Papers

PAVEMENT CHARACTERISTICS AND SKID RESISTANCE

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Summary

Based upon recent information of its members, and the reports of the Technical Committee on Slipperiness and Evenness for the World Road Congress in Prague (1971) and Mexico (1975) the state of the art in member countries has been given. A comparison of recommendations and specifications relating to the skid resistance properties of new and existing pavements is made. A growing awareness of the need for standards for new and existing pavements is established. For new pavements specifications dealing with materials are of great importance, in particular the polished stone value.

The importance of systematic investigations of skid resistance of road networks is underlined, information on the practical approach in some countries and specifications of equipment is given. An overview of compositions and construction methods for both bituminous and cement concrete pavements with sufficient skid prevention properties is given. An economic choice out of the numerous techniques available for achieving sufficient skid resistance should be made with special regard to the possibility of the use of local materials, workmanship of contractors and experience of the highway engineer. For existing pavements techniques are discribed to restore the skidding properties. From the problems in skid prevention the item rolling noise has been selected as a compromise between skid resistance, thus safety, and noise generation, thus environment, has to be found.

In conclusion can be derived that from research and experience, techniques have been made available generally, to offer pavements to the road user with an adequate skid resistance. In education and permanent formation this knowledge should be implemented. At the same time an economic evaluation of skid resistant road surfaces is obvious. Special problems as rolling noise, tolerable water layer thickness and its relation with road geometry need attention in future.

Contents

Section I: PREFACE

In the course of the preparation of the Second International Skid Prevention Conference, several non-American experts were invited to submit a contribution. Most of these experts are also members of the P.I.A.R.C. (Permanent International Association of Road Congresses) Technical Committee on Slipperiness and Evenness. Consequently, the Committee decided at the Berlin meeting in November 1974 to submit a joint contribution for the Sub-Committee on Pavements and the Sub-Committee on Accidents and Human Factors of the International Skid Prevention Conference.

In order to place P.I.A.R.C. in its context, it should be pointed out that its main task is to organize a World Road Congress every four years in one of the member countries and to enable a number of Technical Committees to operate. P.I.A.R.C. (1) includes members from 59 countries, 47 of which are member countries, meaning that their governments are members of P.I.A.R.C. The financial resources of the association are confined to the contributions of members, whether individual members or bodies such as governments, administrations, etc. The Technical Committees of P.I.A.R.C. are concerned with the subjects of cement concrete pavements, road tunnels, flexible pavements, low-cost roads, testing of road materials, winter maitenance, road traffic and safety, economic questions, and slipperiness and evenness.

The Technical Committee on Slipperiness and Evenness was officially formed in August 1949 in order to enable the Permanent International Association of Road Congresses to present, at the 9th International World Congress in Lisbon in 1951, an exchange of views on the skid prevention properties of pavements. At the present time the Committee acts as a centre of exchanges and discussions between experts on problems of pavement skid resistance and evenness. At each world congress of P.I.A.R.C., the Committee submits a report reflecting the evolution of research, knowledge and knowhow in its field. The Committee is in close contact with other organizations and experts working in the same fields of skid resistance and evenness. Since the latter aspect may not be of interest to this conference, the present report deals only with the problem of skid resistance. In accordance with the aims of the skid prevention conference, this report has been based on reports of the Committee to the Prague Congress in 1971 (2) and the Mexico City Congress in 1975 (3).

The specific questions dealt with are:

- Recommendations and specifications relating to the skid resistance of pavements.
- Systematic measurements of pavement skid resistance with a view to conforming with recommendations.
- The design and construction of skid resistance of bituminous and concrete pavements.
- The restoration of the skid resistance of existing pavements.
- The noise problem in relation to road surface characteristics.

This report takes into account information available on 1 June 1976, unless otherwise mentioned in the text.

Section II: RECOMMENDATIONS AND SPECIFICATIONS RELATING TO THE SKID RESISTANCE OF PAVEMENTS

2.1. Introduction

Road surfaces with a low skid resistance can increase the accident rate resulting from a loss of control of vehicles. This is clearly demonstrated on pavements covered with glazed ice. Furthermore, skidding may occur even on dry surfaces with a high skid resistance at all speeds. Hence the grip of the tyre on the pavement may be inadequate independently of the condition of the pavement. The important factor is the relative frequency of skidding under such conditions.

On a pavement covered with glazed ice, the road itself is no longer in contact with the tyre. On a dry pavement, the problem of grip is quite different, so much so that if pavements never got wet quite different surfaces would be used. However, the problem of slipperiness mainly arises on wet pavements, and the present report deals with this question.

The development of high-yield methods of non-destructive testing of roads necessarily implies the definition of standards of quality. On this point, the determination of the quality of a road is not an end in itself, and use can be made of it only if the degrees of quality measured can be compared with standards in order that maintenance may be undertaken if necessary. This naturally leads us to examine the regulations concerning skid resistance which are in force in various countries (2-3).

2.2. Definition of skid resistance requirements

The requirements can consist of specifications on materials (choice of aggregates, components, geometrical characterisitics) on skid resistance properties (evaluated by direct skid testing) or on both. Specifications on materials generally set forth minimum resistance values for aggregate polishing (15) and sometimes minimum macro-roughness values on the pavement in place. Direct measurements of skid resistance is normally carried out in accordance with one or more of the following methods: braking force coefficient, sideway force coefficient, pendulum measurement. In most countries, these specifications constitute recommendations rather than compulsory standards. In certain cases, the contractor is legally required to ensure a given level of pavement skid resistance checked during acceptance testing; in others, he is responsible for maintaining this level for a guaranteed period.

2.3. Analysis of recommendations and specifications

2.3.1. Belgium:

The contractor must conform to the specifications of the Ministry of Public Works for any new or existing roads. These specifications cover aggregate polishing resistance, ignition loss and the type of chip sealing or grooving. Certain skid resistance levels are required when the road goes into service as well as during the three following years. More precisely, specifications governing motorways and main highways are the following:

- Aggregates larger than 8 mm (0.314 in) used in wearing courses must have a polished stone value of at least 50 within a scale of 0 to 100; all aggregates - including sand - must have an ignition loss no greater than 10 percent.
- For cement concrete surfaces, surface treatment is compulsory and the absolute texture depth, measured with a depth meter, must be between 6 mm (0.236 in) and 10 mm (0.393 in) at the time of provisionnal acceptance.

Table 1. Recommended polished stone values

POLISHED STONE VALUE	EVALUATION	COMMENT
Lower than 0.35	Poor	In principle, such an aggregate must not be used for wearing courses.
Between 0.35 and 0.45	Passable	Such an aggregate is to be used only where alignment and traffic conditions are favourable.
Between 0.45 and 0.55	Good	
Higher than 0.55	Very good	The use of such an aggregate is recommended when alignment and traffic conditions are unfavourable (turns, intersections, high speeds, dense traffic).

- The minimum sideway force coefficient must be 0.45 at 80 km/h (50 mph) for pavements on motorways and highways with four lanes or more, and 0.45 at 50 km/h (31 mph) for other roads. These values are applicable for measurement at any point.

The polished stone value is measured with BS 812 (1976) (15) (the crushing of materials larger than 8 mm (0.314 in) is however authorized).

The sideway force coefficient is measured by means of the "odoliograph" and "Stradographe", at an angle respectively 20° and 15° under a load of 2500 N (550 lb), further details are given in table 6.

2.3.2. Czechoslovakia:

National standard recommending criteria CSN 736177 "Skid resistance measurement methods" has been issued on January 1976.

2.3.3. France:

Specifications cover only construction materials and methods in so far as these have an effect on skid resistance properties (4, 5). The definition of standards dealing with skid resistance properly so-called is in fact regarded as very complex. A circular of 11 June 1969 (Ministère de l'Equipement) establishes minimum polished stone values for aggregates used in wearing courses consisting of bituminous mixtures or surface dressings as well as minimum recommended levels of geometrical roughness evaluated by the sand patch test.

Table 1 gives the minimum recommended value for the polished stone test used in surface dressings and bituminous material for wearing courses.

Table 2. Recommended macro-texture

Pavement Class	Sand Patch Test TD mm (in)	Pavement Evaluation
A	HS ⩽ 0,2 (0.007)	Very fine-textured pavements; these pavements are to be prohibited.
B	0,2 < HS ⩽ 0,4 (0.007) (0.015)	Fine-textured pavements; these pavements are to be reserved for sections on which vehicle speeds are only occasionally capable of exceeding 80 km/h (50 mph), e.g. in urban areas.
C	0,4 < HS ⩽ 0,8 (0.015) (0.031)	Medium-textured pavements; these are normal pavements for sections on which moderate speeds are encountered, between 80 and 120 km/h (50 - 75 mph).
D	0,8 < HS ⩽ 1,2 (0,031) (0.047)	Coarse-textured pavements; these pavements are to be used for sections on which speeds are normally higher than 120 km/h (75 mph).
E	HS > 1,2 (0.047)	Very coarse-textured pavements; these pavements are to be used in special cases: danger zones following a straight line on which speeds are very high; zones where there is frequent and moderate frost (condensation when relative humidity is high and temperature near 0°C).

Table 2 defines five categories of all kinds of bituminous and concrete pavements from the point of view of their macro-texture characterized by the sand patch test.

In addition, directives covering the wearing courses, developped for the different pavement techniques, specify the precautions to be taken in particular with regard to formulation and placing in order to obtain suitable skid resistance levels.

2.3.4. Federal Republic of Germany:

The texts existing since 1966 are basically recommendations to the extend that it is considered to be impossible to constantly guarantee certain minimum values of skid resistance (6, 7).

The recommended values for existing pavements, measured with the Stuttgarter Reibungsmesser (braking force coefficient, locked wheel, patterned tyre) are the following:

Speed km/h	(mph)	BFC minimum
40	(25)	0.42
60	(37)	0.33
80	(50)	0.26

Since 1972, in order to quickly determine the initial friction level on newly laid pavements, increasingly greater use has been made of the British portable apparatus (SRT pendulum) in combination with a surface outflow meter. This instrument gives an indication on compliance with existing minimum macro-texture. This indication is combined with values found by means of the pendulum tester (which are related to low-speed conditions) for assessing higher speed skid resistance. In case of doubt, use can be made of the locked wheel braking force coefficient method.

2.3.5. Great Britain:

The texts on skid resistance constitute recommendations. Measurements are carried out with the S.C.R.I.M. vehicle which allows a continuous measurement, over long road stretches, of the sideway force coefficient. The test wheel is inclined 20 degrees and has a smooth tyre of 3.00 x 20 inflated to a pressure of 3.5 bars (3.5 10^5 Pa; 50 lb/sq.in). As the data recorded by the S.C.R.I.M. are processed by computer, a considerable length of road can be measured and analysed in a short time (8).

Table 3. Required polished stone value for sufficient skid resistance on a bituminous pavement as a function of traffic and the required aggregate abrasion value.

Sideway force coefficient at 50 km/h required in summer		Required polished stone value — Lorry traffic per lane and per day: 250	1000	1750	2500	3250	4000
0,30				40	45	50	55
0,35			40	45	50	55	60
0,40		40	45	50	55	60	65
0,45		45	50	55	60	65	70
0,50		50	55	60	65	70	75
0,55		55	60	65	70	75	
0,60		60	65	70	75		
0,65		65	70	75			
0,70		70	75				
0,75		75					
aggregate abrasion value	chipped surfacings	< 14	< 12	< 12	< 10	< 10	< 10
	macadams	< 16	< 16	< 14	< 14	< 12	< 12

(hatched cells) SFC values in these traffic concitions are sometimes achievable with aggregates of extreme hardness and very high resistance to abrasion, such as certain grades of calcined bauxite.

The TRRL has proposed the classification of sites into four categories ranging from the lowest, with little traffic and limited skidding risk, to the highest which includes the approach of intersections and pedestrian passageways in urban areas. For each category, a range of sideway force coefficient values is proposed, from 0.30 to 0.45 for the lowest and from 0.55 to 0.75 for the highest.

There is also a recommendation setting a minimum level of texture depth: 1.0 mm (0.039 in) for bituminous pavements and 0.5 mm (0.020 in) for cement concrete when transversely grooved. Under such macro-texture conditions, the drop in skid resistance between 50 (31 mph) and 130 (80 mph) km/h is 20% in both cases.

In order to comply with these standards, a specification covering the materials allows the highway engineer to choose the aggregate having the polishing resistance suitable for ensuring the desired skid resistance under given traffic conditions (see table 3) (9).

2.3.6. Netherlands:

Two standards, each setting a minimum skid resistance value, are in force.

1. The first is required by highway authorities in order to establish their maintenance criteria. This standard constitutes a recommendation and not an obligation.

2. The second is legally laid down by highway authorities and is aimed at contracting firms which may be penalized for noncompliance with the considered minimum value at the end of the work.

These values are based upon the braking force coefficient method, with 86 percent slipping and a patterned radial tyre. The thickness of the water film is 0.5 mm (0.019 in) and the standard test speed is 50 km/h (31 mph) (speeds of 70 (43 mph) and 90 km/h (56 mph) are also used for special requirements).

For existing roads measures are generally recommended when the skid resistance value is lower than 0.51, immediate measures are to be taken when this value is under 0.46.

For new pavements,a skid resistance value of 0.56 is the minimum value mentioned in the contract. This value should be measured within four weeks after construction.

2.3.7. Japan:

There are no compulsory standards, but two distinct drafts are being studied and are to be used as guides within the framework of new work and maintenance. These are:

1. Recommendations by the Public Works Research Institute of the Ministry of Construction: "Antiskid requirements". They establish minimum friction coefficient values measured with the Japanese heavy test vehicle (of the braking force coefficient test type) at 60 km/h (37 mph). These minimum values are 0.40 for normal roads and 0.45 for difficult sites such as poorly designed curves and intersections.

2. The "Antiskid requirements" of the Japanese Highway Department require that a recently-built road should have a coefficient higher than 0.60 (measured with the Skid Resistance Tester). In the case of values lower than 0.55 confirmed by repeated measurements, the considered section is tested with the heavy test vehicle by the Japanese Highway Department. If the braking force coefficient at 80 km/h (50 mph) is found to be higher than 0.35 no other action is undertaken. If it is lower than 0.28, the road may not be opened to traffic before adequate measures have been carried out for improving the skid resistance. Where values are between 0.28 and 0.35, the road may be opened to traffic but repairs must be considered in case of accidents.

2.3.8. Poland:

Values are recommended for skid resistance evaluated by the locked-wheel braking force coefficient measured with a Cobirtd trailer using a patterned tyre with a load of 400 kg (880 lb) at a speed of 60 km/h (37 mph). A coefficient higher than or equal to 0.35 is considered to be satisfactory in most cases, but those lower than 0.20 indicate a slippery road which requires treatment.

2.3.9. Spain:

There are compulsory national standards but these have been defined only in terms of the polishing characteristics of aggregates used for wearing courses. For bituminous pavements, the minimum values required for the polished stone test, measured with the NLT 174/72 (procedure which is very similar to BS 812.1967), is from 40 to 45 depending on the traffic volume and can be from 50 to 55 in certain special cases.

2.3.10. Switzerland:

Skid resistance is specified in the national standard SNV 640511 which places the sites in three categories and assigns minimum skid resistance values to each one on the basis to the SRT (British portable apparatus). The details of the standard are given in table 4: for roads on which speeds are lower than 80 km/h (50 mph), the value aimed at is 55; the minimum value upon the acceptance testing of the work is 50 and the tolerated minimum value in service is 45.

Lower values indicate the need for treatment. On roads where traffic speeds are higher than or equal to 80 km/h (50 mph) the corresponding values are given as well as for difficult sites such as turns with a radius of 150 m (492 feet), slopes greater than 8 percent, intersections, bridges and tunnel exits. The national standard SNV 640510 defines the manner in which the portable apparatus is to be used, in particular for checking compliance with specifications (standard SNV 640511) during the acceptance testing of the work.

Table 4. Relation between pendulum readings and type of road

type of road	aimed value	min.value in acceptance test	min.value for roads in service
speeds under 80 km/h (50 mph)	55	50	45
speeds over 80 km/h (50 mph)	60	55	50
difficult sites	65	60	55

Table 5. Types of specifications in some countries

Country	Formal specifications of recommandations	polished stone value (1)	macro tecture (2)	BFC	SFC	SRT or similar	minimum skid resistance guaranteed by contractor
Belgium	yes	S	S		S		yes
Czechoslovakia	yes			C			
France	yes	C	C				
Federal Republic of Germany	yes			C		C	
Great Britain	yes	S	S		C		
Netherlands	yes	S	C	S			yes
Japan	yes			C		C	
Spain	yes	S					
Switzerland	yes					S	yes

S = Contractual specification　　C = Recommended or aimed level

(1) B.S. 812 or similar　　(2) B.S. sand patch test or similar

2.4. CONCLUSION

There has been growing awareness of the need for standards covering skid resistance, testified to by the fact that the corresponding requirements are making up an increasingly greater part of the standards concerning new work and maintenance on existing roads.

These standards take on different forms. It is noted that great importance is attached to specifications dealing with materials, in particular with respect to the polished stone value used for wearing courses, as well as to minimum macrotexture requirements and, finally, to the direct measurement of friction.

A significant development is the clearer definition of the responsibility of the contractor to ensure given skid resistance levels. In three countries (Belgium, Netherlands and Switzerland), this is already defined in very precise terms. This aspect of standards governing skid resistance should become the decisive factor of their future development.

Table 5 allows a comparison of main types in effect in different countries.

Section III: SYSTEMATIC MEASUREMENTS OF PAVEMENT SKID RESISTANCE

3.1. Introduction

3.1.1. The skid resistance of pavements must be measured for the following reasons:

a. Predicting the safety on wet pavements
b. Choice of priorities for maintenance of road systems
c. Management of road systems and budgetary programming
d. Gathering information on pavement skid properties for the preparation of standards.

Assuming that it is possible to set thresholds concerning pavement skid resistance, it is possible to compare these objectives with existing values and to deduce recommendations for the future maintenance of roads.

3.1.2. Skid resistance measurement methods can be classified in many ways. In particular, it is possible to distinguish:

. the manual methods (SRT pendulum, macrotexture measurement by sand patch test, surface outflow-meter, etc.)

. methods involving the use of a vehicle and most often making it possible to measure the braking force coefficient or the sideway force coefficient.

The practical capacity can be significantly different depending in particular on utilization constraints (self-contained spray systems, insertion in traffic, recording and analysis of measurement data). In this respect, the following can be distinguished:

- Methods oriented towards research. These are, for example, the equipment of the braking force coefficient type (Remorque LPC and Stuttgarterreibungsmessgarät), of the braking force or sideway force coefficient type (the Stradographe of the CEBTP). These units offer excellent analysis possibilities and often allow further interpretation of assumptions by local studies in the field.

- Methods oriented towards systematic measurements. They are based upon the principle of a continuous measurement (wide-angle braking force coefficient, braking force coefficient with retarded wheels) in which the loss of flexibility is permissible for the benefit of efficiency (f.i. SCRIM).

3.2. Main characteristics of equipment in service

3.2.1. The distinction between high-efficiency equipment and research equipment is not very clear. The main specifications of these equipments are shown in table 6 indicating nevertheless the main utilization tendencies for the different types. In fact, the two types of equipment are complementary and are moreover highly utilized.

3.2.2. Characteristics required of high-efficiency equipment. When a significant relationship has been found between the number or rate of accidents on wet pavement and the skid resistance measured by a given apparatus, this apparatus may be used if it meets the following requirements:

a. It must be reliable, easy to calibrate and as simple as possible.
b. Results of tests must be reproducible and it should be possible to repeat the tests.
c. It should have a high measurement rate and must be economical.
d. Automatic recording or a digitizing system represents an advantage.
e. The equipment must be completely self-contained, with its own water reserve and spraying system, and must be able to carry out tests in traffic without any particular signalling precautions.
f. Its testing speed must make it compatible with traffic (i.e. 50 to 100 km/h (31 to 62 mph) on highway and 30 km/h (18 mph) in town).

All test sites must be determined and clearly identified by lateral marks easily seen from a moving vehicle. These measurements points must be identified by the number of the road, the tested lane and the length.

3.2.3. Specifications on tyres for skid resistance measurements. The P.I.A.R.C. Technical Committee on Slipperiness and Evenness has recommended three types of tyres since November 1974:

- In conjunction with the use of the SCRIM apparatus, a smooth diagonal tyre of dimensions 3" x 20", with a tread in natural rubber.
- For other measuring apparatusses (when mechanically possible) a radial tyre with dimensions 165 R x 15, smooth or grooved. The tread consists of a synthetic rubber, in composition and specifications identical with the ASTM E17 tyre. The external dimensions of the tyre are in the neighbourhood of 165 mm width (6,5 in) and 640 mm diameter (25 in). The machining of a special rim enables this tyre to be fitted to most equipment in service in Europe.
- For some apparatusses, the ASTM E17 tyre, dimensions G.78 x 15 (width 212 mm, external diameter 703 mm), treaded. The nominal load is 492 kg (1000 lb).

At the initiative of the P.I.A.R.C. Committee the P.I.A.R.C. type of tyre has been made commercially available, a series of 800 P.I.A.R.C. tyres were manufactured in 1975, which would be the need for about 4 or 5 years.

3.3. Use of equipment

Depending on the performance of the measurement equipment used, it is possible to choose one of following methods for the organization of systematic measurements:

3.3.1. Continuous nondestructive testing on all roads in order to obtain an average friction coefficient each 10 m or 100 m, over road section 10 to 20 kilometers long, in the most unfavourable wheel trace.

This is possible with the SCRIM (Sideway Force Coefficient Routine Investigation Machine) developed in Great Britain by the TRRL (Transport and Road Research Laboratory). (4).

3.3.2. Nondestructive testing of samples of the network determined at random. The measurement section must be representative for the type of pavement. This procedure assumes good knowledge of the composition of the wearing course and of the traffic on the network. It is this method which is used for mixture in Holland where skid resistance was measured on 3,300 sections of 100 m (320 ft) each which are representative of the 4,800 km (3,000 miles) of twolane roads in the national highway system. The choice of the test sections is associated with a visual inspection so that it is possible to also carry out measurements on doubtful sections.

3.3.3. Selection of accident-prone locations and doubtful sections on the basis of an accident study. This can be achieved by analysing the ratio:

$$\frac{\text{Number of wet-pavement accidents}}{\text{Total number of accidents on wet and dry pavements}}$$

By comparing this ratio for each road section with the overall average for all roads during the same period, and provided comparable weather and traffic conditions are considered, it is possible to pick out the doubtful pavements from the viewpoint of skid resistance (5). This method is used in many regions of Germany (6, 7).

3.4. Conclusions

The systematic measurement of skid resistance can be carried out at a moderate cost, in particular with high-efficiency equipment. It is of great interest for the highway engineer as it allows him to programme his maintenance work in order to obtain a predetermined skid resistance value on the network. Measurements can also be used for accident prevention after a relationship has been established between skid numbers and accidents.

Section IV: SKID RESISTANT PAVEMENTS

4.1. Introduction:

4.1.1. Surface texture of pavements. The skid prevention properties of the surface depend on its surface texture.

a. The coefficient of friction at low speed depends mainly on the angularity of the surface asperities (microtexture).
b. The decrease in the coefficient of friction with increase in speed depends on the dimensions of these asperities (macrotexture) and, more generally, on the extend to which the surface allows the water trapped under the tyre to escape. The less it does so, the more rapidly the coefficient of friction decreases.

Whatever the speed, satisfactory grip can therefore be obtained only on a surface possessing angular asperities. Figure 1 shows the four main types and the terms employed to describe texture (2).
The macrotexture is generally measured by the sand patch test (14).

Table 6. Main characteristics of skid measuring equipment

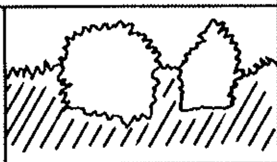
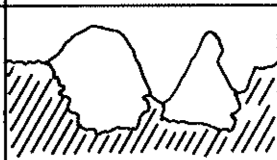
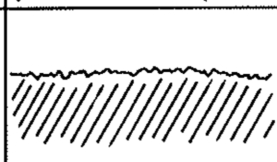
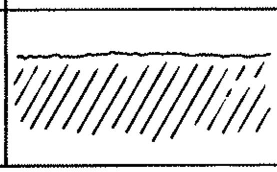
N	Name of the apparatus	SCRIM (GB)	Skiddometer B.V. 8 (S)	RWL Trailer (NL)	Stuttgarter Reibungs-messer (D)	Odoliographe (B)	Single-wheel trailer (USSR)	Remorque L.P.C. (F)	CEBTP-Strado-graphe (F)
1	Measurement method angle slip	SFC 20°	BFC, locked or 13% slip	BFC 86% slip	BFC locked	SFC 20°	BFC locked	SFC locked	BFC or SFC, any slip till locked any angle till 15°
2	Number and position of test wheel	1 – on side of lorry	1 – in axis of trailer	1 – in axis of trailer	1 axis at rear of vehicle	1 right side of car	1 in axis of vehicle	1 single wheel trailer	2 on each side of car
3	Nominal load per wheel	2000 N (440 lb)	4930 N (1090 lb)	2000 N (440 lb)	3500 N (770 lb)	2500 N (550 lb)	4000 N (880 lb)	2500 (550 lb) (1750 to 3000) (358 to 660)	2500 N (700 to 4000) 550 lb (154 to 880)
4	Tyre – size carcass Tread	300 x 20 diagonal smooth	7.5 x 14 diagonal-ribbed	5.60 x 13 diagonal-patterned (PIARC tyre)	6.40 x 13 diagonal-patterned or PIARC tyre	5.60 x 14 radial – smooth	6,70 x 15 diagonal – patterned	165 mm x 15 radial smooth or ribbed	165 mm x 15 radial smooth or ribbed (PIARC tyre)
5	Test wheel suspension	spiral spring shock absorber	spiral spring	oil-pneu-matic	no suspension, shock absorber	spiral spring schock absorber	spiral spring schock absor-ber	oil-pneu-matic	citroen hydraulic suspension
6	Load of un-sprung masses	580 N (123 lb)		900 N (200 lb)		600 N (130 lb)			600 N
7	Watering system	gravity- 3000 l tank on lorry	pressure – tank in vehicle	speed pro-portioned pump, tank in vehicle	gravity plus speed proportioned pump	separate vehicle	Pressured tank by com-pressed CO_2	pressure-tank in vehicle	tank and auxiliar pressured tank in vehicle
8	Water film thickness	0.5 to 1 mm (0.02 to 0.04 in)	0.5 mm (0.02 in)	0.5 mm (0.02 in)	1 mm (0.04 in)	1 mm (0.04 in)	0,5 mm (0.02 in)	1 mm (0.5 to 4) (0.04 in(0.02/015)	1 mm (0.5 to 2) (0.04 in (0.02/ 0.08)

to be continued on the next page

Table 6. Main characteristics of skid measuring equipment (cont.)

N.	Name of the apparatus	SCRIM (GB)	Skiddometer B.V. 8 (S)	RWL Trailer (NL)	Stuttgarter Reibungsmesser (D)	Odiolographe (B)	Single-wheel trailer (USSR)	Remorque L.P.C. (F)	CEBTP-Stradographe (F)
9	Standard test speed	40 to 80 km/h (25 to 50 mph)	60 to 120 km/h (37 to 75 mph)	50 to 90 km/h (31 to 54 mph)	40-60-80-100 km/h (25-37-50-62 mph)	50 to 80 km/h (31 to 50 mph)	40 to 60 km/h (25 to 37 mph)	50 to 140 km/h (31 to 87 mph)	40 to 170 km/h (25 to 106 mph)
10	Sensor	hydraulic	strain gauge	strain gauge	dynamometer	hydraulic	strain gauge	dynamometer	mutual indication
11	Records	digital printer or punched tape	digital printer	potentiometric recorder and digital printer	mechanical recorder	mechanical recorder	electronical recorder	U.V. recorder or digital printer	U.V. recorder
12	Number of machines in service	12	10	3	5	4	1	4	model "65"...2 model "70"...1
13	Main utilizing countries	GB - Aus.- ZA.	S - CH - E - J - D	NL	D - A	B	USSR - PL - CZ	F - NL	F - B
	References	(2)-(8)-(9)	(2) - (12)	(2) - (12)	(2) - (13)	(2) - (12)	(2)	(2) - (11)	(2) - (10) - (12)

Figure 1: Terms used to describe the texture of a road surface

SURFACE		Scale of texture	
		Macro (large)	Micro (fine)
A		rough	harsh
B		rough	polished
C		smooth	harsh
D		smooth	polished

4.1.2. Aggregates. Various tests of mechanical strength (resistance to crushing strength and wear; resistance to fragmentation; static or dynamic compression tests; abrasion tests) are used in different countries. The correlation between the result of the test in the laboratory and the behaviour of aggregates on the road is not always clearly specified.

a. Mineralogical properties. Liability to polishing is generally determined by the British Standard 812 test performed on a clearly specified particle size (8/10 mm or 0.314-0.393 in) (15); this poses a problem for the reception of natural aggregates. In several countries notably Great Britain, France, Belgium and Germany special studies have been conducted. In particular, with a view to obtaining very hard aggregates which withstand abrasion and above all have a high polished stone value, an attempt has been made in Great Britain and France to use synthetic materials. Some of these materials are already on the market (calcined bauxite, corundum, etc.).

b. Angularities. The aggregates must have sharp edges. In order to eliminate rounded surfaces, they must be crushed in as angular a form as possible. The ideal solution would be to spread them in such a way that the edges come into contact with the tyre. But during spreading and subsequent compaction, the flat surfaces tend to become apparent, and this reduces the effect of the angularity obtained by crushing.

c. Particle size. Generally speaking, a large particle size favours the achievment of a satisfactory macrotexture.

4.1.3. Review of the functions of a pavement surface. Problems of slipperiness are involved in the choice of the type of pavement surface. But this problem of choice cannot be reduced to seeking a single characteristic, whatever it may be; it can only be the result of a compromise between different requirements, some of which are moreover contradictory:

- Evenness in order to provide acceptable riding comfort.
- Adequate grip in the light of traffic conditions (number of commercial vehicles, speed, geometrical conditions, etc.)
- Imperviousness (except in special cases).
- Mechanical strength (resistance to cracking, rutting, and wear; distribution of load).
- Resistance to studded tyres.
- Visibility or optical contrast (in liaison with markings).
- Evacuation of surface water.
- Satisfactory time of life.

The influences of the surface characteristics (microtexture and macrotexture) mean that the following conditions must be met to wearing courses:

- Avoid rounded aggregates and use crushed aggregates (possessing sufficient resistance to wear and polishing; suitable edges and harshness of surfaces).
- Ensure that the wearing course has an adequate roughness. This implies that:

a. The composition of the wearing course, the dimensions of the chips and the methods of laying must be such that the aggregates form sufficiently sharp projections.

b. The composition of the wearing course must be such that the asperities do not disappear as a result of the embedment of the aggregates into the wearing course.

c. The aggregate must be strong enough to withstand early fragmentation or wear from traffic. For a given aggregate, liability to fragmentation depends on the type of wearing course. It is less if the surface ensures laterally gripped aggregates.

4.2. Bituminous surfaces

The achievement of bituminous mixes of high quality implies that rapid non-destructive controls relating mainly to the temperatures of rolling and laying and to compactness during and after rolling be carried out regularly (16, 17).

The principal types of bituminous surfaces are described in 4.2.1. and 4.2.5.

4.2.1. Bituminous concrete without chippings. In these surfaces without chippings (by contrast with those described in 4.2.2.) aggregates intended to appreciably increase the macrotexture are not encrusted before compaction. This means that in the composition of the bituminous concrete without chippings there must be a sufficient percentage of fine aggregates (elements above 2 mm (00.78 in)); in general, more than 50% to 55%. The correlative result is an improvement in resistance to rutting if the formulation is properly chosen. The surface texture of these pavements is only moderately high and the skid resistance at high speed is generally no more than average, though adaquate in many cases.

There are three distinct categories of bituminous concretes without chippings:

a. Bituminous concrete (less than 5% of voids). These pavements generally possess excellent mechanical properties. They are impervious. These true bituminous concretes are used notably in Belgium, Great Britain, Holland (18), the Federal Republic of Germany, Switzerland and elsewhere. It is important to take care to choose a rational composition, (including the partial use of crushed stone sand, a 40/60 bitumen, and a good quality filler) and to conform to certain conditions of production, laying, and notably temperature of rolling (19). An example of the specifications of bituminous concrete commonly employed in Belgium for many years now is given below (20, 21).

Particle size composition (percentage by weight of the mixture of aggregate plus filler)	- Stones (round hole sieves) - 16/22 mm (0.629/0.866 in).... 5 ± 5 - 8/16 mm (0.314/0.629 in).... 30 ± 5 - 2/8 mm (0.078/0.314 in).... 20 ± 5 - sand ...36 ± 3.5 - filler.. 9 ± 1.5
nature of binder	- bitumen 50/60 tar with EVT/52-57
percentage of binder to be incorporated in the combined weight of aggregate plus filler	- justificatory note based on CRR method (21) - at least: bitumen ⩾ 6% tar ⩾ 7%

The skid resistance of these bituminous concretes is partly influenced by the polished stone value of the rock, but it is mainly influenced by the texture of the mortar and by the binder. A bitumen of high viscosity favours the achievement of a higher skid resistance. Furthermore certain physical-chemical properties of the asphalt (asphaltened content, for example) have been correlated with the skid resistance.

In some countries (Holland, and to a certain extend in Belgium and the Federal Republic of Germany) small stones are spread before compaction (for instance, in Holland 2 kg/m^2 (0.409 lb/sq.ft) of aggregates). This treatment has only a temporary effect: its purpose is to give the surface a suffucient coefficient of friction at the beginning and to counteract the possible undesirable presence of a film of binder on the surface of the wearing course. But this surface treatment does not make it possible to obtain a surface texture of type "A" (figure 1).

b. Semi-granular mixes. The percentage of voids in these mixes is between 5% and 10%; they are not completely impervious. They contain a higher percentage of elements larger than 2 mm (0.078 in) than the type described in the previous paragraph.

These types of surfaces are used in France and Holland. Their roughness is higher than that of bituminous concrete, and their coefficient of friction is generally more sensitive to speed than in the case of bituminous concrete. Semi-granular mixes 0/14 (0/0.551 in) give a macrotexture slightly superior to that of mixes 0/10 (0/0.397 in). But these mixes have a slightly less satisfactory resistance to fatigue than the concretes previously described in (a) above. Semi-granular mixes must be laid on a foundation which is not easily deformable. Table 7 gives the compositions used in France.

c. Gap graded concretes. In this category may be placed asphaltic concretes used experimentally in various countries. They need to be laid by skilled workers (22).

In the Federal Republic of Germany a special material has been developed and successfully used on urban roads and motorways, thanks to its satisfactory properties of resistance to wear and resistance to creep. It is called "Splitt Mastix Belage" and was developed with a view to reducing the destructive effect of studded tyres and to achieving and maintaining a coarse macrotexture (24). The principal characteristics of Splitt Mastix Belage are as follows:

- A high proportion (70 to 80% by weight) of aggregates of top quality and a gap gradéd (for a 0-8 (0-0.314 in) mixture for example, fraction 2-5 (0.078-0.314 in) 9s very scarce.
- High filler and mortar content.
- The use of very stable fillers.
- The use of a binder with a penetration of 80 or even better 65.
- Additives to increase the rigidity of the mortar, asbestos for example.
- Voids ratio 2% to 3%.

To combat the initial slipperiness with a high mortar content, finely crushed chips may be spread over the still hot surface of the bituminous mix prior to final compaction by heavy rolling (particle size 1/3 mm (0.039/0.118 in) for "Splitt Mastix Belage").

4.2.2. Bituminous concrete with pre-coated chippings. To improve the roughness while preserving the specific characteristics of the bituminous concrete (mechanical strength, imperviousness) some countries have developed on a large

Table 7. Example of a semi-granular mix in France

	particle dimensions in mm	particles larger than 6 mm	particles larger than 2 mm	filler content 80	binder content	nature and hardness of binder	voids ratio in situ(*)
Semi granular mixes	0/10 0/14	25 to 45% 40 to 50%	55 to 70% 60 to 75%	5 to 9%	5.5%	bitumen 40/50 60/70 80/100 depending on climate	5 to10%

(*) 5% to 6% in Northern France 8% to 9% in the South.

scale the roughening system which consists of spreading crushed pre-coated chippings on the bituminous concrete while it is still hot, and driving them in by compaction. Some countries, such as Belgium (25, 26) and Great Britain (27) have been using this form of surfacing commonly and on a very large scale for several years. In other countries, limited use is made of it (in Holland it is in the pilot stage, while it is in current use in the French Jura and in Northern France, as well as in Sweden). "Topeka" and sprinkled hot rolled asphalt are the initial formula of these bituminous concretes with chippings (3).

Bituminous concrete contains 35% to 45% (or in exceptional cases 25% to 53%) of elements larger than 2 mm (0.078 in). Its void ratio is less than 5%. The binder is a hard bitumen with a penetration of 40 to 60. An example of the specifications of bituminous concrete with chippings widely used in Belgium (20) for many years is given.

Particle size composition	- stones 2/12: 35 (± 5) round hole sieves
% by weight of aggregate + filler mixture	- sands : 53 (± 3.5) filler : 12 (± 1.5)
nature of binder	- bitumen 40/50 tar with EVT/52-57
percentage binder incorporated in the weight of aggregate plus filler	- special notice based on practical tests (in general 8% to 9%)

The sprinkled stones (which must be of excellent quality in respect of resistance to wear, polishing and fragmentation) are pre-coated with hard asphalt in the proportion of about 1% by weight of binder and spread in particle size 12/16 (0.472/0.629 in) in the proportion of 7 kg/m^2 (1.43 lg/sq.ft.) or in a particle size of 8/12 (0.314/0.472 in) 5 kg/m^2 (1.02 lb/sq.ft) by means of a chip spreader. Bituminous concretes with chippings possess not only a very high skid resistance at low speeds if suitable stones are used (crushed, with a high harshness and a high PSV), but also a high and durable skid resistance at high speed.

For this type of surface roughening stones should not be allowed to penetrate the bituminous concrete. This being so, an appropriate formulation of the concrete must be adopted, the aim being either to prevent the chippings from penetrating under the effect of traffic, or to compensate this penetration by wear of the mortar.

Bituminous concretes with chippings thus make it possible - by seperating the functions of mechanical strength and skid resistance - to use in the mass of bituminous concrete polishable stones which do not appear on the surface, harshness and roughness being obtained by the use of hard chippings which do not polish easily. This is therefore an economically advantageous solution for regions where there is a shortage of high-performance aggregates.

The laying of the concrete pavement with chippings calls for qualified personnel and favourable climatic conditions. It must be borne in mind that if the job is not done properly (that is to say if the chippings are not embedded) it will be necessary - as a result of the polishing by heavy traffic of the stones in the concrete mass which appear at the surface - to restore the skid resistance.

4.2.3. Gussasphalts and rolled gusasphalts. These surfaces have been used in Germany for several years. Because of their very special characteristics, based upon the behaviour of the very hot bitumenous mixture as a liquid, they cannot be classified under any of the types of surfaces described in the other paragraphs of 4.2.

a. Conventional gussasphalts. Originally this was a surface which was laid manually and used uniquely in urban streets. Subsequently it was decided to considerably increase the quantity of stones and to mechanize the process.

The material is poured on to the road at a very high temperature (220° to 240° C) and sets itself in place without having to be compacted. Its voids content is practically zero and it is totally impervious to water. The bitumen has an average penetration of 20/30. The percentage of stones in the mass is about 50%, and the percentage of filler 20% to 25%. On to the still hot surface are spread (in the proportion of 3 kg/m^2 or 0.61 lb/sq.ft.) small aggregates (1/3 or 2/5 mm, 0.039/0.011 or 0.078/0.196 in) which are pre-coated and embedded by means of light rolling; sometimes a corrugated texture is created.

This type of surface, laid to a depth of 3.5 to 4 cm (1.37 to 1.57 in) seems to have a good resistance to rutting. Its coefficient of friction at high speeds is fairly close to that of bituminous concrete without chippings (4.2.1., type a.). The surface texture is excellent at the beginning of the life of the gussasphalt, but in hot weather the macrotexture always diminishes, especially under heavy traffic.

b. Rolled gussasphalt. Mention should be made of a variant which is still in the experimental stage, rolled gussasphalt (28). 15 to 20 kg/m^2 3 to 4 lb/sq.ft.) of 5/8 mm (0.196/0.314 in) stones are spread on the layer of gussasphalt while it is still hot. Immediately afterwards the surface is rolled with pneumatic tyred rollers. In this way, the top centimetre of the surface constitutes a zone containing a high density of stones and an excellent macrotexture.

4.2.4. Tarmacadams and bitumacadams: pervious surfaces.

a. These surfaces contain 80% to 90% of crushed stones larger than 2 mm (0.078 in) with 3% to 6% of filler, 4.5% to 6.5% of tar (38° to 43° EVT), or 4% to 4.5% of asphalt (180/220 or even 80/100). After laying, these mixes have a void ratio of 10% to 15% or 15% to 20% depending on the particle size districution, the mineralogical nature and the shape of the aggregates. The particle size distribution curve is of the continuous type. This surface, which is essentially permeable, has a high roughness and if the stones have a high PSV, skid resistance will be high even at high speed. It is evolutive (its permeability diminishes slightly with the passage of time). The stones must have a satisfactory mechanical resistance to attrition. These tarmacadams and bitumacadams have less satisfactory mechanical properties under bending than bituminous concretes. Until a few years ago they were used on a large scale in several countries (Great Britain, Belgium (29) etc.). They must be laid on foundations and soils which are insensitive to water.

Table 8. Example of a pervious bituminous mix composition (30)

aggregate grading percent by weight passing (crushed aggregate	19 mm (0.074 in) size bitumen macadam	10 mm (0.379 in) nominal size bitumen macadam
1-in B.S. sieve	100	-
3/4-in	90 - 100	-
1/2-in	50 - 80	100
3/8-in	-	90 - 100
1/4-in	25 - 35	40 - 55
1/8-in	10 - 20	22 - 28
No. 200	3 - 6	3 - 5
Binder content	4.0 - 4.4	4.4 - 4.8
Thickness of the layer	30 mm (1.18 in)	20 mm (0.78 in)

b. In the light of their high permeability, interest in these surfaces has revived in certain countries just recently (Great Britain, Netherlands) as overlay wearing course. They have a good capacity for draining surface water, and they considerably reduce splash and spray by vehicles. These surfaces are particularly worthwhile on sections where geometrical conditions are such as to cause a very thick film of water (junction zones, transition zones, airport runways, etc.). Their use implies the existence of a drain outlet downstream of the cross section. Though their durability (resistance to rutting, the effect of salt, the effect of petroleum products) is questioned by some research workers, it is considered satisfactory by others. The length of life is estimated at 4 to 8 years.

Experimental sections have been built in Great Britain and in the Netherlands. In Great Britain experimental roads were built as long ago as 1967 (30). Table 8 gives the composition of the mixes employed. The voids ratio, which was 20% to 29% at the time of laying, fell to 14% to 20% after a few months of heavy traffic and then remained constant.

4.2.5. Surface dressings. This type of surface (2, 31) comprises a film of binder on which are spread one or two layers of aggregates (a single-layer dressing with single or double chip spreading). The single layer may undergo a second spreading of binder immediately, followed by a second chip spreading, giving a two-layer dressing.

Since the volume of binder spread is low in relation to that of the aggregates, the surface is very granular when new. There are wide channels through which water can run off. Insofar as the aggregate has sharp edges and harsh surfaces, such a surface is extremely skid resistant.These properties can be preserved for a long time only if the aggregates are not loosened by traffic ("plucking"); neither must they penetrate too deeply into the pavement ("tacking"). The aggregates must also be as resistant as possible to fragmentation and polishing.

Adhesion between the aggragates and the binder depends on the mineralogical nature of the aggregates and their cleanliness. Adhesion may be markedly improved by coating the aggregates and doping the binder.

On a bituminous backing, the phenomenon of tacking, due mainly to the puncturing of the backing by the aggregates under the effect of traffic, may be retarded by appropriately adapting the particle size of the aggregates to the hardness of the surface and the intensity of traffic, the largest particles being used on relatively soft surfaces and/or under substantial traffic. Furthermore, wear and polishing must not cause the edges of the aggregates to be blunted too soon.

These two phenomena impose a relatively frequent renewal of the dressings (about once every five years for traffic of any consequence). Nevertheless surface dressing is an economical technique of maintaining pavements. Surface dressings account for an appreciable share of the total area of pavements, particularly on roads carrying average or light traffic. Whereas in Spain this technique is used only for roads carrying light traffic, it is used in Germany, Belgium, France and Switzerland also on roads carrying average and sometimes substantial traffic. The technique is widely used in Great Britain, even on motorways (bituminous surface).

Research is being conducted in several countries with a view to retarding or even completely avoiding the deterioration of surface dressings (loss of aggregates, impaction of aggregates, bleedings, etc.). This research is being carried out on binders, aggregates, and the equipment employed for laying surface dressings. Where binders are concerned (other than those incorporating resin), the incorporation of conventional polymers of high molecular weight such as vinyl polychloride, a thioelastomer, makes it possible to very appreciably improve the mechanical characteristics (elasticity, cohesion) and hence the adhesion of the aggregates, allowing these surface dressings to be used even on cement concrete (e.g. France uses this technique on motorways carrying heavy traffic; it seems that the fragmentation of the aggregates is the principal factor influencing the length of life of surface dressings successfully laid on a cement concrete surface).

Where aggregates are concerned, great interest is being taken in the development of artificial aggregates, which have the advantage in particular of allowing of the choice of a suitable sharp such that the edges always remain pointing upwards. Results so far obtained reveal, however, that though the mechanical strength of such aggregates is excellent, the polished stone value of some of them may prove no more than average.

With regard to laying, the tendency is to have recourse to more accurate equipment which makes better allowance for the increasingly severe conditions to which surface dressings are subsequently subjected. This equipment includes notably medium or high pressure binder spreaders giving a more uniform binder content, self-propelled chip spreaders, and combination sweepers and aspirators to subsequently eliminate rejects.

4.3. Cement concrete surfaces

Cement concrete surfaces pose no problems of rutting as a result of plastic deformation; but in order to obtain satisfactory skid prevention characteristics, adequate surface treatment is necessary, together with effective protection against desiccation and rainfall while the concrete is still young.

In certain cases there may be difficulties in the restoration of the texture. As in the case of bituminous surfaces, choices must be made between different and even contrary technical imperatives, and the contingencies of durability and economy.

In several countries (Great Britain, Switzerland, etc.) the pavement is built in two layers of different concrete composition. This means that in the bottom two-thirds approximately it is possible to use aggregates of lesser quality (in respect of mechanical strength and resistance to polishing) than that of the aggregates on the surface. The result can be a reduction in the cost of transport of aggregates. Such a procedure facilitates the achievement of a satisfactory evenness of the surface. However, these advantages are offset by a complication in the concrete production plant and the concreting train.

Cement concrete pavements generally contain a wearing course whose upper layer incorporates a fairly high proportion of mortar, and in the absence of special surface treatment this leads to a smooth surface texture, incompatible with satisfactory skid resistance, particularly at high speeds. Finishing the fresh concrete with a burlap drag or by means of light brushing, does not give an adequate roughness; it gives a texture of type C (figure 1). Skid resistance at high speeds is often judged inadequate. After a certain length of time and an appreciable volume of traffic, the texture gradually changes into type D (figure 1). This is why the following surface treatments have been developed over the past few years:

1. Grooving of fresh cement concrete.
2. Sprinkling fresh cement concrete with chippings.
3. Stripping of fresh cement concrete.
4. Grooving of freshly set cement concrete.

4.3.1. Grooving of fresh cement concrete. After the concrete has been vibrated and prior to spreading the curing compound (the latter should moreover disappear after a few weeks under traffic) transverse grooves are made in the concrete, using a groover whose comb consists of a single row of metal or PVC bristles or a groover of the curved fork or roller type; or again a vibrating plate. These instruments make it possible to obtain a harsh microtexture superposed on the rough macrotexture of the grooves (absolute depth 5 to 7 mm, 0.196 to 0.275 in or more; spacing 15 to 30 mm, 0.59 to 1.18 in). This treatment gives a high and durable skid resistance, even under very heavy traffic for many years. This mechanized (and hence low cost) process is used in Belgium (32), Great Britain (33), Germany, Spain and France.

As a protection against vibratory noises which are perceptible (in particular with certain radial ply tyres) on cement concrete pavements grooved at a constant pitch or with a sinusoidal texture, it seems desirable to vary the spacing of the grooves.

Transverse grooving considerably facilitates the rapid evacuation of surface water; furthermore it results in an appreciable reduction in the fine spray thrown up by certain trucks in the accompanying noise. In addition reflection, which is particularly troublesome on wet pavements at night, due to the headlamps of oncoming vehicles, and during sunrise or sunset, is greatly reduced.

The achievement of high and durable skid resistance even at high speeds is however closely linked with conformance to various rules: the absence of polishable materials (e.g. PSV greater than 50), the use of coarse natural sand in good quality concrete with a high cement content, the choice of a suitable grooving implement, deep grooving, and effective protection of the fresh concrete.

4.3.2. Sprinkling fresh cement concrete with chippings. After the concrete has been vibrated and prior to spreading the curing compound, a chip spreader is used to spread, on the fresh cement concrete, crushed, hard, not easily polishable stones which have been washed at the time of loading: 4 km/m^2 (0.82 lb/sq.ft) in the case of 12/16 round hole sieves (0.47/0.62); or 6 kg/m^2 (1.22 lb/sq.ft.) in the case of 16/22 round hole sieves (0.62/0.86). Immediately after the chip spreading the stones are embedded. This process allows of the use of polishable crushed stones in the mass of concrete; the economic repercussions of such a procedure are obvious.

The sprinkling of fresh cement concrete with chippings was developed in Belgium a few years ago, between 1949 and 1955, and in 1969, with excellent results (34, 35). This process gives a high roughness, even after twenty years' traffic (texture of type A). The coefficient of friction at high speeds is high. The process of chip spreading and embedding has been fully mechanized (using a patented machine which can work over widths of 3 to 13.50 metres (10 to 15 feet) and operating on fixed framework) by the Belgian Road Research Centre (35). The concrete must be of consistent quality, and sufficiently plastic. Behind the finisher, and prior to chip spreading, the profile must be corrected with an orthogonal smoothing beam. The chip spreading machine has three functions:

- Even spreading of chips by means of a corrugated roller.
- Embedding of the chips in the fresh cement concrete by tamping, using a vibrating beam inclined at 2% to 3% (with a view to uniform embedding of the roughening chips down to two-thirds of their dimension).
- Projection of a curing compound immediately after embedding.

4.3.3. Stripping of fresh cement concrete.

a. This process, used in Belgium in 1959 on an important experimental road, consists of stripping the fresh cement concrete, (removing the laitance and the mortar by energetic brushing) and consequently laying bare the mosaic of stones as soon as the road is open to traffic (37). Some types of cement (blast furnace type) favour the disappearance of the mortar and the appearance of the mosaic of stones under the effect of traffic. The initial macromixture is satisfactory, but it is essential to use hard stones which do not polish easily, otherwise after several years there will be a polished microtexture and the coefficient of friction will be inadequate even at low speeds.

The process was recently mechanized and experimental sections have been built in Belgium.

b. Another process was employed experimentally in Denmark in 1976. It consists of spreading a solution of sugar on the fresh concrete. After twenty-four hours the surface is brushed to remove the laitance and the mortar. The future will show whether this process is worthwhile.

4.3.4. Grooving of freshly set concrete. Concrete roads which have been subjected to traffic and need to have their skid resistance restored may be subjected to various techniques which are described in Section V of this report. Among these techniques are longitudinal or transverse grooving (15).

We shall deal here only with grooving for hardened cement concretes, performed shortly after and before the road is opened to traffic, or after several months of service.

To the best of our knowledge this technique has been developed only on airport runways, notably in France and Switzerland. It is used transversely. It gives rapid drainage of water over a very wide pavement, and can avoid accidents due to aquaplaning. The grooves are 3 to 5 mm deep (0.118 to 0.196 in), 6 to 10 mm wide (0.236 to 0.393 in), and the interval between grooves is either 30 mm or 100 mm (1.18 or 3.93 in).

4.4. Conclusions

Generally speaking, numerous techniques are available for laying surfaces possessing skid resistance properties. Choices must be made between different and even contradictory technical imperatives.

Economic choices must also be made, notably with regard to the use of local materials. The technique adopted for the construction of a pavement greatly depends on local data, such as the practical experience of highway engineers, the competence of contractors, the climate, traffic, etc. The possibilities of restoring surface characteristics must also be taken into account.

Section V: RESTORATION OF THE SKID RESISTANCE PROPERTIES OF PAVEMENTS

5.1. Introduction

The engineer and contractor must be able to have at their disposal processes for restoring surfaces where the skid resistance is deficient either locally ("black spots") or systematically. With a view to taking stock of the situation, a survey by correspondence was carried out, on the one hand, among the members of three PIARC Technical Committees in nine European countries plus Japan and on the other hand with the collaboration of the "Transportation Research Board" in Washington, among the 50 states of the United States of America and the districts of Columbia and Porto Rico.

5.2. Applications

A study of applications emerges that:

a. applications of processes for restoration of the skid resistance are fairly widespread although some processes are fairly new;
b. these techniques are used, with some exceptions, both on bituminous and cement concrete;
c. these treatments are carried out both on old and new pavements;
d. with the exception of Japan, which uses these treatments only for "black spots", these processes are used both in high-accident areas ("black spots") and over the whole network.

Another aim of the survey was to determine the major causes justifying the need for restoring the skid resistance properties. These can be classed in five categories:

1. Causes indirectly connected with surfacings: serious defects in evenness, wear from studded tyres, increases in traffic;
2. Causes directly connected with surfacings: inadequate or non-existent macrotexture, polished microtexture (polishable surface aggregate);
3. Causes specific to cement concrete surfacings: slipperiness of surface mortar (formation of carbonates);
4. Causes specific to bituminous surfacings: binder bleeding from surface;
5. Other causes: an unusually high rate due, for example to the alignment of the road, may be corrected by a surface treatment giving an exceptionally high skid resistance (39).

5.3. Types of techniques

Not included in this study is the technique of laying a new layer of bituminous concrete when its thickness exceeds about 2 mm (0.8 in). The techniques used to obtain skid resistance surface at the time of construction (grooving or spreading chippings on fresh concrete, spreading chippings on bituminous concrete, etc.) have also been left out of this study. Fourteen categories of techniques for restoration of the skid resistance properties have been listed. They can be classified into two groups:

a. Techniques involving the removal of material

1. bush hammering: percussion scouring using percussion tools;
2. milling: grooving by means of hard steel discs (flials);
3. grooving: cutting grooves by means of diamond edged discs;
4. spreading of hydrochloric acid: causing a chemical reaction in the cement mortar;
5. sanding: scouring under the action of an abrasive jet under pressure;
6. flame scouring: spalling of the surface of a cement concrete by means of high temperature;
7. planing: removal of a film of material from the surface using planing or milling machines.

b. Techniques involving the addition of material

8. re-heating and impacting of chippings into bituminous concrete surfacing ;
9. application of a resinous layer with gritting;
10. bituminous bound surface dressing with gritting (traditional or modified binder);
11. slurry sealing, spreading of a bituminous grout;
12. spreading and rolling of granular materials (possibly pre-heated) on the bituminous concrete surface or tack coat;
13. spreading of white spirit: removal of an excess of bitumen from the surface, followed by spreading and rolling granular materials;

Table 9.: Noise increase (dB (A)) related to grooving

Pavement	Surface	Summer tyre			Winter tyre (without studs)			Noise increase versus type of tyre			Noise increase versus speed ✱	
Speed (km/h)		80	100	120	80	100	120	80	100	120	100/80	130/100
normal (texture depth 0.4 mm)	dry	73	78	80	72	78	82	-1	+1	+2	+5	+2
		80	84	86	78	82	84	-2	-2	-2	+4	+2
noise increase		+7	+6	+6	+6	+3	+2	-1	-3	-4	-1	0
normal grooved	wet	78	80		78	81		~0	~1		+2	
		79	82		79	83		~0	1		+3	
noise increase		+1	+2		+1	+2		~0	~0		+1	
✱ for Summertyre	Noise increase versus pavement condition (wet or dry)											
normal	dry	73	72		72	79		-1	+1		+5	
	wet	80	80		78	81		~0	+1		+2	
noise increase		+5	+2		+6	+2		+1	~0		-3	
grooved	dry	80	84		78	82		-2	-2		+4	
	wet	79	82		79	83		~0	+1		+3	
noise increase		-1	-2		+1	+1		+2	+3		-1	

14. re-surfacing with open-textured bituminous concrete up to a maximum thickness of 2 centimetres (0.8 in).

A complete description of the techniques is given in the Conference-Debate on restoration of the skid resistance properties of pavements (38)
This study describes each process, and analyses its limitations and nuisance during the operation and for the environment, its cost, output and durability.

5.4. Choice of the best suited methods

As far as we know, it seems that depending on the types of surfacings to be treated and according to the result to be obtained, the following techniques can be adopted:

a. Techniques yielding a lasting effect

Bituminous concrete.

When the bulk of the surfacing contains polishable stones, three solutions may be comtemplated whatever the origin of the slipperiness:

- re-heating and impacting chippings,
- surface dressing with a bituminous binder, the binder being improved in case of heavy traffic,
- thin open-textured bituminous surfacing.

When the bulk of the surfacing contains polishing resistant stones, two cases should be considered:

- if the slipperiness is imputable to too fine a macrotexture, the three solutions hereabove are applicable,
- if the slipperiness is imputable to bleeding or to surface dirtying, the same three solutions still apply but two more solutions are valid: bush hammering and milling.

Cement concrete. When the bulk of the surfacing contains polishable stones, there is presently no satisfactory solution, but grooving reduces the thickness of the water film and may thereby help to improve skid resistance. It may be hoped that the recent applications of surface dressings with improved binders turn out to be successfull.
When the bulk of the surfacing contains polishing-resistant stones, two groups of solutions are possible:

- against mortar smoothing, or dirtying: bush hammering, hydrochloric acid spreading or planing,
- against too fine a macrotexture: milling or grooving.

b. Emergency treatments. Certain kinds of treatment, in spite of their poor durability, may be extremely useful because of their low cost and possible application in circumstances where other treatments are not applicable for various reasons (time of year, lack of funds, non-availability of large machines, etc.).:

- light bush hammering and planing, spreading of hydrochloric acid, sanding: during winter, a light scouring of the surface and an attack on the aggregates is carried out while awaiting spring;
- spreading and impaction of chips of granular material: during a period of heat, a temporary remedy can quickly be applied to the serious phenomenon of the bleeding of bituminous surfaces or surface dressings.

c. Alignment of the macrotexture. When the macrotexture is unaligned, as by chipping, only a reduction of the water film thickness may be expected, whence an appreciable gain in skid resistance at high speed. In this case, the noise nuisances seem tolerable.
In the case of aligned macrotexture, if obtained as by grooving, the controversy remains open:

- Transverse grooving entails a lower output at execution, an optimal transverse drainage, a sometimes high noise (especially in case of equally spaced grooves), an appreciable gain of skid resistance at high speed.
- In the case of longitudinal grooving, highest output at execution, no transverse drainage, sometimes water accumulation, no noise, but rail effect affecting motorcycles, limited gain in skid resistance at high speed, but better guidance in the curves.

Let us hope that valid accident statistics will permit to settle the dispute between the fierce tenants of the two opposite solutions.

Section VI: ROLLING NOISE

6.1. Context of the problem

6.1.1. Traffic noise has become gradually more perceptible, to the point where it constitutes a nuisance for people who live alongside roads carrying heavy traffic in urban zones and sometimes in rural zones. The solution to the problem is not simple, because the relative level of rolling noise varies with the type of vehicle and the conditions under which it is being driven (speed, engine revolution, etc.). From this point of view, we make a distinction between two categories of vehicles: "heavy" and "light". For the former, rolling noise is generally negligble under all conditions, especially when climbing gradients. For the latter, rolling noise tends to equal or even exceed other sources of noise, at least at speeds above 60 km/h (37.3 mph), though, driving in urban surroundings, engine noise comes to the fore because of frequent acceleration and deceleration.
However, independently of the very liberal existing regulations concerning engine noise (intake, engine, exhaust), rolling noise is nowadays a matter of concern to highway engineers (41).

6.1.2. The phenomena generating rolling noise are:

- Aerodynamic effects.
- Compression and expansion of cavity air.
- Tyre vibrations.
- Vibration of the vehicle.

The relative importance of these different phenomena has been only very partially established (42, 43); it may be noted however that the last three of them are unquestionably linked with the dimensions of the asperities of the surface.

6.2. Examples of studies carried out

6.2.1. Studies carried out in Switzerland (44). In accordance with the standardized method, studies have been carried out with vehicles with their engines switched off, the microphone being placed at 7.5 metres (24.6 ft).

Figure 2: Coefficient of longitudinal friction: envelope for all surfaces.

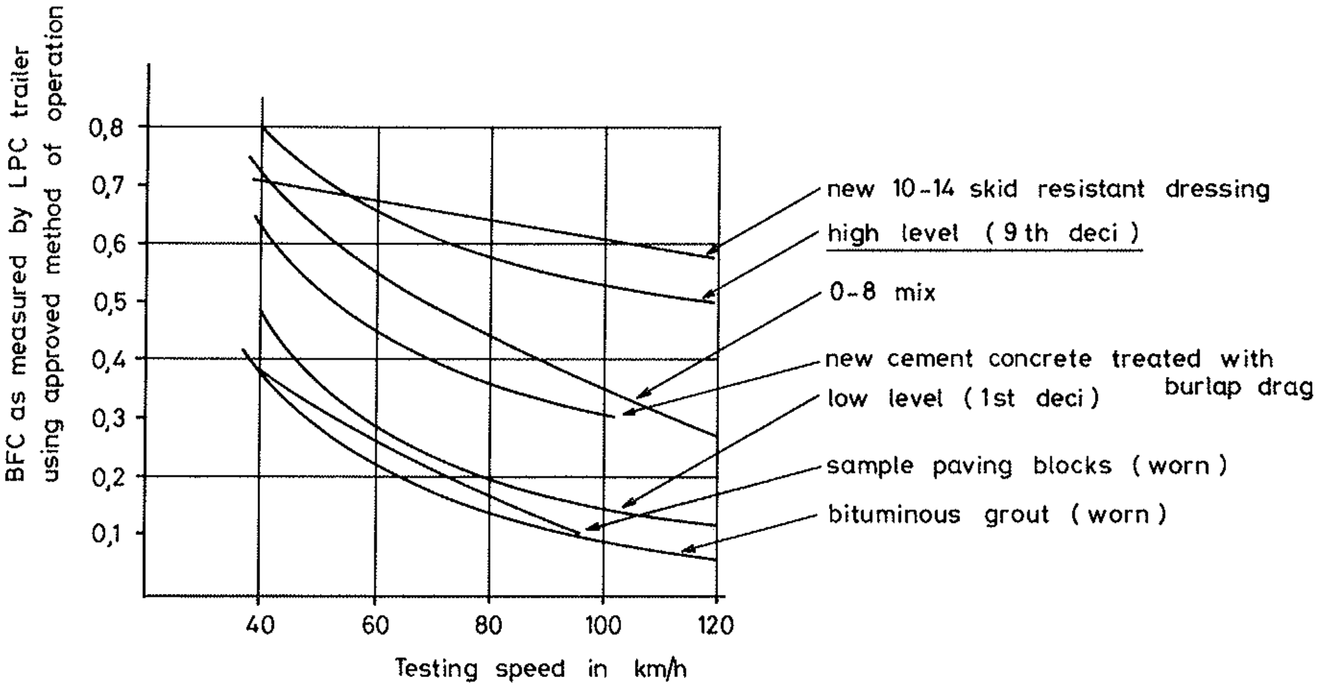


Figure 3.: Relation between noise and roughness

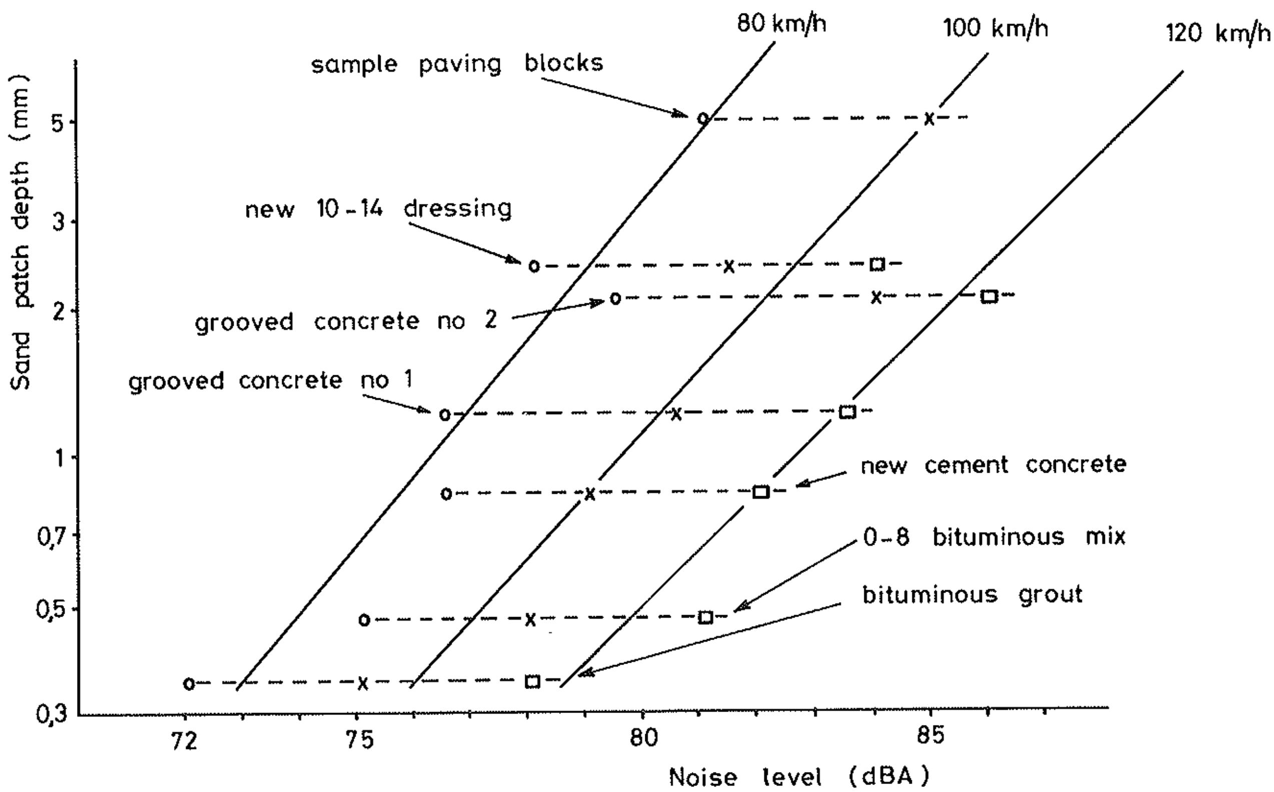
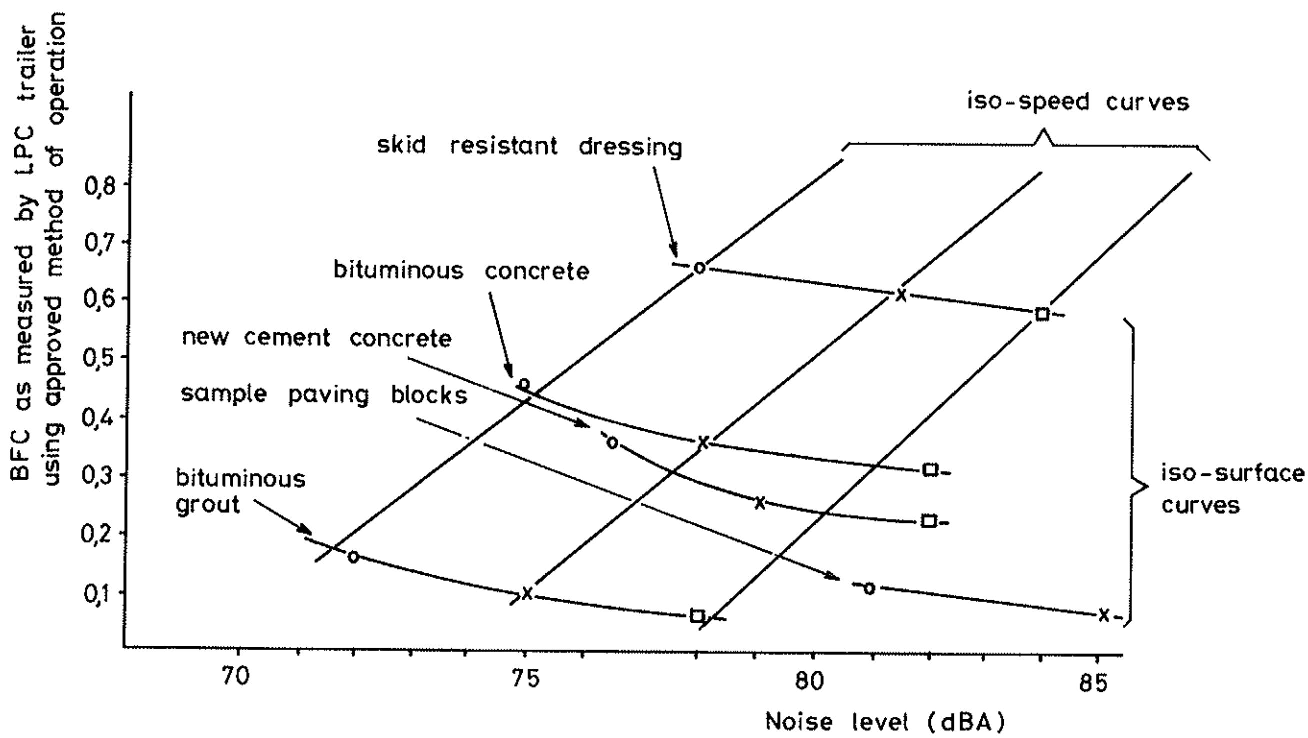


Figure 4.: Test of relation between noise and skid resistance



Note: The texture of the paving blocks is quite different from that of the other types of surface.

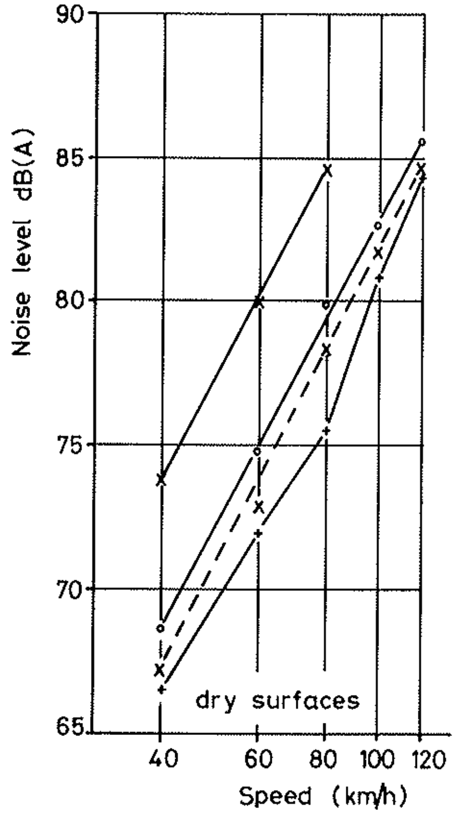
Table 10: Noise level (dBA) - outside the vehicle
- engine switched off
- dry surface

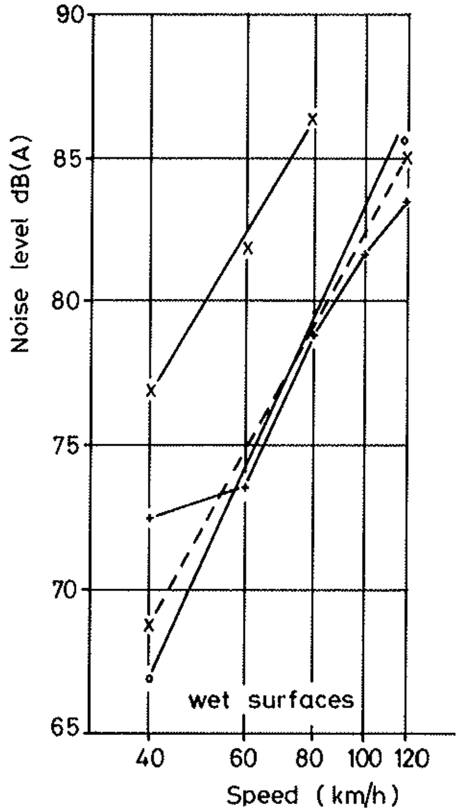
Surface	speed 80 km/h	speed 100 km/h	speed 120 km/h
Smooth dressing	72	75	78
Fine mix	75	78	81
ungrooved concrete	76.5	79	82
Skid resistant dressing	78	81,5	84
Paving blocks	81	85	-

Figure 5.: Rolling noise produced by a vehicle on dry surface

Figure 6.: Rolling noise produced by a vehicle on wet surface

Key: x——x paving blocks
o——o grooved concrete
x– – –x cement concrete
+——+ bituminous surface





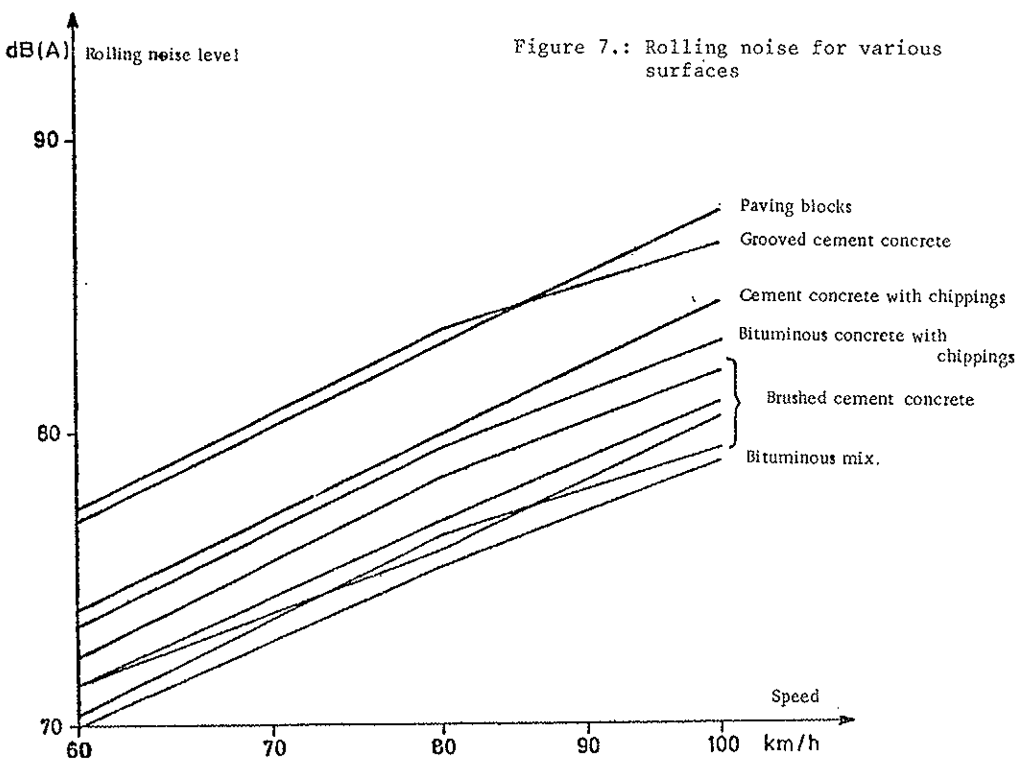


Figure 7.: Rolling noise for various surfaces

Tests were performed on normal cement concrete (texture depth 0.4 mm, 0.015 in) and on grooved cement concrete (texture depth 1.0 mm, 0.039 in), dry and wet, with normal tyres and with unstudded winter tyres.

Results are given in table 9. Analysis of these results shows that:

- The difference between the two types of tyres is less than the accuracy of measurement.
- Wetting of the pavement produces a considerable increase in rolling noise, though this increase is less on a grooved pavement.
- Speed increases rolling noise on dry and grooved pavements; the effect is much less marked on wet pavements.
- Transverse grooving of the pavement very appreciably increases rolling noise; this effect is however less marked on wet pavements.

6.2.2. Studies carried out in France (45). Tests performed under similar conditions (engine switched off, dry pavement, microphone at 15 metres, 49.2 ft) gave analogous results for a wide range of surfaces (table 10). Analysis of the results shows that:

- The noise level increases with speed; the order of classification of the different surfaces is not modified.
- The noise level is generally related to the roughness.
- There is a very marked relationship between the noise level and the skid resistance properties:

  a. for a given surface, noise increases with speed, while skid resistance diminishes;
  b. at a given speed, noise increases with skid resistance.

These relationships are valid for the surfaces studied; we note in particular that bricks are one of the noisiest surfaces, and one of the most slippery. These relationships are shown in figures 2, 3 and 4.

6.3. Summing up

6.3.1. Depending on the nature of the surface, we know that the rolling noise level of a vehicle may, all factors being equal, vary by about 10 dB (A) at most. But results relating to individual vehicles cannot be immediately transposed to traffic in general; the influence of the surface on the overall noise level will depend on the composition of the traffic, the average speed per category, the gradient of the pavement and numerous other factors. Up to the present, no systematic study has been carried out in this field.

Only figures 5 to 7 express the results of measurements made in Belgium (46, 54) with a light vehicle with its engine running, and table 11 gives an example of the influence of the surface on the noise level in the case of a motorway in service.The increase in rolling noise with roughness is still appreciable, but greatly attenuated (averaging 3.5 dB instead of 6 to 10 dB).

6.3.2. The NCHRP Guide (47) and the SETRA (48) recommend, with regard to traffic noise, applying a corrective term of -5 or 0 or +5 db (A), depending on whether the surface is smooth, normal or rough. Since no quantitative criterium is available, the classification of a pavement in one or other of these three catagories is left to the judgement of the user, who might, a priori be tempted to fall back upon the notion of skid resistance. But data concerning the relationship between the noise level and skid resistance are still very imprecise.

Characterizing the surfaces studied in terms of their "profile ratio", Waters (49) obtains no correlation with their noisiness. Looking at the problem from the point of view of tyres, Sakagami (50) has found a relationship between surface noisiness and the profile ratio. Gachignard and Sardin have attempted to use a similar parameter to characterize surfaces, but unsuccessfully (51). These same authors obtain an apparently better correlation on the basis of the sand patch depth (52). However, the pertinence of this parameter remains to be verified in the case of surfaces with a special texture, such as grooved concrete pavements, a feature of which is that the increase in noise level with speed is greater than average, and subjectively, the noise spectrum itself is peculiar to such pavements.

Furthermore, according to Leasure, cited by Favre and Pachiaudi (42), the influence of subjectively assessed roughness may be either positive or negative depending on the type of tyre.

More recently, the initial results of a study carried out by the TRRL (53) suggest that the relationship between texture depth and noise level may differ depending on whether the pavement is cement or bituminous. However, it may be noted that all the cement concrete pavements examined were grooved in one way or another, which makes it possible to attribute the difference in noise level just as much to the binder as to the type of texture.

Some of the results obtained by the CRR in Belgium (54) are such as to support this second interpretation; cement concrete pavements with chippings may, for an equal average sand patch depth, present noise levels markedly lower than grooved concrete pavements, and comparable to those obtained with asphaltic concrete incorporating chippings (figure 7).

6.3.3. In conclusion, it can be said that at the present time a descriptive parameter of texture which is linked with the noise produced remains to be determined, and that in principle the demands of safety and acceptable noise level are not incompatible.

Section VII: CONCLUSIONS

7.1. Minimum values of skid resistance

In many non-American countries, the minimum values of skid resistance are laid down for the road system as a whole. These values have been established on the basis of analyses of accidents or of the properties of materials. In some countries, minimum values are also laid down in contracts for the construction of new roads.

7.2. Construction of pavements possessing a satisfactory skid resistance

In general, we know how to construct a satisfactory skid resistant pavement. The use of rocks resistant to polishing is very important. In addition, an adequate macrotexture must be obtained by means of a proper mix formulation.

7.3. Skid resistance levels

It is desirable to establish national rules relating to skid resistance levels. These levels should be laid down in the light of the volume of traffic, the availability of materials, questions of safety, and economic and legal questions.

7.4. Restoration of skid resistance

When skid resistance is inadequate, a new surface can be laid or one of the numerous treatments described can be applied.

7.5. Informing engineers of the formulation of surfaces

Very appreciable progress has been made as a result of the publication of directives or recommendations, and following the establishment of acceptance conditions for new pavements. Usages in various countries are summed up in the report.

7.6. Systematic treatment of deficiencies in the road system

These deficiencies, which are not necessarily related directly to skid resistance, may however be a contributory cause of accidents on wet pavements. The report does not deal with this aspect, but in certain countries (notably France) studies of this type are in progress, in particular regarding motorways.

7.7. Thickness of the water film and geometry of the pavement

Research is necessary to establish criteria for the acceptable depth of rutting. Studies have been carried out on the relationships between the geometry of the surface, skid resistance, and water film thickness; but little information is available concerning safety and the real thickness of water films.

7.8. Development of surfaces possessing high skid resistance

A considerable effort has been made in certain countries to develop and employ special surfaces, (particularly in the United Kingdom). But existing solutions are costly, their application is tricky, and research is proceeding in this field.

7.9. Relation between skid resistance and rolling noise

At present time a descriptive parameter of texture which is linked with the noise produced remains to be determined.

Table 11. Noise levels (L_x) measured on French motorway in service with different surfaces.

Test	time	L_{99}	L_{95}	L_{90}	L_{50}	L_{10}	L_5	L_1	L_{eq}	T.N.I.	veh./h	% P.L.
					Transversely grooved concrete							
1	11h00	58	61	63	74	83	85	87	79	113	637	14
2	11h06	61	64	76	76	84	85	87	80	108	886	13
3	11h13	62	65	66	75	83	85	88	79	104	713	17
					Bituminous surface							
1	11h26	54	58	59	69	80	82	86	76	111	724	16
2	11h33	57	59	61	71	79	81	84	75	103	767	17
3	11h40	58	60	62	71	80	82	86	76	102	724	16

L_x = in Db (A)   T.N.I. = traffic raise index in dB (A)   % P.L. = % heavy vehicles

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