20	14	10	10	10	10	10	10	10	10	10	11
Passages/30 min.	23	13	23	22	21	23	21	27	24	20	19	19	10	19	21	15	20

Fig.13. TIME TAKEN TO COMPLETE THE DIFFERENT STAGES OF ROLLING

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