WHAT DOES THE CONCRETE RESISTIVITY TEST REALLY MEASURE?

The Standard Method of Test for Electrical Resistivity of a Concrete Cylinder Tested in a Uniaxial Resistance Test (AASHTO TP119) and the Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration (AASHTO T358) are used to measure the overall resistivity of the specimen, which includes the effect of the microstructure and the resistivity[i] of the pore solution.[1,2]

Two types of concrete with the same resistivity, therefore, can have very different microstructures and potential durability (Figure 2).

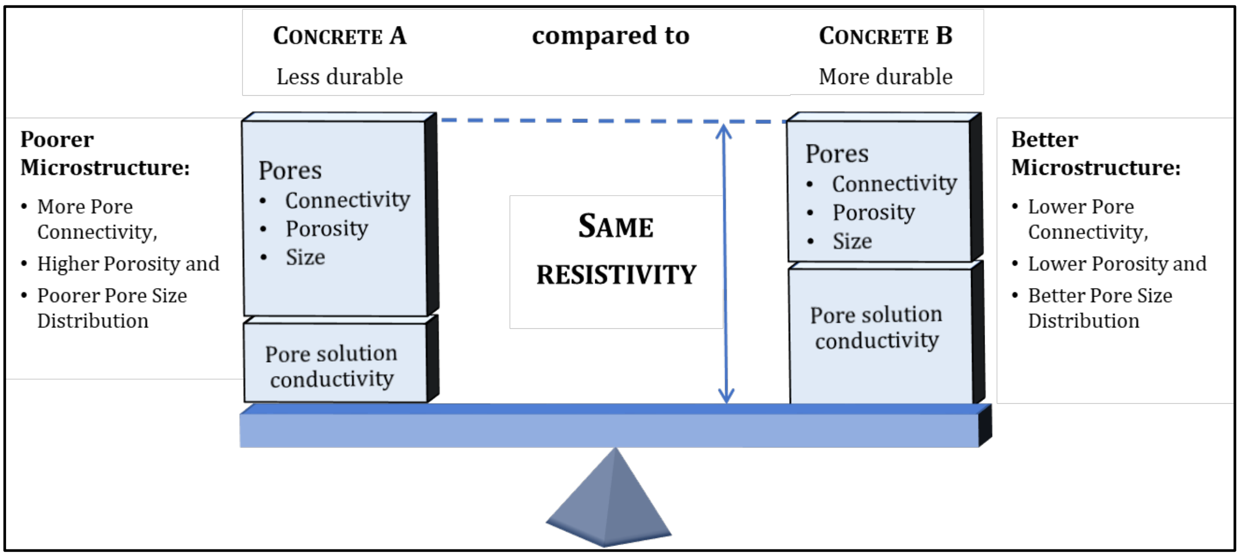

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Figure 2. Chart. Two saturated concretes with the same resistivity but different potential durability resulting from different pore structures.

WHY SHOULD WE USE THE FORMATION FACTOR INSTEAD?

The formation factor is not a new concept but just recently has gain interest in the concrete industry.[3] Formation factor is the ratio of concrete resistivity to its pore solution resistivity. It is equivalent to the inverse of the product of porosity and pore connectivity, as shown in the equation in Figure 3. The formation factor has a direct relation to concrete's bulk diffusion coefficient.[4] The formation factor is used as an input into the durability models used in a performance related specification (PRS) framework.

When used instead of concrete resistivity, the formation factor provides an indication of the total pore volume and how the pores are interconnected among each other. These parameters are directly related to concrete's durability, consequently the formation factor can be used for lifecycle analysis modeling.[5,6]

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[i] Conductivity is the inverse of resistivity.

$$F = \frac{\rho}{\rho_0} = \frac{1}{\varphi . \beta}$$

Figure 3. Equation. Formation factor.

Where:

F	=	Formation factor	φ	=	Concrete porosity
ρ	=	Concrete resistivity (bulk or surface)	β	=	Concrete pore connectivity
ρ_0	=	Pore solution resistivity			

To calculate the formation factor, as shown in the equation in Figure 3, the resistivity of the concrete (either surface or bulk) and the resistivity of the pore solution are needed. The resistivity of the pore solution can be obtained in several ways. PP84-18(7) proposes the three approaches (Figure 4). Figure 4 also includes a fourth method. The flow chart in Figure 4 describes each method from left to right as follows:

- Measure it experimentally. For that, the pore solution is expressed from the concrete and the solution resistivity is measured.(8) This is a complex process that requires special equipment and skills.
- Use mathematical models to estimate pore solution resistivity based on the mixture proportions and the materials used. Bentz et al. developed a simplified model for this estimate, which is normally referred to as the NIST model.(9) Two main issues have been raised regarding using this model:
    - Its reliability, especially for estimation of pore solution resistivity of binary and ternary mixtures. For example, Figure 5b shows about 60 percent average error in estimating the pore solution resistivity of fly ash mixtures.
    - Alkalis (Na^+ and K^+) are the main contributor to electrical conductivity (inverse of resistivity), but they leach out of the concrete when specimens are cured in a moist room or in lime-saturated water. This effect is expected to increase the errors in Figure 5. Alkalis leaching out of the concrete not only pose a problem by increasing the error on the resistivity estimation, but also creates conditions in which the specimen is no longer similar or representative of the concrete placed in the field. Figure 6 shows the measured K^+ concentrations in the limewater used to cure each of the 4 concrete mixtures over a 56-day period. As shown, significantly different amounts of K^+ were observed to leach out of samples from different mixtures.
- Assume a value of 0.1 Ω.m per AASHTO PP84-18.(7)

“Bucket Test”

The “bucket test” was proposed to streamline the formation factor calculation. Despite its name, however, the “bucket test” is not a test but a method for curing and conditioning specimens. Using the “bucket test”, the specimens are placed in a designed synthetic solution of Na^+, K^+, Ca^{2+}, OH^-, instead of a standard lime-saturated water bath or moist room. The composition of this synthetic solution, and consequently, its resistivity, is known. The “bucket test” was proposed because it could resolve the two issues previously mentioned: alkalis leaching, and the need to measure the pore solution resistivity.

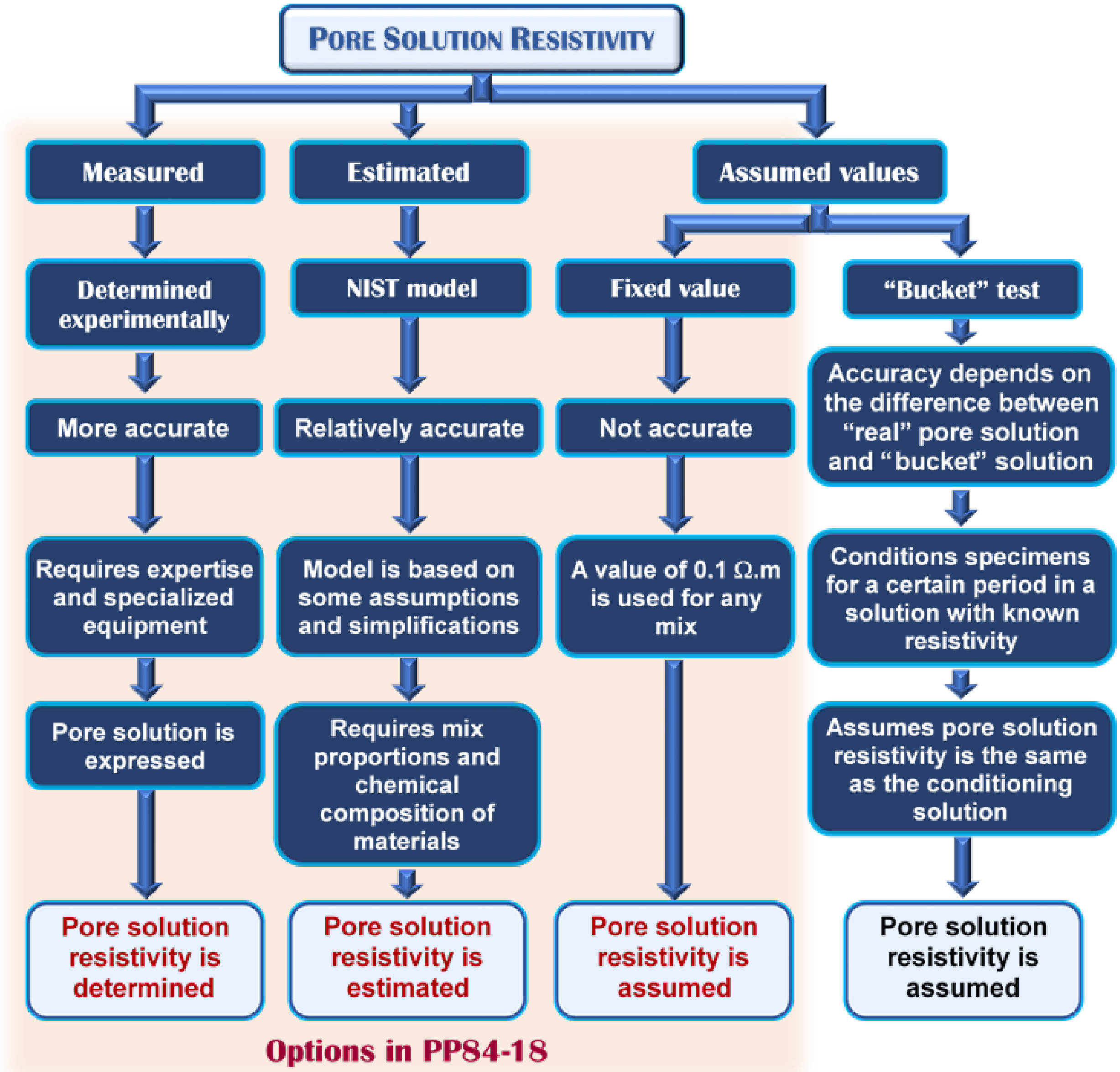

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Figure 4. Flow chart. Area with light red background represents the three AASHTO PP84-18[7] options to obtain the resistivity of the pore solution. On the right-hand side, a recently proposed option for pore solution resistivity, known as “bucket test,” is shown.

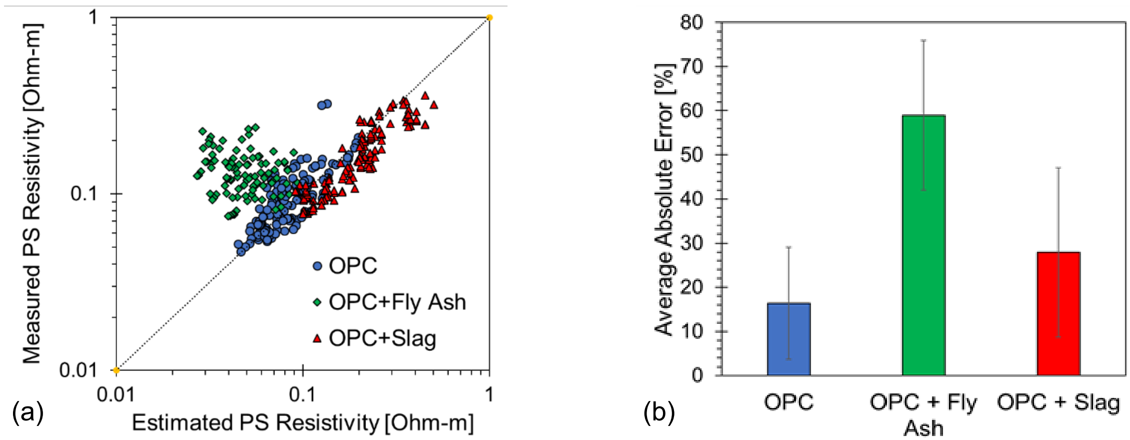

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Figure 5. Graphs. Pore solution resistivity estimation according to Bentz et al.[9] All tests were carried out on specimens that were sealed cured and not exposed to alkalis leaching: (a) Comparison between measured pore solution resistivity and estimated pore solution resistivity (b) Average absolute error of estimation. Total of 67 mixtures considered, with minimum w/cm = 0.30, maximum w/cm = 0.56. Mixtures included: 25 ordinary portland cement (OPC) mixtures, 42 binary mixtures, where 19 contained fly ash (20 percent to 60 percent of fly ash), and 23 contained slag (20 percent to 76 percent of slag).

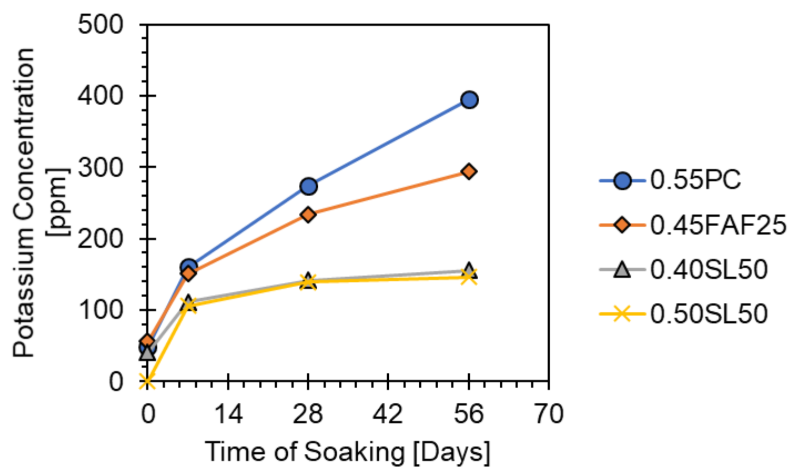

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Figure 6. Graph. Potassium leached from specimens cured over a 56-day period in limewater (specimen/limewater volume ratio of 1:2 and a pore volume/limewater ratio of approximately 1:13). Mixtures nomenclature: first number refers to w/cm ratio; PC stands for portland cement; FAF stands for class F fly ash; SL stands for slag cement; last number refers to the percent replacement in mass for binary mixtures.

Alkalis leaching is minimized when the solution used in the bucket has a composition approximating the composition of the expected concrete pore solution.

If the pore solution resistivity is already known, there would be no need to measure it. In the "bucket test," it is assumed that pore solution in the specimen eventually equilibrates with the pore solution in the bucket. The specimen would have the same resistivity as the solution in the bucket, resulting in the equation in Figure 7 for the formation factor.

$$F = \frac{\rho}{\rho_{bucket}}$$

Figure 7. Equation. Formation factor calculation for the "bucket test".

Where:

ρ	=	Concrete resistivity (bulk or surface).
ρ_{bucket}	=	Resistivity of solution in the bucket = pore solution resistivity of specimen.

It is uncertain, however, if the curing solution in the bucket can penetrate the specimen sufficiently such that the resistivity of the pore solution specimen matches the one in the bucket. If it does not, then the resulting formation factor may overpredict or underpredict the formation factor because the bucket solution is not the same as the pore solution. Choosing the correct curing solution is the key point for this approach (Figure 8), because it leads to a lower error in the pore solution resistivity estimation.

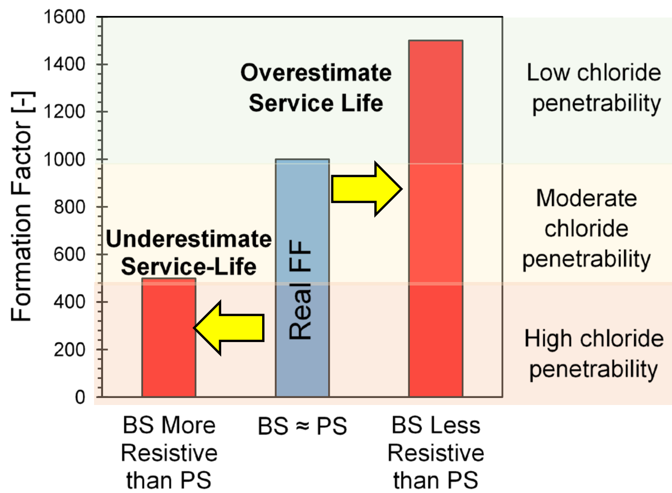

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Figure 8. Chart. Effect on formation factor of assuming a bucket solution (BS) with resistivity equal, higher, or lower than that of real (measured) pore solution (PS). Chloride penetrability ranges are based on AASHTO PP84-18.[7]

FILLING THE GAPS ON THE FORMATION FACTOR – CURRENT RESEARCH AT TURNER-FAIRBANK HIGHWAY RESEARCH CENTER

Researchers at the Federal Highway Administration's Turner-Fairbank Highway Research Center (TFHRC) are working on closing the gaps for the reliable determination of the formation factor. The research on the formation factor can be summarized as follows:

Aspects related to concrete resistivity

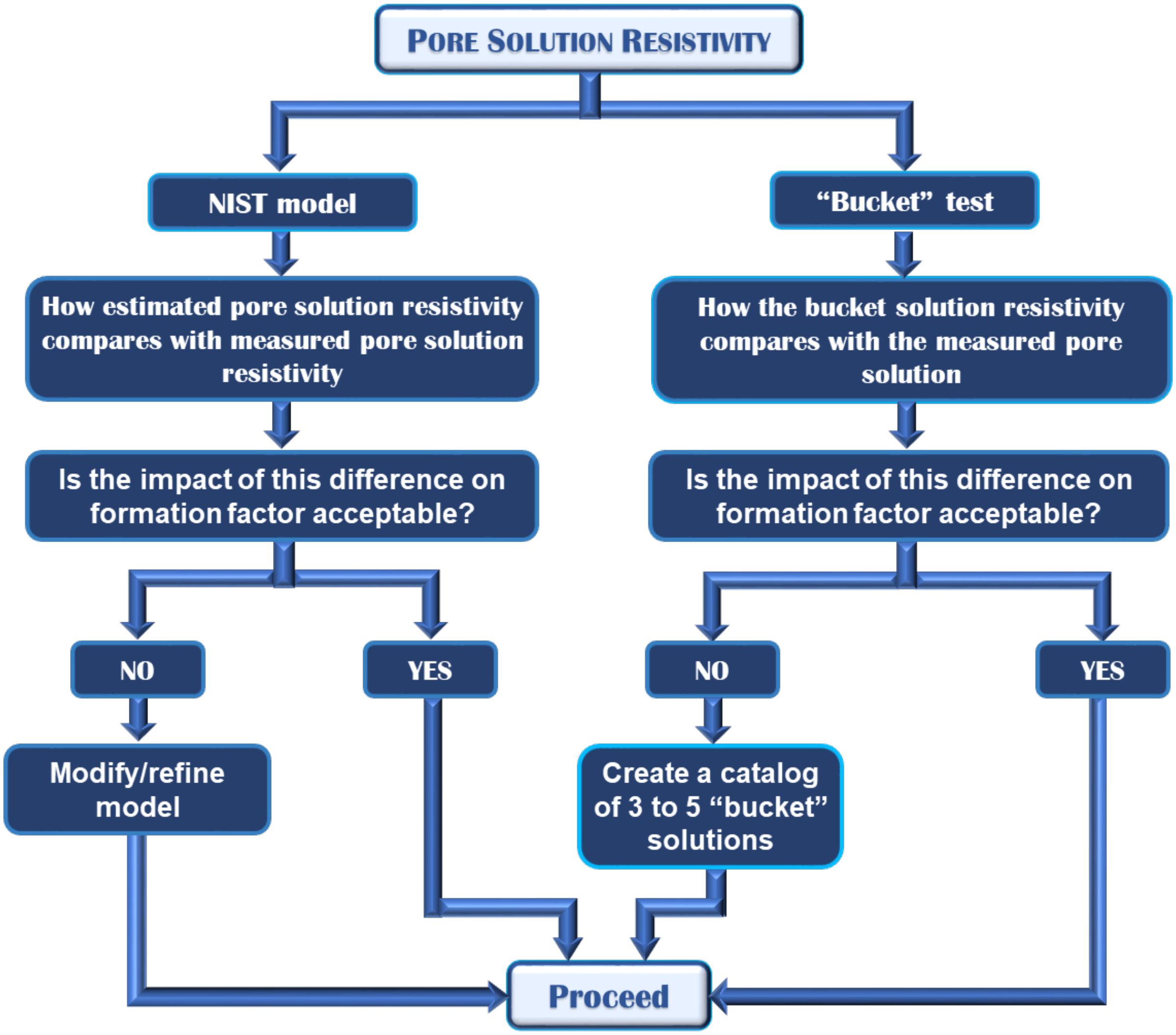
Degree of saturation (DOS): Previous research has shown that the resistivity of concretes is affected by DOS[10,11,12] and temperature.[13,14,15] Research suggests that a correction needs to be applied to the results of concrete resistivity with DOS lower than 100 percent and with a correction of the temperature outside a certain narrow range (21 °C to 25 °C). A collaborative study between TFHRC and *National Ready Mixed Concrete Association* (NRMCA) is looking at how seven different curing regimes affect the DOS and degree of reaction.

A sensitivity analysis will examine the impact of DOS on the formation factor, comparing actual values with simulations, and determine the need to correct the concrete resistivity based on DOS.

Aspects related to pore solution resistivity

Figure 9 shows a simplified flow chart for the research at TFHRC using two different approaches for obtaining the resistivity of the pore solution: the NIST model and the bucket test.

- NIST model: Inputs affecting capability of the NIST model to predict the pore solution resistivity will be considered. In addition, the mathematical model itself will be analyzed and modified or refined if needed. Parameters considered for further investigation in the NIST model include:
    - Degree of hydration (DOH): One of the inputs for the model is the DOH and/or degree of reaction (DOR). A sensitivity analysis will be conducted to evaluate the impact of DOH or DOR on the NIST estimate and whether the error on the formation factor obtained is significant when comparing actual values with simulations.
    - Free alkali factor (default value 0.75): Preliminary data showed that there is a need to better estimate the free alkali content (one of the model's input) for binary and ternary mixtures instead of using a fixed value.
    - The NIST model considers only sealed curing and may need to be modified to include other curing conditions.
- "Bucket test": In addition to the mixtures that are part of the collaboration with NRMCA, TFHRC intends to consider typical State DOT mixtures. If a single bucket solution yields an unacceptable error on the formation factor, a catalog of three to five bucket solutions can be created to represent typical DOT mixtures' pore solutions. DOTs could choose a bucket solution from this catalog based on their specific mixture that would result in a good approximation of the formation factor.



Source: FHWA

Figure 9. Flow chart. Research approach related to the pore solution resistivity.

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Key Words— formation factor, pore solution resistivity, concrete resistivity, bucket test, concrete durability, degree of saturation, degree of hydration.

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