A CONCRETE STRENGTH MODEL TO OPTIMIZE CONCRETE MIXTURES

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Instructions on using the Excel Spreadsheet for the Concrete Strength Model (CSM): Concrete Strength Model.xlsx
And Spreadsheet for Mixture Proportions and Strength Data
CSM_batch_strength_calc.xlsx

USING THE MODEL AND LIMITATIONS

An Excel spreadsheet has been developed to predict strength of mixtures using this model based on data developed from several specifically recommended trial batches. The spreadsheet includes four tabs:
- User Instructions – access to the user's guide (pdf)
- Trial Batches for user input;
- Strength Prediction; and
- Concrete Mixture Constants.

Trial Batches

Three sets of trial batches of concrete are required to *calibrate* the model for the specific materials used:

Set 1 — Mixtures with cement only; do not use chemical admixtures or SCMs.

Set 2 — Mixtures used in Set 1 with chemical admixture.

Set 3 — Mixtures used in Sets 1 and 2 with the addition of an SCM, such as fly ash.

The accuracy of the strength predictions by this model relies on the accuracy of the data generated from the trial batches. The following are important:
- Accurate weights of materials for the trial mixtures;
- Accurate moisture content of each aggregate used – absorption and total moisture before batching
- Accurate density (unit weight) for each batch mixed;
- If several batches will be mixed, a larger quantity of aggregate should be stockpiled and properly mixed before quantities are extracted and weighed for the batch; and
- A representative sample of the aggregate should be taken before each concrete mixture is made to determine the total moisture content of the aggregate. Accurate measurements of aggregate moisture and associated concrete mixing water content is critical for the model to accurately predict strength.

The size of the trial batch will depend upon the amount of concrete needed for the tests performed, and the number of cylinders cast. The required tests are slump, density (unit weight), and air content by the pressure method. The **density of fresh concrete is required** and the model will not use the data for any mixture if this is not input in the spreadsheet.

Concrete used to perform slump, density, or air content tests should not be used to cast cylinders. Before a trial batch is introduced, the mixer should be *buttered* by using a smaller batch mixture similar in proportions to the first batch that will be mixed. The *buttering* mixture is introduced into the mixer and mixed for a couple minutes and discharged so that the inside of the mixer is adequately coated with mortar. The mixer is now ready for the first trial batch and subsequent batches if they are made in reasonably quick order after the first. If there is going to be a long delay between subsequent trial batches, such as overnight, the mixer should be washed out and buttered again before the subsequent trial batches are mixed.

Trial Batch Quantities

On the "Trial Batches" tab of the Excel spreadsheet input the specific gravity of all the concrete materials in row 10.

Assume the following trial batch quantities in lb/yd^3:

Cement	= 600
Mixing water	= 300
SSD sand	= 1135
SSD coarse aggregate	= 1750
Total weight	= 3785
Theoretical unit weight	= 3785 ÷ 27 = 140.14 lbs/ft^3.

Every Trial Batch **must** include a Name of ID for the mixture input Mix Name/ID field. If this field is not filled, the calculations will not be performed.

Input the batch quantities in the appropriate locations in the spreadsheet. Batch quantities should be based on SSD aggregates and actual mixing water content after adjustment for aggregate moisture content. Record slump, air content measured by the pressure method, and density (unit weight). If the adjustments for moisture content have been done correctly and the air content is on target, and the batch quantities for the laboratory trial batch have been correctly determined, the measured density (unit weight) should be close to the theoretical unit weight.

To achieve this, it is critical that the moisture content of the aggregates is accurately measured. If aggregates used have a low absorption (<1.0%), the lab may consider using air-dry aggregates. This requires a large indoor space to spread out enough sand and aggregate for a period of time to dry to a stable moisture condition. Once a stable aggregate moisture content is achieved, the water content of all trial batches will be reasonably accurate. This procedure was used by the USBR laboratories in Denver. When aggregates are in an air-dry condition, the batch weight of water will be greater than the mix design mixing water content to account for the water that will be absorbed by the aggregates. With aggregates that have a higher absorption, prepare the aggregate in a moisture condition greater than SSD and make the appropriate adjustment to the weight of batch water.

All this extra effort is to ensure that the input on the concrete mixture proportions and w/cm is accurate to improve the accuracy of the prediction by the model. Once the model has been properly calibrated with the materials and the trial batches, it will be able to propose mixture proportions for target strength. For example, if the specified strength on a project is 4000 psi concrete mixture and the intent is to over-design by 1000 psi for a target strength of 5000 psi, the model will suggest the mixture proportions that will produce a target strength of 5000 psi at 28-days or other selected test age. The proposed mixture will vary based on the water reducing admixture dosage and the percent of SCM selected. The proposed mixture will also vary based on target air content.

Set 1 Mixtures

The first category Set 1 mixtures are entered in rows 11-20 in the "Trial Batches" spreadsheet tab. This permits 10 trial batches for this set. These mixtures are with cement only and should not contain water reducing admixtures or supplementary cementitious materials. Even though these are not typical mixtures used in practice, it is important to produce these mixtures to calibrate the model to the cement and aggregates used. Ensure that the rows are completed sequentially without leaving blank rows.

Trial batches for Set 2 and Set 3 concrete mixtures establish additional model *constants* for the water reducing admixture and supplementary cementitious materials used.

The recommendation for Set 1 is a minimum of five mixtures with varying w/c ratio that will average to 0.50. For example, the w/c ratios of 0.35, 0.45, 0.50, 0.55, and 0.65 will average to 0.50. The aggregate constants will be specific to the aggregates used, and if the average w/c is 0.50 these aggregate constants can be compared to other evaluations using different aggregates. A separate spreadsheet file should be used with different aggregates. The effect of air content on concrete strength is adequately addressed in the model based on the actual measured air content, thereby accurately achieving a target air content, such as 6.0% for all batches, is not necessary.

The five mixtures for Set 1, discussed above could be five non-air entrained mixtures or five air entrained mixtures or any combination of air entrained and non-air entrained mixtures. Set 1 mixtures are the most critical mixtures used to calibrate this strength prediction model. Preparing more mixtures, exceeding five, will improve the estimate of the model constants and improve its predictability. An ideal maximum number of Set 1 mixtures would 10 mixtures; five non-air entrained and five air-entrained mixtures. The average W/C ratio for the 10 mixtures should be 0.50.

The model uses the predicted volume of hydrated product to predict strength from these Set 1 mixtures. The model constants developed from the Set 1 mixtures will be unique or specific to the cement, sand, and coarse aggregate used in the mixtures.

Concrete Strengths (Ages)

The measured compressive strength at different ages are entered for each mixture in the same sheet and on the same row for each mixture. Fields are provided to record measured compressive strength at ages of 1, 3, 7, 14, 28, 56, 70, 90, 180, and 365 days. It is not required to test concrete for strength at all these ages. The user picks the ages for strength testing and makes the appropriate total number of cylinders. Accuracy of strength prediction is improved if three cylinders are tested at each test age, but two cylinders for each age is adequate. Record the average strength of the cylinders tested at the same age. If the user initially inputs the strengths for 3, 7, and 28-days, the model will develop preliminary estimates of the constants. If additional cylinders have been cast for testing at later ages, such as 90 and 365- days, these data can be added when available. The same test ages should be used for all of mixtures in this and subsequent sets.

The model can be used to propose mixture proportions to achieve strengths up to the maximum age tested (in the Strength Prediction tab). Or it can be used to predict strength of alternative mixture proportions to the maximum age tested (in the Strength Prediction tab). When planning the batches and its size, the different test ages and maximum age should be established. All cylinders to be tested at different ages should be prepared from the same concrete mixture.

Set 2 Mixtures

The second set of concrete mixtures contain water-reducing admixture(s). Input for Set 2 mixtures should be in rows 21 to 100. Each subset of mixtures with the same water-reducing admixture dosage should be entered in rows of 10, i.e. 21-30, 31-40, 41-50, 51-60, 61-70, 81-90, and 91-100. For the subset of mixtures in rows 21-30, use the most common dosage of water-reducing admixture, for example 5 oz/100 lb. cement (cwt). For example, if the most common dosage used is 5 oz/cwt, target a slightly higher dosage at around 5.05 oz/100 weight. The model will predict strengths for dosages of 5.0 oz/cwt. The model will show an error if a prediction is needed for water-reducing admixture dosage greater than 5.05 oz/cwt. Make concrete cylinders from these batches to be tested at the same ages as tested for the control mixtures in Set 1.

To improve the prediction accuracy for admixture dosage a second subset of mixtures with a different admixture dosage can be added in rows 31-40. The dosage can be lower than the commonly used dosage for mixtures in rows 21-30, which will improve the strength prediction for mixtures containing an admixture at dosage of 5 oz/cwt or lower. Alternatively or additionally, a higher target dosage, say 6.5 oz/cwt, could be used and prediction would work with water-reducing admixture dosages up to 6.5 oz/cwt.

In this model admixture dosage is based on the total weight of cement and supplementary cementitious material (which will only be used in Set 3 mixtures).

It is suggested, if possible, that a subset of mixtures in rows 21-30 or 31-40 etc. have an average w/c ratio of 0.50. However, this is not a strict requirement. It is also not essential to make 10 mixtures in each subset, but at least five is recommended.

If a user wishes to use a combination of two admixtures, the ratio of the dosage of the two admixtures should be fixed at say 50/50 or 75/25 for all mixtures in Set 2. A separate copy of the Excel file with the Set 1 mixtures included in rows 11-20 should be saved to input a different water reducing admixture or an admixture combination.

The space provided to input data for admixtures will likely not be needed. Space provided allows for seven dosage levels of water-reducing admixtures, one each for rows 21-30, 31-40, 41-50, 51-60, 61-70, 81-90, and 91-100. All these rows do not need to be filled in to establish the model constants for the admixture being used.

Set 3 Mixtures

The third set of concrete mixtures to be input in rows 101 – 200 should contain a supplementary cementitious material, such as fly ash or slag cement. Each subset in Set 3 should contain the same percentage of SCM by weight of cementitious material. Each subset with the same percentage of SCM should be input in sets of 10 rows: 101-110, 111-120, 121-130, 131-140, 141-150, 151-160, 161-170, 171-180, 181-190, and 191-200. Similar to concrete mixtures with water reducing admixture, the most common percentage of SCM should be input in rows 101-110, for example concrete mixtures with 20% fly ash. The user should target trial batches with quantity of SCM marginally greater than the target quantity, for example use 20.5% fly ash if the target quantity is 20%.

If a user wants to add use 50% SCM (use 50.5%) prepare these mixtures and input the data in rows 111-120. The model will calculate constants for SCMs for 0% replacement up to the maximum percentage used. In the first case the model determines a constant for 0 up to 20.5% (SCM mixtures in rows 101 – 110); in the second case for SCM content between 0% and 50.5%. Space is provided for 10 different percentages of SCM. For example, 10%, 20%, 30%, 40% SCM can be input in first four subset rows. If the user wishes to add percentages not previously used, for example 17%, these mixtures can be added in the next available spaces. It is recommended to prepare at least five mixtures for each percentage SCM for the model to accurately determine the SCM constant. These mixtures in Set 3 may or may not contain a water-reducing admixture. For the least variability with using a water-reducing admixture, use the same dosage per 100 weight of total cementitious for each of set of fly ash mixtures, if possible. If possible, for each group of mixtures the varied w/cm ratios used should average to 0.50.

For a different SCM or combinations of SCMs, such as slag cement and fly ash in the same mixture, save the file with the control mixtures in Sets 1 and 2 as a separate file to input the data for these mixtures. The ratio of the SCMs used in these combination mixtures should remain the same, such as 50/50 or 75/25 for the set of mixtures.

Changing Cement or Aggregate

Create a new model with a new file if a different cement or different set of aggregates is used.

Predicting Strength

The "Strength Prediction" tab can be used after information of Trial Batches has been input for all three sets of mixtures. There are two options:

Part 1: The user will first enter a mixture with the quantities of each material in Column "B" and the specific gravity of materials in Column "C". The user will suggest a chemical admixture dosage and percentage of SCM. The mix design and the WRA dosage and SCM contents should be within the range used for the trial batch mixtures for calibrating the model. The model will predict the strength for the mixture entered in Row 22.

Part 2: The user can enter a strength level in Row 28 and the model will suggest mixture proportions to produce that strength using the same coarse aggregate content, water-reducing admixture dosage, SCM percentage, and air content as input in Part 1. The fields in Part 1 have to be input for Part 2 to work.

Caveat

Strength Predictions are based on the accuracy of mixture proportions used and of strength data generated from the trial batches. Errors in a trial batch, even small ones like a small change in air content will result in a small prediction error. Prediction error increases with each material added. For example, the prediction error increases with an increase in entrained air, addition of an admixture, or with the addition of an SCM. The goal is to minimize the error in each trial batch. Increasing the number of trial batches will improve the prediction and decrease the prediction error resulting from an error in single trial batch for a set of materials.

The predictions in this model are based on trial batches made at laboratory temperatures and for standard cured strength test specimens cured in the laboratory. If specimens cured in the field is higher than lab temperature, the 28-day strengths will be lower, and vice versa. The author has data demonstrating why and how temperature changes strength; however, these changes are not included in this model.

Concrete Mixture Constants

The tab "Concrete Mixture Constants" in the spreadsheets reveal the constants generated for the cement only mixtures; for the mixtures with water-reducing admixtures; and for the mixtures with SCMs. These constants can be compared with constants generated by using different cements or aggregates at different locations by the same producer.

Mixture Proportions and Strength Data Spreadsheet

A separate spreadsheet is provided for calculating trial batch quantities and strength data. These data can be copied into the Concrete Strength Model spreadsheet.

The Batch Calculations tab performs two functions:

The mixture proportions based on SSD aggregate for 1 cubic yard are input into Part 1. When ready to prepare trial batches, measure the moisture content (and absorption) of the aggregates and input the size of the trial batch in cubic feet. The spreadsheet will provide the batch quantities for the trial batches based on wet aggregate weights.

Complete the trial batch and perform the fresh concrete tests.

In Part 2, input the actual quantities used for the trial batch, the measured slump, unit weight, and air content. The spreadsheet will calculate the mixture proportions in lb/yd^3 on the basis of SSD aggregates. This information is captured at the bottom of the sheet and can be copied and pasted (**AS VALUES**) into the Concrete Strength Model spreadsheet for each trial batch performed.

Use a separate spreadsheet for each trial batch.

The Strength Data tab can be used to record the information when measuring strength at different ages. Input all the required data to calculate the strength of individual specimens and the average strength at each age. These data are captured at the bottom of the sheet and can be copied and pasted (AS VALUES) into the Concrete Strength Model spreadsheet for each trial batch performed. If strength was not measured at specific ages, delete any "zero values" pasted in the main spreadsheet.

Use a separate spreadsheet for each trial batch.