A Study on Permeability Characteristics of Asphalt Pavements

Rajan Choudhary, Vikramkumar R. Yadav, Abhinay Kumar and Anirudh Mathur

Abstract Ingress of moisture during early pavement life leads to undue deflection, increase of pore pressure under traffic, stripping of bitumen from aggregate and ultimately, reduction in strength. It is important to evaluate the sensitivity of asphalt mixes to the ingress of water, which can be quantified in terms of permeability (or hydraulic conductivity). The primary objective of the present study was to characterise permeability of a newly laid asphalt pavement through field-based and laboratory-based measurements. Field permeability of a newly laid pavement was measured at different sections in longitudinal as well as transverse directions. Cores were extracted from the locations where field permeability tests were conducted. Loose mixtures were also collected from plant and were compacted in laboratory to different air void contents through variable compactive effort. Permeability of field cores and laboratory compacted mixtures was determined in laboratory. Results indicated significant differences in field and laboratory permeability values. Field permeability showed a strong positive correlation with laboratory determined permeability of cores and compacted samples. Transverse variation of permeability was also found to be quite significant. All measured permeability values had a positive correlation with air voids. Statistical modelling of permeability–air void data was also attempted.

Keywords Asphalt mix permeability · Moisture damage · Air voids · Hyperbolic model

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1 Introduction

Asphalt concrete (or bituminous concrete) is a widely used pavement construction material and plays an important role in the performance and durability of road transport infrastructure. About 98% of all highway pavements in India are surfaced with asphalt concrete. Moisture-induced damage is major distress observed on asphalt pavements in India. Intrusion of water is detrimental to pavement durability and can lead to an early onset of moisture-induced distresses such as stripping, cracking and reduction in load-bearing capacity [1–3]. The first step in addressing these distresses is to measure the receptiveness of an asphalt mixture to the ingress of water. This can be quantified in terms of its permeability (also termed hydraulic conductivity). Mathematically, permeability refers to the coefficient of permeability (k) defined by Darcy's law (Eq. 1):

$$Q = kiA \tag{1}$$

where $Q =$ discharge flowing through the specimen; $i =$ hydraulic gradient; and $A =$ cross-sectional area of specimen perpendicular to the direction of flow. Equation 1 is based on the assumptions that the specimen is saturated and homogeneous, and that the flow is one-dimensional and laminar.

Water from precipitation entering a pavement surface would tend to flow in both vertical and horizontal directions since the flow is not confined. Under this perspective, evaluation of permeability of pavement in situ is preferred as it is more representative of the actual conditions. Field permeability determination is also advantageous as it is a non-destructive test and does not involve disfiguring a newly laid pavement surface through the extraction of cores. However, what is not known during field permeability measurement is whether the pavement layer is fully saturated and whether the flow of water is truly vertical, which are the two essential assumptions made in Darcy's law used for permeability calculations. Such limitations can be overcome if a core is extracted from the constructed pavement and evaluated for permeability in laboratory under controlled conditions of saturation and unidirectional flow. This approach has the advantage of the validity of Darcy's law, nevertheless does not simulate the actual flow regime encountered in the field. None of the aforementioned two approaches (permeability measurement on core or in field) would be beneficial for an asphalt mix designer since the testing is carried out after the mix has been placed and compacted. Consequently, laboratory permeability measurements can be made on asphalt mix specimens prepared in the laboratory to assess if the field permeability values correlate well with the laboratory permeability.

Several studies have focused individually on the evaluation of field permeability of asphalt pavements [4–6] or on laboratory permeability of field-recovered cores [7–9] or on laboratory permeability of specimens prepared in laboratory [1, 3, 10]. Other studies have attempted comparisons of permeability of cores and compacted specimens in the laboratory [11, 12] or comparisons of field and core permeability [13, 14]. However, comparisons with all the three approaches for permeability determination have not been fully investigated.

2 Research Objectives

The primary objective of the present study is to understand general differences in magnitudes of permeability of a newly constructed asphalt pavement using the following three approaches:

- Field permeability (evaluated at the site itself), designated as 'field' permeability.
- Laboratory permeability of extracted cores, designated as 'lab (core)' permeability.
- Laboratory permeability of laboratory compacted mix, designated as 'lab (compacted)' permeability.

The specific objectives framed for this research are:

- To study the permeability of an ongoing paving project through field-based and laboratory-based testing. Laboratory-based evaluation consists of permeability measurement of field-recovered cores as well as compacted Marshall specimens in laboratory.
- To identify correlations between permeability values obtained through the three approaches.
- To study if field permeability varies significantly across the pavement width, i.e. transversely.
- To model permeability obtained from the three approaches as a function of air void content of the asphalt mix.

3 Methodology

In this study, an asphalt paving project was selected that involved construction of an asphalt course with an intermediate lane width of 5.5 m at the outskirts of Kishanganj city in the state of Bihar. Batch mix plant supplying the asphalt mix for the project was visited on the day of mix production. Loose mixtures were collected from the haul truck at hot-mix plant only before it departed for the paving site. The loose mixtures were then immediately brought to quality control lab (located at the hot-mix plant) in closed containers and compacted with varying blows of Marshall hammer. Some portion of the loose mix was kept separately for maximum specific gravity (G_{mm}) evaluation. On the following day, the paving site was visited for conducting field permeability testing and extraction of cores from the locations where the mix was actually laid and compacted. Overall methodological flow chart for the present study is shown in Fig. 1.

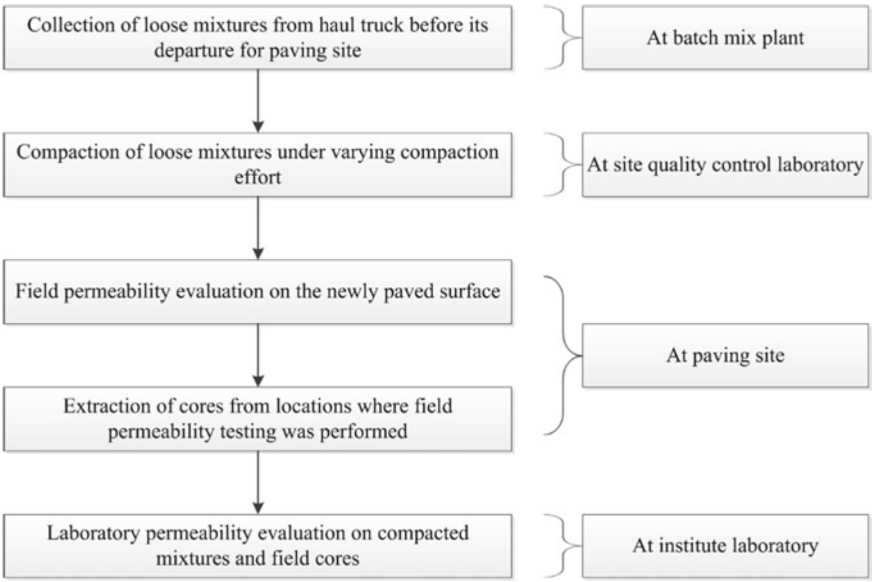

Fig. 1 Overall experimental flow chart

Figure 2 presents the locations on the constructed pavement where field permeability testing was performed. A total of 18 locations were selected at 6 chainages spaced at 30 m. At each chainage, permeability was evaluated at three transverse locations: near the right edge, centre and near the left edge. This was done to investigate the transverse variation of permeability. Cores were extracted from the same

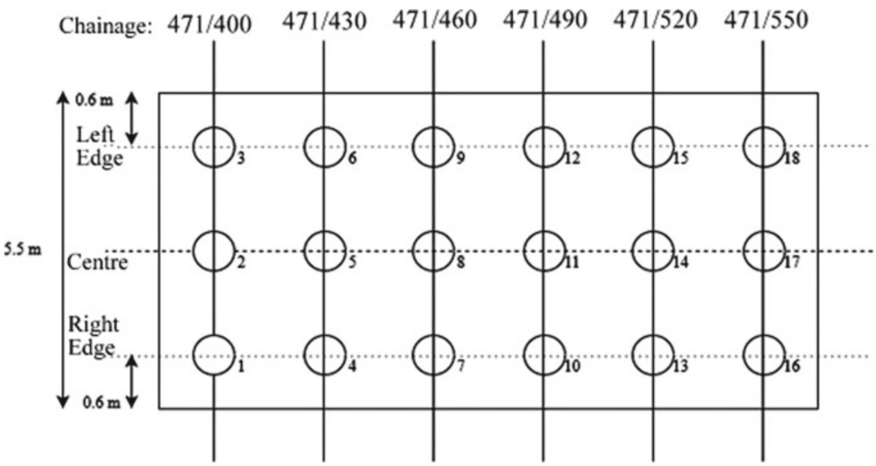

Fig. 2 Locations for field permeability testing

locations (shown in Fig. 2) chosen for field permeability evaluation, once the field permeability measurement was over.

3.1 Field Permeability Evaluation

National Center for Asphalt Technology (NCAT) developed a testing set-up to measure the permeability of asphalt mixes in the field. The NCAT asphalt field permeameter is based on the falling-head principle. Schematic diagram of a similar fabricated permeameter for field permeability measurement is shown in Fig. 3. This permeameter uses a four-tiered standpipe with decreasing inside diameters from bottom to top. For highly permeable surfaces, it would suffice to use the bottommost tier only. For low permeable surfaces (such as dense-graded asphalt layers), more tiers are included so that head fall can be accurately measured within a reasonable amount of time. It is important to ensure that there is no leakage between the base of the equipment and the pavement surface. Preliminary trials were conducted with plumber putty, silicone rubber and moulding clay to select an appropriate sealant material. Results of the trials showed that plumber putty took unreasonably longer time to set on the surface, while the silicone rubber was not effective in sealing the surface deformities and allowed leakage from above the pavement surface. Moulding clay was found to be the most effective measure in preventing water leakage and was selected for the study. Clay has also been used as a sealant for field permeability in a previous study [1].

As per the procedure developed by NCAT, equipment is placed on a cleaned pavement surface after application of the sealant. Counterweights are added to counteract

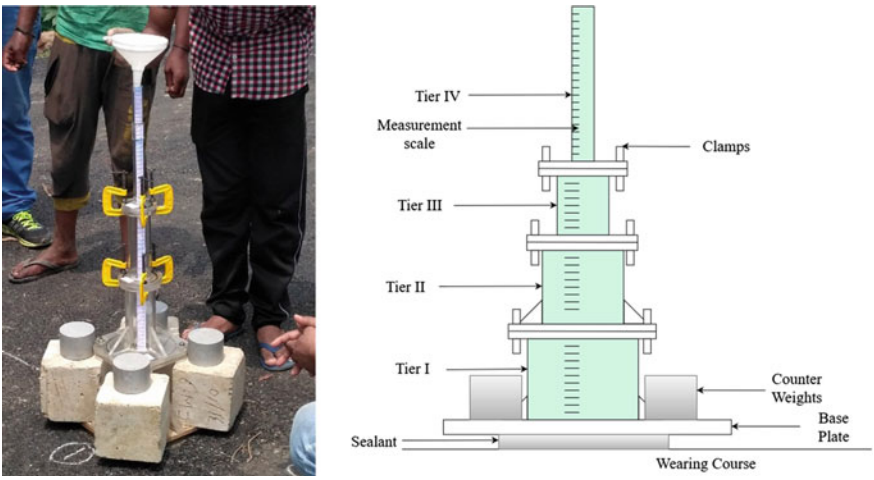

Fig. 3 Field permeameter: **a** photograph, and **b** schematics

the uplift pressure created at the base by the head of water. The water is added gradually from the top, and the rate of flow of water through the pavement is indicated by the time required for a suitable drop in head. Collected data are used to compute permeability based on the falling-head principle (Eq. 2):

$$k = \frac{aL}{At} \ln\left(\frac{h_1}{h_2}\right) \tag{2}$$

where k = permeability (cm/s); a = cross-sectional area of tier of standpipe used during measurement; A = cross-sectional area of pavement surface (area enclosed within the sealant); L = thickness of pavement layer (found from extracted core); and t = time (seconds) for head drop from h_1 (cm) to h_2 (cm). The test was repeated three times at each spot, and the average results were reported.

3.2 Laboratory Permeability Evaluation

A laboratory permeameter shown in Fig. 4, based on the falling-head principle, was fabricated for permeability measurement of field cores and the laboratory compacted mix samples. For determination of permeability, a specimen was saturated under water by application of 4 kPa vacuum pressure for 30 min. The saturated specimen was securely wrapped with thin plastic and placed in the sample holder of the permeameter. A thin annular ring of moulding clay was applied on the top circumference to prevent side leakage. Water was then filled in the standpipe above the specimen,

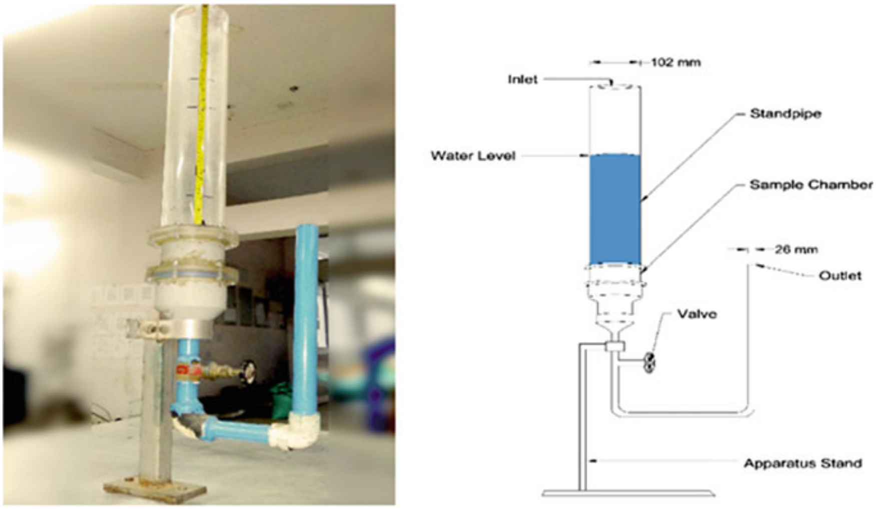

Fig. 4 Laboratory permeameter photograph and schematics

and the time (t) needed for the head to drop from initial value h_1 to the final value h_2 was recorded to compute permeability as per Eq. 2.

3.3 Evaluation of Air Voids

Air void content of laboratory compacted mix samples and field cores was obtained from the bulk density (G_{mb}) and theoretical maximum density (G_{mm}) measurements. Corelok vacuum-sealing device was used for G_{mb} and G_{mm} measurements as per ASTM D6857. Air void (AV) content was finally obtained as per Eq. 3:

$$AV = \frac{G_{mm} - G_{mb}}{G_{mm}} \tag{3}$$

It is to be noted that the same G_{mm} values were used for AV calculations of both field cores and laboratory compacted mix samples.

4 Results and Discussion

4.1 Transverse Variation of Field and Lab (Core) Permeability

Field permeability was determined at 18 locations of the paving project as per the layout shown in Fig. 2. Permeability testing was performed on each of the three transverse locations at the six chainages with three replicate measurements. Results of average field permeability at each location are shown in Fig. 5. Repeatability of the field permeameter used was assessed through the coefficient of variation (the ratio of the standard deviation to average, expressed as percentage) of multiple readings taken at the same location of testing. The coefficient of variation was less than 10% at all locations (with the exception of 15.4% at left edge of chainage 471/460). This showed that the permeameter used in the study produced acceptable repeatability. The data in Fig. 5 indicate that for most sections, the field permeability lied between 150×10^{-5} and 300×10^{-5} cm/s. The lowest permeability was observed at chainage 471/400, the starting chainage. This may be attributed to the fact that during compaction, this chainage received more roller passes compared to the following chainages.

The transverse variation of field permeability at any chainage can also be seen from Fig. 5. Permeability testing was performed at the centre of pavement as well at an offset of 0.6 m from the edges. The 'centre' permeability remains the minimum than at the edges. The results seem to indicate that the pavement edges offer higher permeability than the centre. This is likely as the centre of the pavement will be

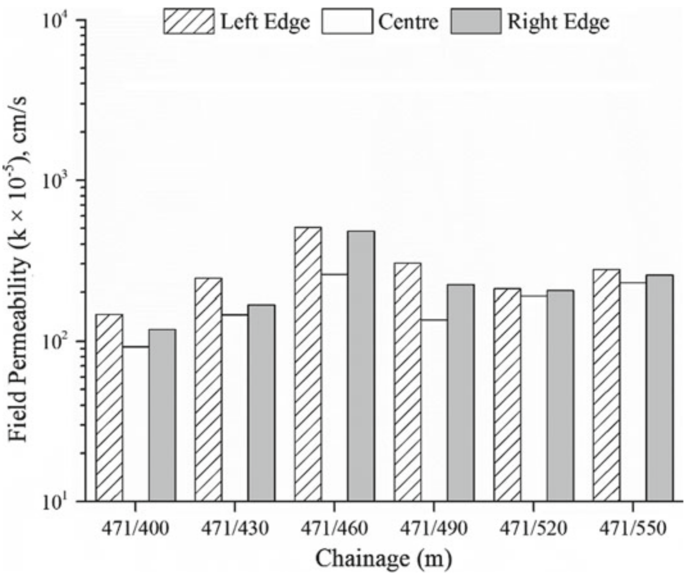

Fig. 5 Field permeability results

subjected to more overlaps during rolling operations and hence will be more densely compacted when compared to the edges.

Figure 6 shows the permeability of cored specimens extracted from the exact same location where field permeability testing was conducted. The cores were brought to the laboratory and evaluated for permeability. Hence, this permeability is designated as 'lab (core)' permeability. The figure is plotted to the same vertical scale as the field permeability (Fig. 5). A direct observation from Figs. 5 and 6 is that the lab (core) permeability is about an order of magnitude greater than the field permeability. The two permeabilities are compared in the next section of the paper. Further, it is observed that the transverse variation of lab (core) permeability is similar as in field permeability (permeability at the centre is lower than at the edges). It is to be noted that field and laboratory permeabilities were evaluated using different instruments under varying test conditions (sample saturation and unidirectional flow in case of laboratory permeability). In spite of that the lab (core) permeability values are able to capture the transverse variation of permeability occurring in the field.

To statistically examine the significance of differences shown by the two permeability tests, analysis of variance (ANOVA) followed by Tukey's honest significance difference (HSD) comparisons (at 5% significance level) was performed separately on field and lab (core) permeability values. The influence of location (left, centre or right) on permeability was statistically analysed, and the results are shown in Table 1. Based on statistical analysis, permeability along the left edge is significantly higher than at the centre, suggesting that permeability can show significant variations across

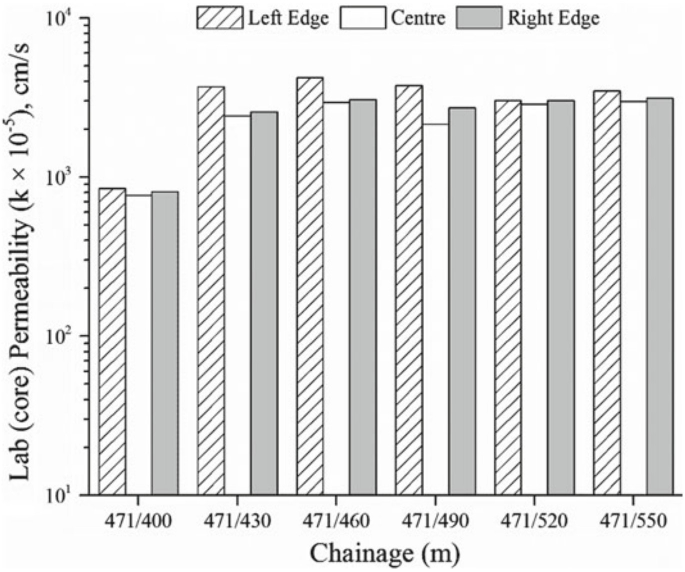

Fig. 6 Lab (core) permeability results

Table 1 Results of statistical analysis on field and lab (core) permeability

Comparison	Field permeability		Lab (core) permeability	
	p-value	Significant?	*p*-value	Significant?
Left versus centre	0.009	Yes	0.030	Yes
Right versus centre	0.139	No	0.791	No
Left versus right	0.494	No	0.131	No

the pavement width. This is likely due to non-uniform compaction achieved along the left edge compared to the centre of the section.

4.2 Field, Lab (Core) and Lab (Compacted) Permeability Comparisons

Laboratory permeability tests were conducted on loose mixtures collected from haul truck and compacted in the laboratory with varying blows of Marshall compactor. The information about the air void content of cores could only be obtained after extraction and testing of cores in laboratory. Consequently, prior information about sample air void content that will be achieved during compaction of loose mixtures was unavailable. For this reason, a 1200 g mass of loose mix was taken during compaction. Using varying compaction effort, a range of air voids was achieved. Five groups of air voids were formed to categorise field, lab (core) and lab (compacted) permeability values so that they may be compared at similar air void contents. Figure 7 presents details of air voids along with the permeability values in each group.

Results indicate that the laboratory permeability is higher than the field permeability. Field results are expected to provide higher permeability based on the argument that the flow of water may occur in any direction during field testing, whereas the flow remains unidirectional in the laboratory permeameter. However, the results clearly deviate from what was anticipated. In general, the lab (core) permeability is found to be 8–16 times the field permeability. It has been widely accepted that asphalt pavements become undesirably permeable above in-place air voids of 8% [13, 15]. In the present case, air voids were always above this threshold. Therefore, it is undeniable that the pavement and the mixes considered in the study had high interconnected air voids. Cores as well as compacted samples have more interconnected voids which provide sufficient flow paths for water transmission. Moreover, the vertical flow may also get interrupted due to underlying tack coat/asphalt layer during field testing. Interconnected voids that extend through the sample thickness allow higher permeability values during laboratory evaluation as there is no interruption to the vertical flow. Similar findings were also reported in the study by Cooley et al. [16].

Figure 7 also illustrates the magnitudes of lab (core) and lab (compacted) permeability values. Compacted samples produce lower permeability than the cores. This is because of higher thickness of the compacted samples than the cores. Thickness of cores ranged from 20 to 40 mm, whereas thickness for compacted samples varied from 60 to 70 mm. A higher sample thickness offers more barriers to flow and hence reduces the propensity of the voids to become interconnected, thus decreasing the

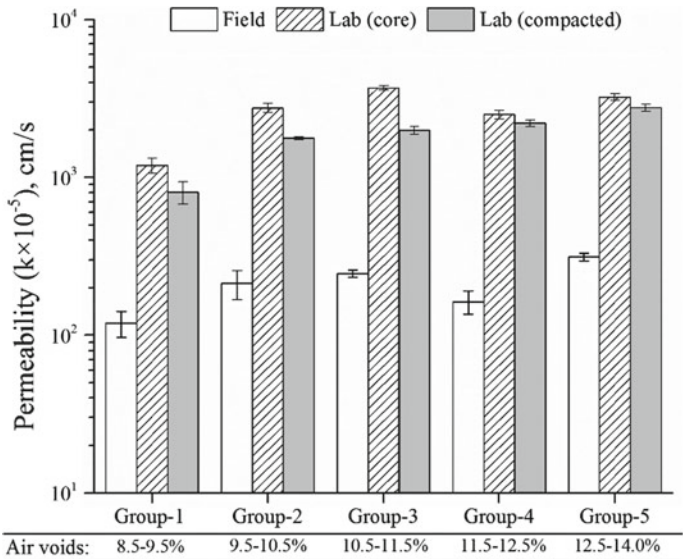

Fig. 7 Comparisons of field, lab (core) and lab (compacted) permeability

Table 2 Permeability correlations

Correlation	R-value
Field versus lab (core)	0.825
Field versus lab (compacted)	0.819
Lab (core) versus lab (compacted)	0.732

permeability. Lab (compacted) permeability values are, on an average, 30% lower than lab (core) permeability.

Correlation between field, lab (core) and lab (compacted) permeability values was determined using the Pearson correlation coefficient (R-value). Results obtained are presented in Table 2. Strong linear correlations ($R > 0.80$) exist between field permeability and laboratory permeability. A fairly good correlation is observed between the permeability of compacted samples and cores ($R = 0.732$).

4.3 Permeability–Air Voids Relationships

Air void content is the single most important factor affecting the permeability of asphalt mixes. Many studies in the past have attempted to model permeability solely as a function of air void content of the mix [1, 3, 17]. Figure 8 presents plots of permeability as a function of air voids for field, lab (core) and lab (compacted) permeability values. In all the three cases, the permeability appears to demonstrate an increasing trend with air voids. An important observation from Fig. 8 is that scatter in the plot is greater for field and lab (core) permeability than the lab (compacted) permeability. This is attributed to better control over air voids in the laboratory during compaction of loose mixes. On the other hand, variation in permeability–air void plot may be due to factors like localised segregation, non-uniform compaction, non-uniform lift thickness, etc.

An attempt was also made for developing regression models to capture the trend of permeability values with air void content. The models mostly reported by researchers to model permeability–air voids relationships were used, viz. linear, power law, exponential and hyperbolic models. Table 3 presents the details of each model, its mathematical form and statistical indicators of fit: coefficient of determination (R^2) and root-mean-square error (RMSE). The effect of scatter can be seen in terms of lower R^2 and higher RMSE for field and lab (core) data with linear, power and exponential models. Hyperbolic model performed the best with lowest RMSE and highest R^2 in all the cases.

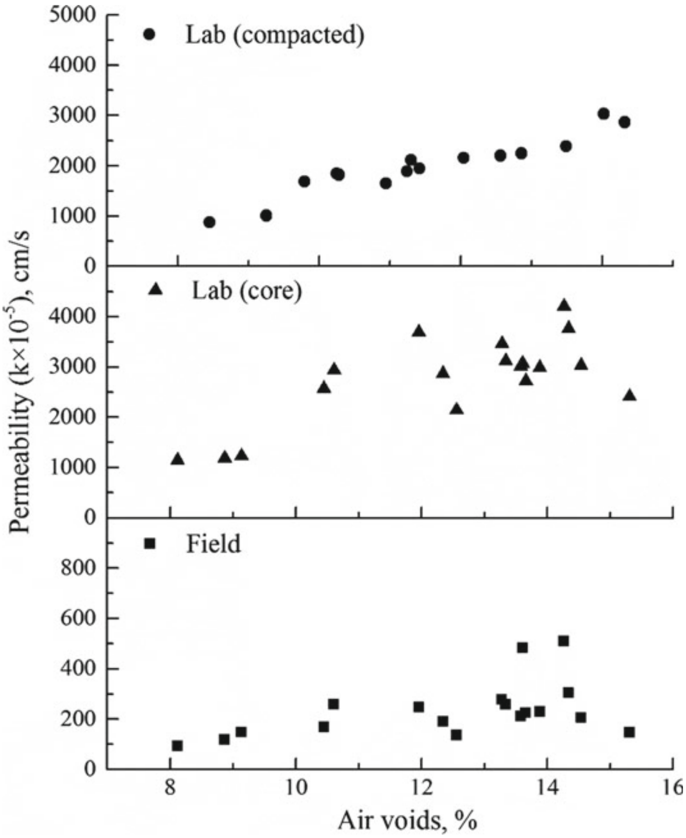

Fig. 8 Permeability–air void plots

Table 3 Results of statistical modelling of permeability–air voids data

Model	Form	Field		Lab (core)		Lab (compacted)	
		R^2	RMSE	R^2	RMSE	R^2	RMSE
Linear	$y = a + bx$	0.232	100.7	0.577	666.4	0.917	192.8
Power	$y = ax^b$	0.229	100.9	0.548	689.4	0.911	200.5
Exponential	$y = ae^{bx}$	0.199	102.8	0.500	724.8	0.897	215.5
Hyperbolic	$y = \frac{a}{(1/x)-b}$	0.919	2.144	0.886	231.4	0.921	9.896

Note y: permeability; x: air voids; a, b: model parameters; RMSE: root-mean-square error

5 Conclusions

Based on the results and analyses, the following conclusions are drawn:

- There was a significant difference in field and laboratory permeability values, even though both of them were measured using the falling-head principle. Laboratory permeability was found to be an order of magnitude greater than the field permeability.
- Field permeability showed strong positive correlations with laboratory determined permeability of cores and compacted samples.
- Field permeability significantly varies in the transverse direction with permeability at the centre lower than at the edges.
- Field, lab (core) and lab (compacted) permeability values had a positive correlation with air voids.
- Statistical modelling of permeability as a function of air voids indicated that hyperbolic model performed well with the lowest RMSE and highest R^2 in comparison with other models.

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