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"A Comprehensive Review of Sub Base Layer Permeability and its Influence on Pavement Performance"

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Abstract

India has one of the world's longest road networks, spanning over 6.61 million kilometres of road length. Most of the roads constructed are having poor drainage characteristics, causing premature failure which leads to high maintenance cost before reaching their design life. Drainage has been extensively used in pavement structures to intercept water from entering pavement through various sources. An effective pavement drainage design depends on comprehensive understanding of drainage methods and their effectiveness. The performance of the pavement drainage layer depends on the stability and the drainage effective of the material used in the construction. The purpose of this study is to review the various studies that researchers have conducted on efficient road and highway drainage systems. Selection of material, drainage effectiveness and the influencing factors were analysed, which provides a reference for sustainable drainage design.

Key Words: *Pavement performance, co-efficient of permeability, recycled material*

INTRODUCTION

Presence of water in pavement systems is known to be one of the main factors contributing to premature pavement failure. Moisture can infiltrate pavements through various sources such as surface infiltration, rising groundwater, seepage from higher ground, capillary action and vapor movement. Surface moisture infiltration through cracks is the primary and largest source of moisture infiltration in pavements. Moisture intrusion into flexible pavements can reduce the strength and durability of the pavement layers, resulting in moisture damage and pavements distress. Excess moisture can also enter the pavement subgrade and thereby accelerate pavement damage as a result of subgrade softening or frost action. A properly designed drainage system may help to prevent excess moisture from entering the pavement layers and subgrade and reduce the chance of moisture-related damage. Standard pavement design approaches prioritize density and stability over drainage characteristics, resulting in poor drainage ability of pavement system. India has one of the world's longest road networks, spanning over 6.61 million kilometers of road length. Most of the roads constructed are having poor drainage characteristics, causing early failure which leads to costly repairs and replacements before reaching their design life. Designing pavement systems thus requires careful consideration of drainage ability of pavement system.

Moisture induced damages in pavement

VA Diyalje (1985) investigated probable cause for pavement distress along a roadway which have failed 5 years after construction. The combination of the poor drainability of the subbase and the presence of entrapped water caused premature failure in the pavement. Improper drainage maintenance also, entraps moisture inside the pavement structures, thereby accelerating pavement damage [9]. In some cases, the poor drainage systems caused more damage to the pavement compared to pavement where no drainage system had been present [14]. The presence of water in base and sub-base granular materials and seasonal variations of water content in structural layers strongly influence bearing capacity of pavements. The un-drained water develops an excess of pore-water pressure, under wheel loading, causing reduction in the layers stiffnesses and increase in pavement distress. Michael (2008) studied that water has a detrimental effect on performance of pavement, either by weakening subsurface materials or eroding material by free water movement [25]. The main causes for flexible pavement failures is due to the weakening of the sub-base, base, or sub-grade when saturated with water. In concrete pavements movement of water erodes the subsurface material, creating voids under the concrete surface. Thus, accumulation of moisture can adversely affect pavement performance leading to accelerated pavement deterioration.

The continuous presence of moisture in the pavement subgrade can significantly affect pavement performance through reduction in subgrade moduli. Nantung (2015) found that resilient modulus reduced as much as 25% when sub- grade moisture content increases 2% above optimum moisture content [30]. Investigation on flexible pavement failure in Euthopia indicated that premature failure in pavement is due to use of improper gradation of material used in base and sub-base layer resulting in CBR value lower than the minimum standard requirement. Due to this reason, material used were not able to resist traffic loads resulting in rutting [7].

Background

Recognition of the need to consider drainage in the pavement design process led the AASHTO Pavements to require the inclusion of drainage considerations in AASHTO Guide for Design of Pavement Structures-1986. Guidelines provides subjective procedure to establish quality of drainage was to calculate the time required to drain the base layer to 50 percent saturation (T_{50}). The drainage quality levels presented in Table 1. These criteria are recommended for use in both flexible and rigid pavement design.

Table 1: Drainage Quality Levels [1]

Quality of Drainage	Duration required to remove water	
	Calculated	Recommended
Excellent	2-4 hr	2 hr
Good	½ -1 day	1 day
Fair	3 – 6 days	7 days
Poor	18 – 36 days	1 month
Very poor	> 36 days	Does not rain

In 1979 NCHRP Synthesis of Highway Practice observed that many pavements are subject to moisture-related problems and has convinced that subsurface drainage design criteria and principles should be part of the pavement structural design procedure for better and more economical pavements. [15]

In the 1993 AASHTO Guide for Design of Pavement Structures, drainage was considered as one of the design factors for highway pavement. Drainage effects are considered in terms of the effect of moisture on road bed soil and base strength for flexible pavements and the effect of moisture of subgrade strength and base erodibility on cement concrete pavements [27].

Reports concerning drainage of water from the base and subbase materials were published Harry R. Cedergren (1994) pointed out that the life of a poorly drained pavement is reduced to one third or less of the life of a well-drained pavement. He believes the permeability of the pavement base course should be between 10,000 ft/day (3.53 cm/sec) and 100,000 ft/day (35.25 cm/sec). He also stated that the permeability increases 40,000 times if the drainage layer material is coarse and open-graded aggregates [6]. Hassan and White (1996) further refined drainage system. They recommended a dense-graded asphalt mixture be placed on the prepared subgrade to act as a filter, thus reducing moisture migration both into the subgrade from the pavement and from the subgrade into the pavement. Further, the study also concluded that primary source of moisture that enters a pavement system is through surface infiltration. Thus, an open- graded asphalt mixture layer was recommended over the dense-graded asphalt layer to serve as a drainage layer for the pavement.

Unstabilized bases, frequently referred to as granular bases, are the most commonly used sub-base layer in flexile and rigid pavement consists of crushed stone, sand-gravels, sands, and a variety of waste and byproducts. The materials gradation and properties for unstabilized base should meet the requirements of AASHTO M 147. It recommends permeability of material used should be approximately 150 ft/day and not exceeding 350 ft/day.

Ministry of Road Transport and Highways (MoRTH) -5th Revision, 2013 specifies use of natural sand, crushed gravel, crushed stone, crushed slag, or combination of these in sub-base layer depending upon the grading required. The materials shall be free from organic or other deleterious constituents and shall conform to the gradings and physical requirements given in Table 2.

Table 2: Grading for GSB material as specified in MoRTH 5th Revision (2013) [23]

IS Sieve designation	Percentage by weight passing IS sieve					
	Grade I	Grade II	Grade III	Grade IV	Grade V	Grade VI
75.0mm	100	-	-	-	100	-
53.0mm	80-100	100	100	100	80-100	100
26.5mm	55-90	70-100	55-75	50-80	55-90	75-100
9.50mm	35-65	50-80	-	-	35-65	55-75
4.75mm	25-55	40-65	10-30	15-35	25-50	30-55
2.36mm	20-40	30-50	-	-	10-20	10-25
0.85mm	-	-	-	-	2-10	-
0.425mm	10-15	10-15	-	-	0-5	0-8
0.075mm	<5	<5	<5	<5	-	0-3

Wyatt and Macari (2024) study on subsurface drainage features found that for a properly drainable pavements, presence of subsurface drainage is not alone is adequate and subsurface drainage system must be designed considering expected rate of inflow to the pavement system. The structural integrity and drainage capacity, of subbase materials are highly affected by the distribution of grain sizes, i.e., gradation, in the aggregate mix. Thus, specifying proper material gradation and particle size distribution is requisite for achieving satisfactory pavement performance [38].

Permeability of Sub-base Material

A subsurface drainage system usually drains water by gravity. For the conditions that exist within the pavement structure, the assumption of laminar flow of Darcy's law is satisfactory. The application of Darcy's law requires a determination of the coefficient of permeability, k, which is a measurement that represents the drainage property of materials. Laboratory determination of the coefficient of permeability of materials utilized as base and subbase is essential for highway pavement design, especially for subsurface drainage systems. Scheme of constant head permeability test used to determine laboratory permeability value shown in Fig 1:

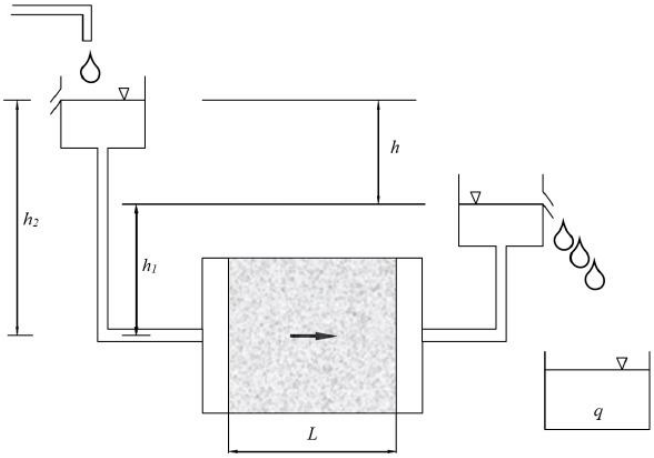


Fig 1: Constant Head Permeability Test Setup [11, 12, 17]

The co-efficient of permeability may be found by applying Darcy's Law as:

$$k = \frac{QL}{th_L A}$$

where, k: coefficient of permeability, Q: flow volume in time t, L: length of flow, t: time of flow

h_L: head loss ($h_1 - h_2$), A: area of total cross section

Many highway agencies have set specifications on permeability value for untreated permeable layers to be used in the of highway drainage design. The drainage design is based on a coefficient of permeability and the value ranges between of 0.18 to 0.36 cm/sec. However, because of the variability involved in the testing and the construction of the drainage layers, laboratory permeability greater than 0.36 cm/sec is often preferred by designers [10].

The studies on drainage characteristics of granular sub-base material confirming to graduation requirement as per MoRTH and AASHTO-57 using semi model pavement indicated all the highest coefficient of permeability of 3675.66 m/day for Grade III. Since it is an open gradation, structural stability can be improved by working in combination with Grade IV &V. Grade IV & V full fills both structural stability and permeability criteria. Grade I & Grade II showed no flow because of dense material gradation and thick particle interlocking. These grades are suggested to use in areas where there is need of structural support to pavement rather than drainage requirement. The co-efficient of permeability obtained for Grade III is much better result than AASHTO-57 indicating effectiveness of MoRTH gradation for granular subbase layer [32]. The similar trend was observed during laboratory evaluation of horizontal permeability of granular subbase material [12, 17, 22]

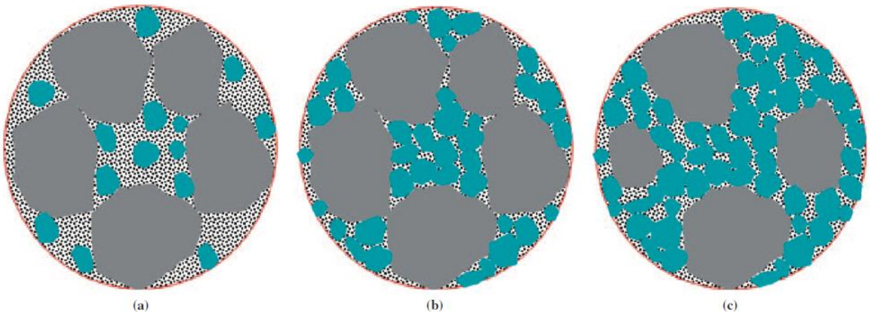
Factors influencing permeability Subbase Layer

The function of subbase layer is to reduce wheel loading-induced stresses on the underlying layers so that the stresses transmitted to the subgrade will not result in excessive deformation. In its dense condition, the granular base has a high bearing capacity and a low coefficient of permeability that may not quickly drain the water out of the pavement structure. On the other hand, a drainable base, i.e., open graded, is known to quickly drain the water and are likely to lose its stability under wheel loading, if not confined [29, 20]. Thus, to optimize the pavement performance, an aggregate base must have a good structural integrity, represented by its stiffness and it must also have an adequate drainage capacity to dissipate the excess water pressures.

Gradation of Aggregates and Maximum Size of aggregates

Aggregate base/granular subbase materials, is typically a mixture of the gravel, sand, and fines fractions. Gradation of these material greatly influence particle packing and porosity characteristics (Fig 2) [39]. A study on drainability characteristics of several types of unbound granular materials used in pavement bases showed that the average hydraulic conductivities for the open and dense-graded materials were 3.6×10^{-1} to 3.0×10^{-4} cm/s (1,021 and 0.85 ft/d), respectively and effective porosities for the open and dense-graded materials were 68% and 27% respectively. The study shown significance and effectiveness of gradation of material on drainage characteristics [7]. Aggregate gradation is one of the factors that have a significant effect on co-efficient of permeability, k values of aggregate bases/sub-bases. Study on permeability of M-AASHTO #67, M-AASHTO #57, OKAA aggregate gradation indicated higher k value of 1,777 ft/day (0.87 cm/sec) for M-AASHTO compared to other gradations. From the laboratory studies, it is evident that the amount of fines in an aggregate mix significantly influences the measured permeability value. It also important to note that, co-efficient of permeability is inversely proportional to the compaction effort. Co-efficient of permeability, k value decreases with increase in compactive efforts. These findings are consistent with the findings from [11, 28]. The permeably test results on washed and non-washed sand with varying compaction efforts indicated the reduced k value with increase in compaction rate. Also, decrease in permeability water co-efficient is more significant in washed sand compared to un-washed sand, which indicates that smaller fraction sands are more sensitive to compaction and thus the permeability of the material [11]. Study on two limestone aggregate base blend in Oklahoma revealed that aggregates broke under the impact compaction energy resulting in finer gradation after compaction. In addition to gradation characteristics, upper limit (UL), lower limit (LL), and percentage fines have a significant influence on OMC, MDD and permeability value as shown in Fig 3 [29]. The UL of each gradation, in general, exhibits higher OMC and MDD values than the corresponding values of the LL. The presence of smaller particles in LL gradation allows for more particle packing and new particle arrangement will lead to a reduction in the void ratio and an increase in density [35]. In addition to particle size distribution, permeability k value affected by pore characteristics such as pore size, pore shape, and tortuosity of the flow path. The compaction condition in turn influences these pore properties [27].

Fig 2: Particle packing of gravel–sand–fines fraction mixture with different gravel-sand-fines ratios:



(a) large, (b) optimum, and (c) small [39]

The effect on maximum size of aggregate on permeability of open graded base material is another important factor to be considered. Laboratory investigation and statistical analysis of the resulting data to determine the effects of top size, aggregate gradation, and porosity on the permeability of unbound roadway base layers indicated no substantial difference in the measured coefficient of permeability when the top size was increased from 38 to 63 mm if the percentage of finer fractions remains relatively constant. Statistical analysis resulted in an R^2 value of 17% indicating little correlation between k value and top size [10].

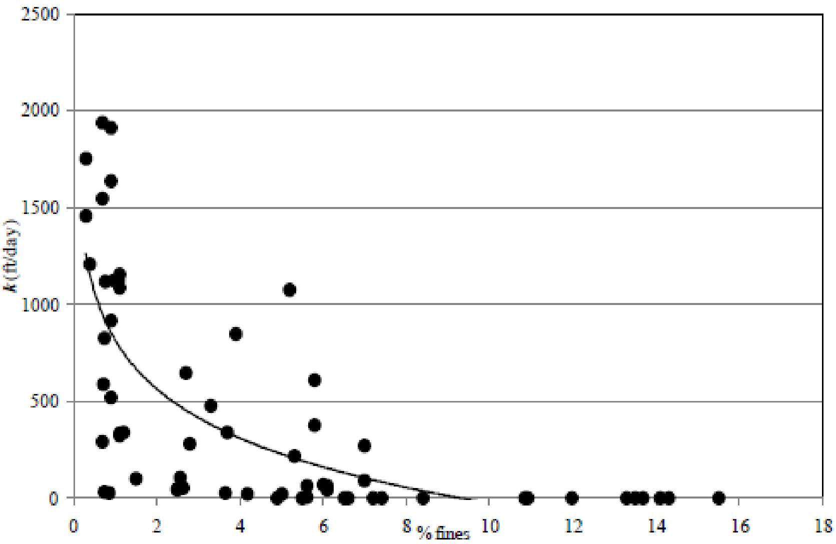


Fig 3: Effect of Percentage Fines on Permeability Value [29]

Hydraulic Gradient

The effect of hydraulic gradient on permeability co-efficient depends on material type, compaction rate and amount of hydraulic gradient. The horizontal permeability tests conducted at different gradients shows that with optimum compaction rate, permeability value decreases with increase in hydraulic gradient [11, 17]. Conversely, at higher value of hydraulic gradient the flow become non-linear and Darcy's law is not valid for such flow conditions. The influence of hydraulic gradient on water permeability is negligible when hydraulic gradient is upto 1.0; such conditions correspond to Darcy's Law [11, 32]. Thus, hydraulic gradient is the one of the effective parameters affecting permeability value and it is important to select suitable hydraulic gradient value while conducting permeability tests.

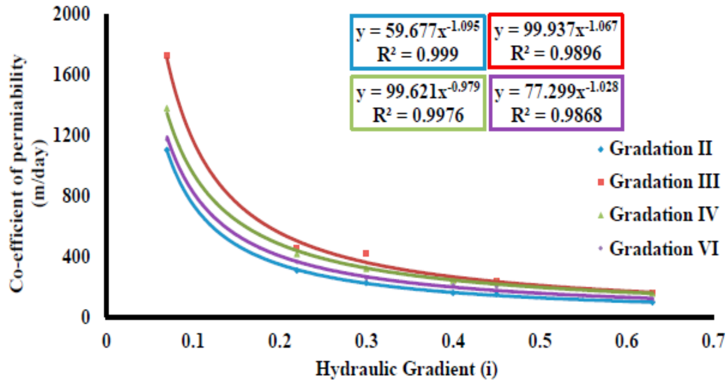
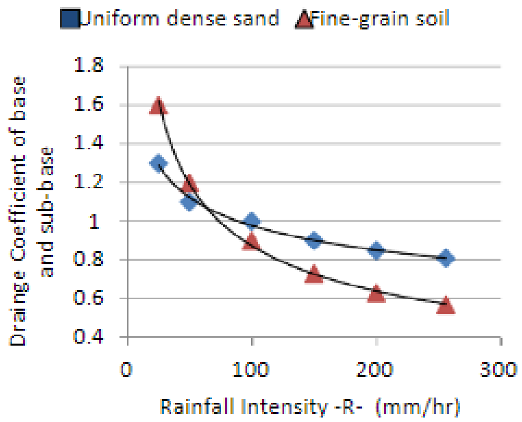


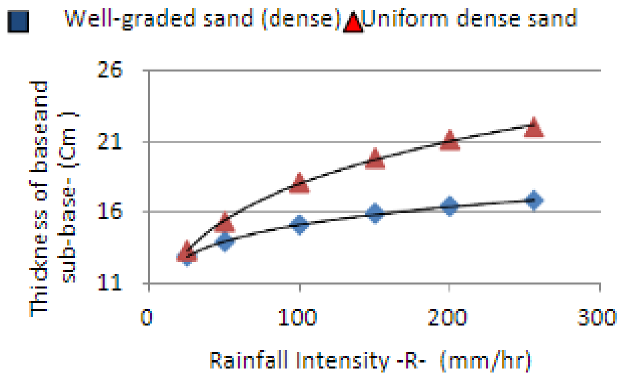
Fig 4: Coefficient of horizontal permeability at different hydraulic gradient [17]

Rainfall Intensity

The amount of water that can drain from a base course depends not only on the physical properties of the material, but also on the cross-sectional geometry of the pavement. The rainfall intensity is another governing factor in pavement drainage design. The quality of drainage material measured in terms of permeability vary exponentially with rainfall intensity for a particular pavement thickness and carriageway width. The increase in rainfall intensity will cause a decrease in the drainage coefficient and increase in the thickness of sub-base and base layers. The study on flexible pavement design with various rainfall intensity indicated that, with rainfall intensity (256 mm/hr) yielded thickness and drainage coefficient (46 cm, 0.57) respectively and rainfall intensity (25 mm/hr) resulted in thickness (18.5cm, 1.7) respectively. Studies showed increase in the rainfall intensity resulted in increase in the infiltrated water to the sub-base and base and layers [2].



a) Rainfall intensity v/s drainage co-efficient



b) Rainfall intensity v/s drainage thickness

Fig 4: Relationship between rainfall intensity, drainage co-efficient and drainage thickness [2]

Other factors

Turbulent flows of water due to runoff water, affect the integrity of base granular materials. When the fine fractions are dragged from the granular skeleton surface, the material gradation is modified [21]. Pumping in pavement migration of saturated subgrade fines into overlying granular layers which has adverse effect on performance and service life of the pavement. The mechanisms of pumping of fines at the subgrade-subbase interface causes the penetration of the subbase particles into the subgrade soil with consequent reduction of subbase layer thickness. The use of geotextile between the subbase and subgrade layers is an effective means to reduce pumping of subgrade fines in pavement by providing both separation and filtration [4, 5].

Recycled material for base/sub-base Layer

In addition to virgin aggregates, various recycled materials can be a good source of aggregate for base and subbase under a concrete pavement, especially when sustainability is of concern. The utilization of recycled materials as unbound base courses in the construction of new roads has gained popularity over the past two decades. Recycled roadway materials are typically generated and reused at the same construction location, resulting in significant savings in both time and cost. It has been observed from some municipalities that utilization of recycled materials cost reduces overall cost by as much as 30% compared to conventional crushed-stone base material [37]. The most common recycled materials used in different layers of flexible pavements are Reclaimed Asphalt Pavement (RAP), Recycled, Concrete Aggregate (RCA), recycled bricks, recycled glass and fly-ash (FA).

The RAP material obtained by cold recycling methods and combined to obtain gradation confirming to AASHTO. The results showed decreased OMC and MDD of RAP aggregated compared to virgin aggregates [34]. CBR value of about RAP is about 68% lower than that of VA. This is because of the reason that bitumen surrounded the RAP aggregates inhibits compaction. Resilient modulus and shear strength measurements in this study showed improved M_R value and shear strength parameters for recycled aggregates compared to virgin aggregates except for FA [31]. Permeability test results on various recycled material and aggregate mixtures revealed that the hydraulic conductivity of recycled material is higher than VA, indicating that these materials provide adequate drainage. Hydraulic conductivity of foundry sand and aggregate mixtures showed lower values compared to 100% aggregates. This is anticipated given that the fine sand particles from the foundry sand occupy the gaps between the aggregates during the packing process. Thus, the study showed that RAP, FA and RCM will be good substitutes for virgin aggregates as base/subbase materials in road construction. However, some of the studies indicated that VA exhibits higher permeability value compared to RAP [34]. This is expected as interlocking between the asphalt-coated aggregates in RAP and the VA particles tends to decreases the air voids and thus making base material impermeable.

The results of the pavement design analysis obtained on the various RAP-virgin aggregate blends indicated higher surface thickness to protect the weak granular base [36]. Cement treated RAP exhibits increased CBR and M_R value and there by slightly lower base thickness requirement. 100% RAP aggregate could be successfully utilized as a conventional base material when stabilized with cement. Further, it is to be noted that cement used in the blend may be limited to 3% as higher percentage of cement increases the fine content which fill up the spaces in between the aggregates which in turn reduces the hydraulic conductivity of the material [34].

Conclusions

A properly designed drainage system can help prevent excess moisture from entering the subgrade. Presence of moisture in pavement structural layers leads to water induced distresses, i.e. critical rutting and fatigue cracking of overlying bound layers, the progressive shear failure and excessive plastic deformation. As evidenced by many studies, long-term flexible pavement performance depends on effectiveness drainage system provided which can be measured in terms of stability and drainage ability. The findings of the study summarized as follows:

- In areas with a higher rainfall or high-water tables, the use of an open-graded granular material should be considered, rather than a dense-graded material, as the open-graded material appears more effective in terms of permeability

- The large-sized aggregates in open graded material are usually considered to be stronger and less expensive to produce than small sized aggregates. The maximum size of aggregate in drainage layers should be based on a strength evaluation.
- Increase in fines and small-size particles in sub-base/base leads to a decrease in permeability Thus, it is essential to restrict the amount of fines without compromising the stability requirement of the material.
- Use of geotextile separator/ filters are advisable to provide long term drainage efficiency of subbase/base later by preventing pumping and intrusion of fines into drainage layer.
- Unbound aggregates are becoming increasingly scarce and expensive. Replacement of certain percentage of unbound aggregates with RAP can be permitted in pavement applications without detriment to the CBR and permeability potential. Addition of cement with RAP improves the performance of these material bur the percent of cement has to be restricted to 3%.

Scope for further studies

Several laboratory studies have been conducted to investigate the effect of permeability on the long-term performance of pavement. There is insufficient evidence in India to estimate the impact of sub-surface drainage on pavement performance through field investigations and research. Thus, it is necessary to evaluate the possible impacts of subsurface drainage on pavement performance by construction of test tracks by simulating field conditions in the experimental design. The specifications related permeability criteria not taken into account in IRC: 37-2018 and MoRTH specification and provisions must be made for the same. By considering performance of existing pavement numerical models can be developed to predict the permeability of subbase layers under different loading and environmental conditions. Cement Treated and Recycled materials are excessively used in present day pavement construction. Permeability aspects of these material to be evaluated through various laboratory and field studies.

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