1. Introduction

Recent trends in concrete design, especially in pavement design, have been towards high early strength concretes, meeting design specifications well before necessary. These high early strengths are usually achieved by high cement contents, causing often overlooked secondary effects, such as drying shrinkage (Figure 5), which can result in cracking and premature durability problems. In order to have an effective PCC mix design, all such effects should be considered. The 1st and 2nd order issues are recognized as:

1st Order Issues
- strength
- often times rapid strength gain
- workability

2nd Order Issues
- shrinkage
- fracture properties
- load transfer
- economy
- appropriate strength development rates

This literature review, conducted using common concrete textbooks, considers all of these competing issues in constructing a concrete mix design theory which will help optimize the O’Hare Modernization Program’s PCC Mix Design to deliver a durable and efficient concrete. Based on these theories, a multivariable testing program will be devised, the results of which will likely be utilized in dictating the specifications for the new concrete runway pavements at the O’Hare International Airport.

2. 1st Order Issues

A typical compressive strength versus water/cement (w/c) ratio curve is presented in Figure 1. The Modulus of Rupture has an empirical correlation with compressive strength, presented in Figure 2. As the compressive strength increases, the ratio of the modulus of rupture to compressive strength ratio will decrease, confirmed in other
findings reported in Table 1. The general trend, however, is that both the compressive and flexural strengths increase substantially within the first 28 days. As specifications often call for 28 day strengths, mix designs conservatively satisfying this strength criterion within 7 days may well be over-designed in one respect (strength) and deficient of others (shrinkage, etc).

Our testing program will consider the use of 1½” top size coarse aggregates as well as the normal ¾” top size. The larger aggregate top size will lead to a somewhat lower compressive strength, an effect that is more pronounced at lower w/c ratios (Figure 3). From the plot, however, it can be seen that with the expected w/c ratio of around 0.40, a change from ¾” to 1½” will decrease the compressive strength by less than 10%. This increased top size will result in more well graded aggregates, possibly leading to a larger aggregate fraction (to be discussed later), and may also improve 2\textsuperscript{nd} order properties such as fracture and aggregate interlock.

The final suggested specification for this study, workability, is crucial for concrete runway pavement design because the pavement is typically slipformed. Workability is, however, not considered in the core of this program as it is a variable easily regulated by the contractor via chemical admixtures and proper final mix design. Although not considered in the mix design, the fresh concrete properties such as slump will be recorded during the laboratory testing portion of this mix design, providing a rough idea of workability.

3. 2\textsuperscript{ND} Order Issues

Two important secondary effects are shrinkage and appropriate strength development rates. Figure 4 shows the influence of w/c ratio and aggregate content on shrinkage. Typical aggregate contents are at least 70% by volume but can be increased by a more graded aggregate sample, possible with a larger aggregate top size. As can be seen in Figure 4, if high enough aggregate contents are achieved, shrinkage can be greatly reduced at any w/c ratio. Shrinkage as a function of cement content, water content, and w/c ratio is presented in Figure 5. It is suspected that neither Figure 4 or 5 considered autogenous shrinkage (both were referenced to journal articles published before 1980). Neville noted, “In practical terms, at a constant water/cement ratio, shrinkage increases with an increase in the cement content because this results in a larger volume of hydrated cement paste which is liable to shrinkage. However, at a given workability, which approximately means a constant water content, shrinkage is unaffected by an increase in the cement content, or may even decrease, because the water/cement ratio is reduced and the concrete is, therefore, better able to resist shrinkage”. As the w/c ratio is lowered, the shrinkage becomes less dependent on cement content, being true until the w/c ratio is below around 0.40 and autogenous shrinkage dominates (not depicted in Figure 4). The scope of investigation for this plot is from 300-800kg/m\textsuperscript{3}, a much larger scope than will be considered during our design process. Traditionally, O’Hare mixes contain as much as 350kg/m\textsuperscript{3} cement but the expected new designs will be around 250kg/m\textsuperscript{3} (both with around 60kg/m\textsuperscript{3} fly ash). These numbers are in the range where the w/c ratio curves are
converging and the shrinkage greatly reduced. Cutting the cement content will also reduce the strength gain development, causing it to better follow the intended strength rate development curve.

Other secondary effects which are of consideration are fracture properties, load transfer, and economy. Fracture properties are expected to be heavily dependent on coarse aggregate top size and, although they will not be considered during the first rounds of testing, the fracture properties of all mixes will be noted and further testing altered accordingly. Load transfer, much as fracture properties, is dependent on coarse aggregate top size and will be treated in a likewise manner. The effects on economy are easily realized when noting that cement is responsible for a large portion of total materials cost, especially considering the current shortage, and the new mix designs will have a much lower cement content than the past high early strength/ high cement content mixes.

4. OMP Laboratory Test: Approach

The specified 28 day Modulus of Rupture (MOR_{28}) values are expected to be around 700psi for the airport pavements at O’Hare. The goal of this laboratory testing initiative is to recommend design specifications (minimum w/c ratio, max paste content, fly ash content, coarse aggregate nominal top size, etc) which will ensure a qualified concrete mix to conservatively meet this MOR_{28} while also optimizing the often ignored secondary effects.

Using known data/plots for compressive strength versus w/c ratio and an empirical formula for MOR as a function of compressive strength, a MOR versus w/c ratio plot can be constructed for mixes at different ages (i.e. 7, 14, and 28 days). Laboratory tests will then be run on mixes similar to the standard O’Hare and St. Louis Lambert Airport mixes in an attempt to isolate where a suspected minimum prescribed w/c ratio might fall. On this more accurate plot, the minimum specified MOR_{28} of 700psi will yield a maximum w/c ratio. From this w/c ratio limit, another w/c ratio will be specified roughly one standard deviation of MOR_{28} away, resulting in a minimum w/c ratio. Any w/c ratio falling between these two limits should result in sufficient flexural strength, although only a minimum w/c ratio will be specified. This innovative means of indirectly specifying strength by a minimum w/c ratio and other specifications can more easily be regulated in the field, as the batch ticket reports the minimum w/c ratio. It is also notable that there is no concern of quality control issues emerging from extra water added to a mix at the time of placement for workability issues as this can only raise the w/c ratio, keeping it within specifications.

Having a minimum w/c ratio set and assuming that the fly ash content will be 20-25% of the cement content, w/c ratios in the normal range, coarse aggregate nominal top size and cement content will be varied to investigate the shrinkage, aggregate interlock and fracture properties. This data will result in a suggested specification for paste content limits and a recommendation for the possible use of larger than normal coarse aggregates.
5. Figures and Tables

Figure 1. Influence of the water/cement ratio and moist curing age on concrete strength.\textsuperscript{1}

Figure 2. Modulus of rupture versus compressive strength for normal-weight concretes.\textsuperscript{2}
Figure 3. Influence of the aggregate size and the water/cement ratio on concrete strength.\textsuperscript{1}

Figure 4. Influence of water/cement ratio and aggregate content on shrinkage.\textsuperscript{3}
Figure 5. The pattern of shrinkage as a function of cement content, water content, and water/cement ratio.

Table 1. Relation between compressive, flexural, and tensile strength of concrete.

<table>
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<tr>
<th>Strength of concrete (psi)</th>
<th>Modulus of rupture</th>
<th>Tensile</th>
<th>Ratio (%)</th>
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<th>Tensile strength to compressive strength</th>
<th>Tensile strength to modulus of rupture</th>
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<td>Tensile</td>
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<td>Tensile strength to modulus of rupture</td>
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6. References

