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Transport properties of concrete pavements with excellent long-term in-service performance

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Abstract

Excellent long-term performance in concrete pavements is associated with both concrete strength and durability properties like permeability and chloride ion penetration resistance. Water and air permeability are investigated, as is the rapid chloride permeability test (RCPT). Strong relations between compressive strength and permeability and chloride ion penetration resistance of typical ordinary Portland cement (OPC) concrete pavements are observed. Effects of environmental exposure on permeability and RCPT results are explained. Through-depth variation of permeability and RCPT results within a pavement slab are shown and discussed.

Keywords: Durability; Long-term performance; Permeability; Mechanical properties

1. Introduction

1.1. Background

This paper describes a portion of a Federal Highway Administration (FHWA) study in which 15 older pavements were examined that span a broad range in strength and permeability [1]. These pavements have shown primarily good to excellent performance over their 11- to 51-year service lives. This paper addresses the role of concrete strength on associated durability properties such as permeability and chloride penetration resistance. All of the studied test sections have typical concrete mix designs for pavements with respect to materials used and mix proportions. All contain ordinary Portland cements (OPCs) and none contain mineral additives such as fly ash or slag. The test sections cover all four major climate regions of the United States (see Fig. 1). While these studied test sections represent only a minute fraction of in service pavements, they provide significant information about the importance of permeability on pavement performance.

1.2. Overview

The most common measure of concrete quality is compressive strength. However, compressive strength alone cannot accurately predict long-term pavement performance, which is based not only on load carrying capacity, but also on concrete durability. Thus, either relations between compressive strength and durability properties like permeability are needed, or additional performance criteria that assess durability must also be considered.

The durability of pavement concrete can be defined as its ability to resist chemical and physical attack, primarily from environmental exposure. Particularly under harsh environmental conditions, creating a highly durable concrete is important (e.g., Refs. [2,3]). In this study, durability is measured through concrete permeability and chloride penetration resistance. The permeability and chloride penetration resistance are measures of the resistance of a concrete to the ingress and transport of water, salts, and other pollutants. A low permeability reduces the ingress and movement of fluids and is therefore beneficial.

Reduced permeability and chloride penetration resistance are important in both reinforced and unreinforced pave-

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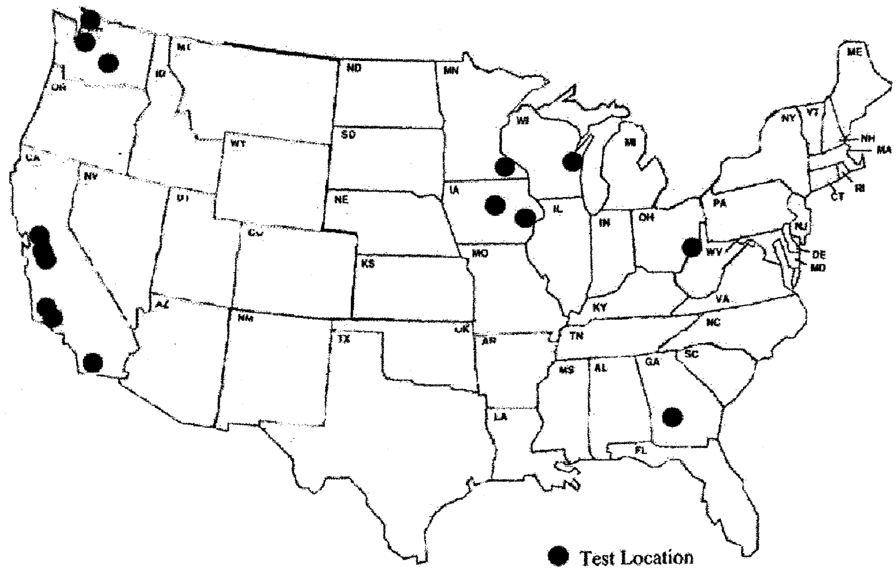

Fig. 1. Locations of the 15 studied pavement test sections.

ments. In addition to corroding reinforcing steel, the presence of salts can lower the freezing temperature of the pore solution, deepening the freeze–thaw cycle effected zone in the concrete. Salts also tend to be hygroscopic (moisture absorbing), keeping the concrete in a higher saturation state than if they are not present [4]. The presence of salt can significantly increase the severity of freeze–thaw damage.

The influence of permeability and chloride penetration resistance on pavement performance will be evaluated in the context of increasing concrete strength. The influence of environmental exposure and curing conditions on permeability are also considered. Similarly, the relative importance of achieving low permeability in each climate region is discussed based on general trends observed in the data.

2. Experimental methods

While there are many aspects to durability, it has been observed that the best measure of a bulk concrete's durability may be its permeation properties [5–8]. The literature also indicates that concrete permeability and chloride penetration resistance play important roles in spalling and transverse cracking distress modes, both of which can be durability related distresses.

Permeability and chloride penetration resistance are distinguished in that the former measures the movement of a fluid through the concrete, while the latter measures the diffusion of chemical species through the concrete. In this study, chloride penetration resistance is measured using the procedure of ASTM C1202, the rapid chloride permeability test (RCPT) [9]. The RCPT is a measure of conductivity, which is related to diffusion. However, it is an index test, and the results do not provide a coefficient of diffusivity. High RCPT results, measured in coulombs of charge passed in 6 h of testing, are indicative of a more diffusive concrete.

There are many methods available for measuring permeability in concrete. These methods typically inject a liquid or gas into the concrete either under pressure or through gravity flow. In this study the Florida field permeability test (FPT), and the Torrent air permeability test are used to support the results from the RCPT described above. The FPT injects water into the sample under pressure, while the Torrent test uses vacuum to pull air from the concrete voids. These methods are described in detail elsewhere [10,11].

All chloride penetration resistance and permeability tests in this study are conducted on concrete samples cored from the pavement slab. Fig. 2 illustrates the configuration of RCPT test specimens within a 100-mm (4 in.) diameter cored pavement sample. The top 12 mm (1/2 in.) of the core is discarded to avoid the effects of the potentially highly distressed or contaminated surface zone. Test samples are taken successively below the discarded region. As will be emphasized later, the location of the sample is critical, as RCPT and permeability values can vary significantly through the pavement depth.

As was noted, the air permeability method applies a vacuum to the surface of the concrete, and measures the vacuum loss over time. The method is extremely sensitive to sample surface cracking and surface roughness. When measuring air permeability at the exposed surface of pavement cores, high variability results. By instead measuring the air permeability on a saw-cut face of the concrete, the variability can be greatly reduced. As with the RCPT, the depth of the measurement location within the concrete affects air permeability results. Air permeability measurements are taken near the top, middle, and bottom of a 150-mm (6 in.) diameter core sample on saw-cut faces of the

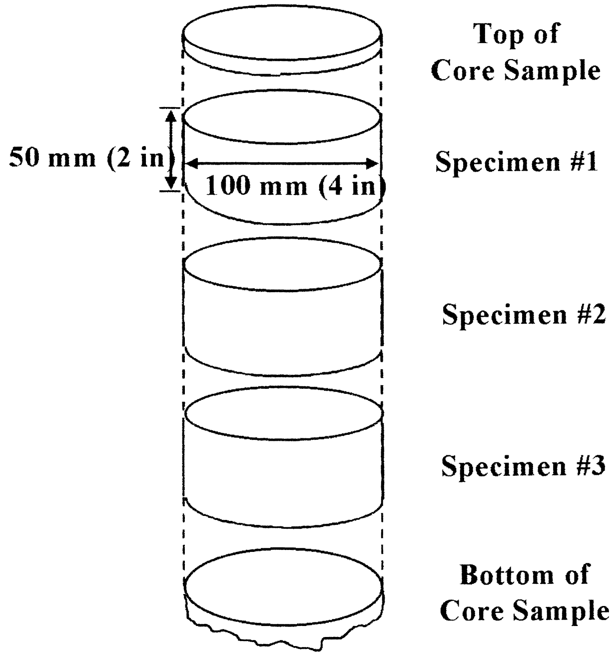

Fig. 2. RCPT specimen configuration for specimens cut from a concrete pavement core sample.

core. As with the RCPT, the potentially contaminated upper concrete surface is removed.

Water permeability is also measured on 150 mm (6 in.) diameter cores. However, the water permeability measurement is taken within a 22-mm (7/8 in.) diameter drilled hole at two depths in the concrete, near the top surface and closer to the bottom surface. As before, measurement depth is important.

Concrete compressive strength was determined where possible on 150×300 mm (6×12 in.) cylindrical samples using ASTM specifications for obtaining, preparing, and testing the samples [12–14]. However, the sample thickness was in many cases less than 300 mm (12 in.), as limited by the pavement thickness. The ASTM C42 depth correction factor was applied to those samples.

3. Results

Compressive strength can be correlated with a number of other mechanical properties, and serves as the benchmark property. For example, the development of compressive strength and permeability are each influenced heavily by the development of the concrete microstructure, causing them to be related. However, because strength and permeability relate to the microstructure differently, these correlations should be approached with care.

Permeability depends heavily on the capillary porosity and the interconnectedness of capillary pores. Strength, on the other hand, is influenced by a much wider range of pore sizes, with total pore volume being much more critical than interconnections between pores (e.g., Refs. [15,16]).

To avoid the time-dependent changes in the compressive strength and permeation properties, it is valuable to discuss permeability versus compressive strength relations by comparing their ultimate or final values. In this study, the pavement samples have been cored in the field after many years of curing and exposure. The concretes come from a number of different climate regions and are composed of various raw materials. They also have different exposure and loading histories. Nonetheless, they exhibit a surprisingly homogeneous trend with respect to the compressive strength versus permeability and RCPT relations. Table 1 lists the pavement test sections by climate region, along with their ages and average strength and permeability values. Strategic Highway Research Program, Long Term Pavement Performance (SHRP-LTPP) database codes are used for state and test section identifications where applicable [17].

Table 1
Pavement test sections and average strength and permeability values, sorted by climate region

	LTPP		Age at time of testing	Compressive strength	RCPT result (C)			Torrent air permeability (10^{-16} m^2)			Water permeability (cm/s $\times 10^{-11}$)
Climate region	State ID	Section ID	(years)	(MPa)	Top	Middle	Bottom	Top	Middle	Bottom	Top
Dry-no-freeze	06	3017	20	38	5555	3647	1996	1.032	0.188	0.015	303.4
	06	3021	24	33	4611	4620	3629	4.426	0.591	0.172	–
	06	7456	26	37	2744	2532	1190	–	–	–	–
	06	CS1	26	45	1970	1637	566	–	–	–	–
	06	CS3	26	58	1345	796	432	–	–	–	–
	06	I-10	51	38	3769	3184	1220	1.632	0.524	0.086	–
Dry-freeze	53	3019	11	56	400	132	89	0.893	0.027	0.017	56.1
Wet-freeze	19	3006	22	46	1995	1282	681	0.693	0.161	0.009	117.2
	19	3055	28	42	1656	1426	1546	0.033	0.087	0.114	–
	27	4054	25	54	1184	768	679	0.125	0.079	0.046	53.6
	39	3801	13	45	1505	1375	1291	0.086	0.033	0.008	–
	55	3008	22	62	225	288	312	0.042	0.028	0.034	48.7
Wet-no-freeze	53	3011	20	60	787	385	336	7.103	0.004	0.029	42.9
	53	3812	33	75	427	334	268	0.220	0.030	0.020	16.9
	13	GA1-5	26	37	6928	4309	2951	0.399	0.317	0.172	155.1

3.1. RCPT versus compressive strength relation

In Fig. 3, the RCPT chloride penetration resistance versus compressive strength relation is plotted for the field specimens. The results are for the top specimen in each core sample. In Fig. 3, the average compressive strength for each pavement test section is plotted against the average of all RCPT data points for that test section. In each case two to four samples were tested in strength and RCPT.

A power law regression fit of the data yields a good correlation (R^2 = .70). Hence, the regression represents the compressive strength versus RCPT relation for these concretes despite their different mix designs and environmental histories.

The significance of this relation comes on several levels. First, it is evident that the changes in RCPT values are captured by changes in compressive strength. This is best explained by the role the concrete microstructure has on both properties. As the microstructure develops, the capillary and gel pore structure densifies. In turn, the compressive strength develops and chloride penetration and permeability decrease [18,19].

The indication here is that compressive strength can be used as a rough comparative or predictive measure for chloride penetration resistance or permeability of OPC pavement concretes. Specifically, it is seen that chloride penetration can be greatly reduced with increases in strength. At lower and moderate strengths, the reduction in chloride penetration with increasing strength is dramatic. By moving from 35 to 45 MPa the ultimate compressive strength, the RCPT results can be expected to decrease from over 4000 to under 2000 C (a drop of two RCPT classes). At high strength, however, the benefits to chloride penetration resistance are less pronounced. The chloride penetration decrease by moving from 60 to 70 MPa ultimate compressive strength is only a few hundred coulombs within the same RCPT class.

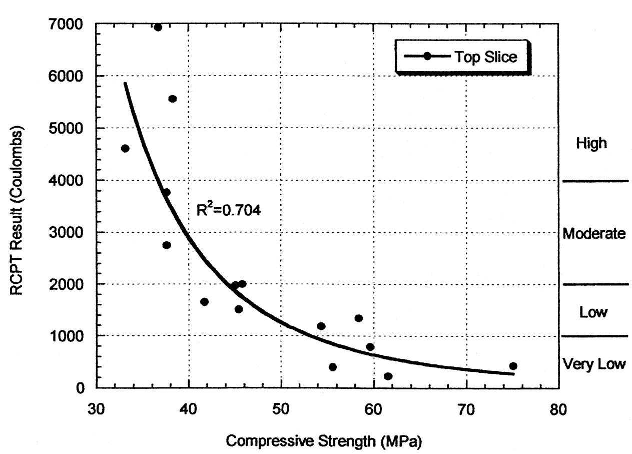

Fig. 3. Long-term RCPT result versus compressive strength relation for pavement concretes from field study. Permeability values are for the upper portion of the concrete. All values are averages for each test section.

A similar trend was found by Armaghani et al. [20]. They also noted the tight relation at higher strength and lower chloride penetration, with increasing scatter in RCPT results at the lower strength end of the relation. Shilstone [21] also recognized the importance of permeability, indicating that both high strength and low permeability were needed to ensure good performance.

Fig. 3 suggests that increases in strength produce lower and lower chloride penetration levels. From a durability perspective, continued strength increases are beneficial, and there is no need to put an upper limit on strength. Where very low permeability or chloride penetration is needed, it can be achieved by increasing strength. However, it is also seen that good long-term permeability can be achieved without very high ultimate strength levels of above 55 to 60 MPa. Thus, very high strength is not needed for most applications. This is important in several ways. Primarily, there is economic importance, as increased strength is usually associated with increased cost. In addition, very high strength can lead to negative effects on other concrete properties, such as increased brittleness, high autogeneous shrinkage, and thermal deformations at early ages [22,23].

Another important observation from the compressive strength versus RCPT relation is that very low RCPT levels are indeed observed at the high strength end of the curve. The indication is that OPC concretes, without the help of mineral or chemical additions, can produce good to excellent ultimate permeability levels when higher ultimate strengths are achieved. However, it should be noted that the OPC concretes require a long time to reach these permeability levels. The studied concretes have had ample opportunity to develop such low permeability levels in the field. It is known that the use of mineral additives can significantly reduce permeability even at younger ages (e.g., Refs. [24,25]).

3.2. Torrent air permeability versus compressive strength relation

In Fig. 4, the air permeability is plotted against compressive strength. Compressive strength values are, as before, averaged across the entire concrete depth. In Fig. 4, air permeability is plotted on a log scale because the technique can span five orders of magnitudes in its readings. Air permeability results at the middepth of the concrete are used to avoid the surface region, which produces more variable results even on a saw-cut surface. Again average values for each test section are used for both strength and permeability.

As with the RCPT results, the relation between compressive strength and permeability for the tested pavements shows a high coefficient of correlation (R^2 = .83). In this case, a logarithmic function is used in the regression analysis. In both the RCPT and Torrent tests, the transition from moderate to low "permeability" class occurs at approximately 45 MPa. In climate regions where permeability and chloride penetration resistance are critical, this will become a threshold strength level to ensure adequately low permeability in typical OPC concrete pavements.

3.3. Florida FPT water permeability versus compressive strength relation

As with the air permeability test and the RCPT, water permeability exhibits a good correlation with compressive strength (R^2=.73). In Fig. 5, water permeability at the top of the concrete is shown versus compressive strength. As before, the compressive strength is averaged over the entire concrete thickness. All values plotted are averages for each pavement section.

The permeability data is again plotted on a log scale to cover the several orders of magnitude in readings, and a logarithmic function is used in the regression analysis. Some scatter in the water permeability data is observed. This is likely due to the configuration of the test setup, which measures only a small test area (1.25-cm high circular area and 2.2 cm diameter). This leads to higher variability in the data because of inhomogeneity in the concrete samples.

As with the RCPT and Torrent tests, the results of the water method also span a range of permeability classes. In this case, the moderate–low boundary is slightly higher at 50 MPa. The fact that all three methods are so similar in the strengths they require to reach low permeability for OPC concrete pavements adds a great deal of confidence to the recommended strength levels that will be presented.

It should be noted that there are several different water permeability testing techniques, and that each gives a different range of values and classification levels. This indicates that the measured permeability coefficients are test dependent, and do not represent an absolute or intrinsic material property of the concrete. Armaghani and Bloomquist [26] suggest that differences between methods are likely caused by test configuration differences and assumptions used in the derivations of the various permeability equations. However, these methods are valuable as qualitative measures of concrete permeability.

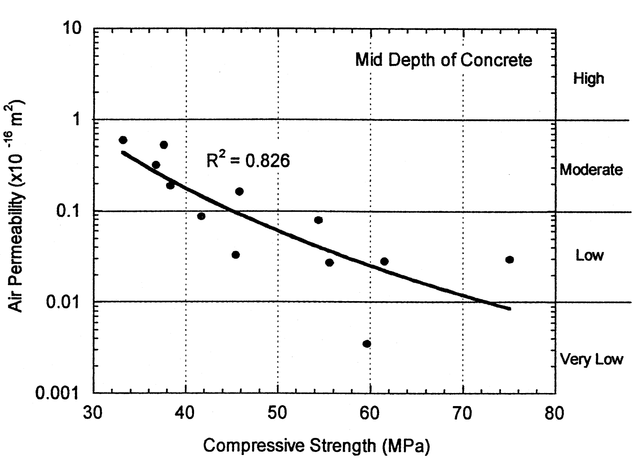

Fig. 4. Long-term air permeability at the middepth of the concrete versus long-term compressive strength for the pavement specimens. All values are averages for each test section.

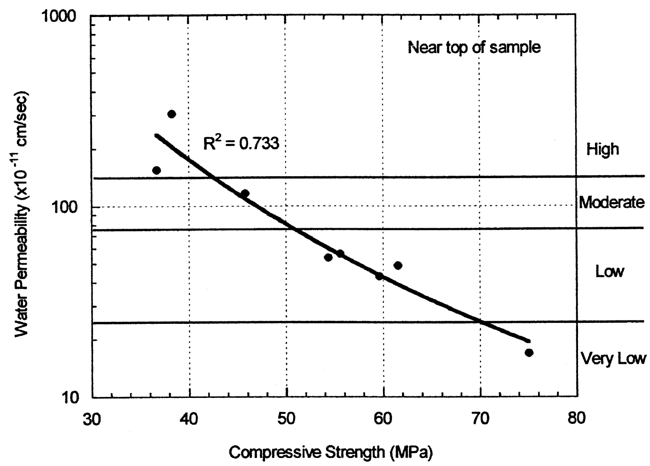

Fig. 5. Water permeability versus compressive strength for the pavement specimens near the top of the sample. All values are averages for each test section.

4. Discussion

4.1. Importance of climate region on required permeability levels

Environmental exposure influences the measured concrete properties such as strength and permeability. The impact of environmental exposure on long-term permeability in the various climate regions and the importance of achieving low permeability in the various climate regions are of interest.

In this section, RCPT results are used to demonstrate the desired trends and observations. The RCPT results are used here primarily because a large number of dependable data points are available. Similar observations can be made with the other methods.

If the data in Fig. 3 is broken down by climate region, as seen in Fig. 6, it can be noted that the majority of "high" (above 4000 C) RCPT value pavements fall in the dry-no-freeze climate region. These are California pavements (06-3017 and 06-3021). The Georgia concrete (13-GA1-5) shows a similar response, but is classified as a wet-no-freeze section. This is also logical, because the hot Georgia summers resemble southern California's climate for much of the year. For these good performing pavements, permeability does not appear to be a critical factor.

Other wet-no-freeze concretes, such as those from the cool, wet Washington state climate in the Seattle area (test sections 53-3011 and 53-3812) have consistently "very low" RCPT values. These two pavements likely exhibit very low permeability because they have experienced ample curing with moderate temperatures and high precipitation amounts. For these concretes such low permeability may not be needed.

It is believed that the hot dry climates of Georgia and southern California lead to a more porous microstructure and the occurrence of cracking. Both of these factors would lead to high permeability and chloride penetration, while decreasing the concrete strength. The water permeability test, in particular, appears to be highly sensitive to cracking, as test pressure opens up cracks and makes meaningful data impossible to obtain. It can be noted that several of the test sections, particularly those from the hot dry regions, exhibited such cracking. Several researchers have recently demonstrated that permeability and chloride penetration are significantly increased by cracking in the concrete [27,28].

The concretes in the wet-freeze region exhibit at worst "moderate" permeability, and in several cases "low" to "very low" permeability and RCPT values. These concretes include the Iowa (19-3006 and 19-3055), Ohio (39-3801), Wisconsin (55-3008), and Minnesota (27-4054) sections. Such pavements can be expected to require much greater protection from deicing salts and freeze–thaw damage. Thus for those pavements to perform well, lower permeability is essential.

While the importance of permeability in different climate regions can only be inferred from the limited field study, it is not surprising to find that the permeability levels break down roughly by climatic region. Since nearly all of the studied pavements had good performing concretes, it would be expected that those with higher permeabilities would fall in climates where permeability is less of a factor.

4.2. Variation of permeability with depth

In each pavement section, the highest permeability or RCPT value is in the top slice of the concrete near the surface. This is likely caused by a combination of curing

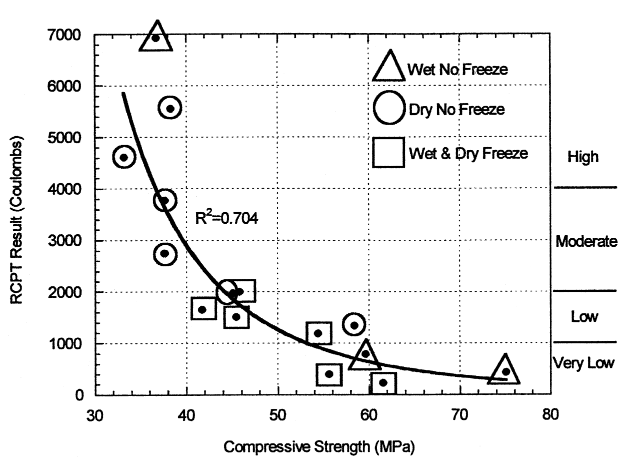

Fig. 6. RCPT results versus compressive strength relation broken down by climate region.

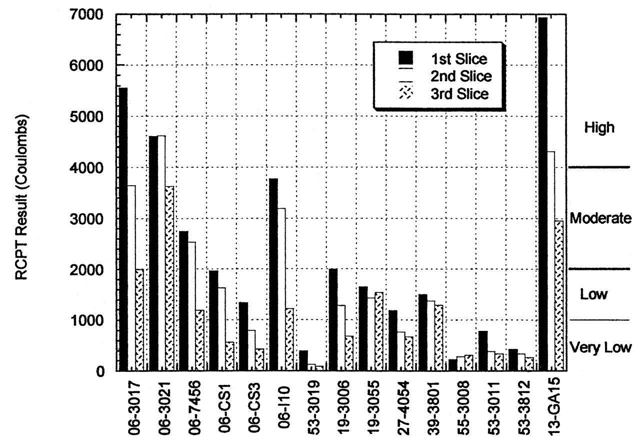

Fig. 7. RCPT results at three depths within the concrete. The first slice is nearest to pavement surface. All values are averages for each test section.

and environmental factors. For the field concretes, successively lower samples within a specimen yield lower permeabilities and RCPT values.

In some cases this drop can be significant, with the RCPT value of the top slice being four or more times that of the third slice from the top. The pavements vary by as much as two RCPT classes through their depth (see Fig. 7). This is most evident in the hot climates, where the surface concrete can exhibit very high permeability. The California concrete (06-3017) for example jumps from "high" at the top to "low" at the third slice. The high permeability in the upper portion of the pavement is most likely caused by a combination of curing related factors. Evaporation and thermal gradients can alter the degree of hydration near the surface, increasing the porosity. At the same time, distresses like shrinkage cracking and bleeding can open porous channels in the concrete that increase interconnected pore spaces near the surface [2,29]. The wet-freeze sections also tend to have higher permeability near the surface. However, this is most likely due to distress and salt ingress related to the harsh environment.

The wet-no-freeze sections from Washington State, which have most likely had the most uniform curing in their wet, temperate climate, also exhibit fairly uniform through-thickness permeability values. In general, the lower permeability sections exhibit the most uniform through-thickness behavior. Samples cast in the laboratory do not show significant through-thickness variation.

5. Conclusions

The durability of pavement concrete can be defined as its ability to resist chemical and physical attack, primarily from environmental exposure. In this study, durability is measured through concrete permeability and chloride penetration resistance. A low permeability reduces the ingress and movement of water, salts, and other pollutants, and is therefore beneficial.

Concrete permeability and chloride penetration resistance of OPC concrete pavements are closely related to compressive strength. Higher compressive strength results in lower permeability. Thus the increased compressive strength in higher strength concretes is associated with low permeability, and in turn improved durability. Based on the limited field study, it appears that a long-term compressive strength on the order of 45 to 50 MPa is required to ensure low permeability and chloride penetration for good performing OPC concrete pavements not containing mineral additives such as fly ash or slag.

Furthermore, the improvement of permeability becomes decreasingly significant with higher and higher strength. Thus, ultimate compressive strengths exceeding approximately 65 MPa provide little additional benefit from a durability point of view.

Establishing the desirable strength range to achieve needed diffusion levels appears to be highly dependent on the climate region in which the pavement is to be placed. Low permeability would be recommended for pavements placed in "freeze" environments, where the use of deicing salts and the occurrence of numerous freeze thaw cycles are prevalent. In nonfreeze environments, particularly desert climates, there does not appear to be any permeability requirement, so no strength requirements are needed from a durability perspective.

Through-thickness variation of permeability and RCPT results is evident in field concretes, and is most significant in hot dry climates. The permeability decreases with depth in the pavement, highlighting the effect of curing and exposure on the long-term permeability. For the sake of evaluating overall pavement durability, though, the top portion of the concrete that is most subjected to environmental effects is most critical. This layer acts as a protective buffer for the underlying concrete and steel reinforcement.

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