Water-to-Cement Ratio and Aggregate Moisture Corrections

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Two of the most commonly specified requirements for concrete used in the manufactured concrete products industry are the design compressive strength (*f*' c) and the maximum water-to-cement ratio (w/c). These two values are inversely related, which means that as the water-to-cement ratio increases, the compressive strength decreases. Not only does the w/c ratio have a strong influence on compressive strength, but it also affects the permeability and ultimately the durability of the concrete. Both of these properties become extremely important when the precast product will be subjected to a corrosive environment or freeze-thaw conditions, or when it is required to provide a watertight structure.

Concrete is designed to withstand a certain maximum load per area before failing, known as compressive strength A number of factors influence the concrete's ability to withstand the force from an applied load, such as the size, type, quantity and gradation of aggregates, the type and quantity of cement and/or supplementary cementitious materials, the amount of mix water, the age or maturity of the concrete, and the production practices used in placing, consolidating and curing the concrete. Small changes in any of these variables can have a profound effect on the concrete's compressive strength, permeability and durability. To account for such variables, mixes are designed to meet an average or required compressive strength (*f*' cr), which is greater than the design strength. Procedures for determining the average or required compressive strength are addressed in chapter 5 of ACI 318 and are covered in the May/June 2004 *MC* magazine article titled "Standard Deviation" (available at www.precast.org).

Once general requirements such as the required compressive strength, air content and slump have been established, initial mix designs may be developed following the guidelines in ACI 211.1, "Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete."

Water-to-cement ratio
The maximum water-to-cement ratio may be established by the customer or

authority having jurisdiction based on anticipated exposure conditions. The target w/c ratio can also be selected from available data on the actual materials that will be used. If no such data is available the w/c ratio can be selected from table 6.3.4(a) of ACI 211.1 based on the required compressive strength. The lower of the two w/c ratios should be used for the mix design.

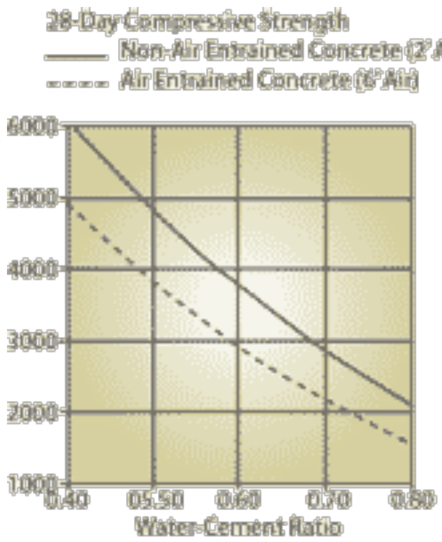
The water-to-cement ratio is the weight of water provided in a mix divided by the weight of cementitious materials. The total weight of water includes all batch water and free water from the surface of aggregates. If the amount of water is provided in gallons, it can easily be converted to pounds by multiplying the total gallons by 8.34 pounds per gallon. Cementitious materials include portland cement, blended cements and supplementary cementitious materials such as fly ash, silica fume and slag. Because of this, the water-to-cement ratio may be referred to as the water-to-cementitious materials ratio (w/cm). When calculating the w/c ratio, the total weight of all cementitious materials is used in the denominator.

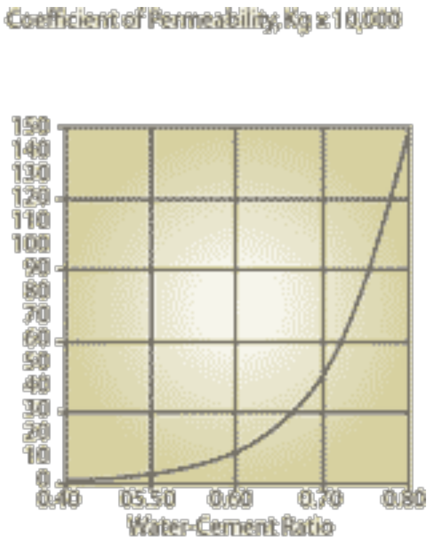
1 gallon of water = 8.34 pounds of water

$$w/c = \frac{weight\_water}{weight\_cementitious\_materials} = w/cm$$

Table 6.3.3 of ACI 211.1 may be used to select the required amount of batch water based on the desired slump and maximum aggregate size. The amount of cement and/or cementitious materials is then determined by dividing the selected water weight by the w/c ratio. As the amount of batch water is increased to achieve greater workability, so is the amount of cement in order to maintain the required water-to-cement ratio. The workability of a concrete mix is provided by the paste, which fills the voids between aggregates. The paste acts as a lubricant that reduces internal friction between aggregates while increasing workability. As the aggregate decreases in size, the amount of paste must increase to account for an increase in aggregate surface area.

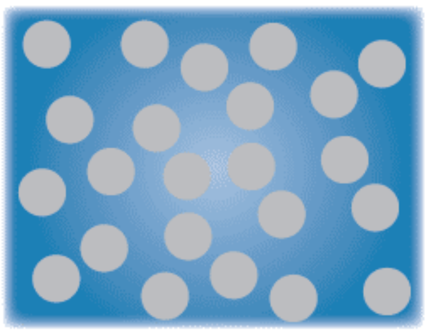
For both economical reasons and concerns with durability, it is often desirable to use the largest size aggregate possible to minimize the amount of paste in the system. Water-reducing chemical admixtures are often incorporated into a mix to achieve the required fresh properties for placing and consolidating concrete, ensuring that both a lower w/c ratio and a paste content can be maintained. Water alone should never be used to improve the workability of fresh concrete. Using water to assist in finishing operations or working bleed water back into the top surface of the concrete should also be avoided as these practices will increase the water-to-cement ratio of the top layer of concrete, which will lead to future durability problems.



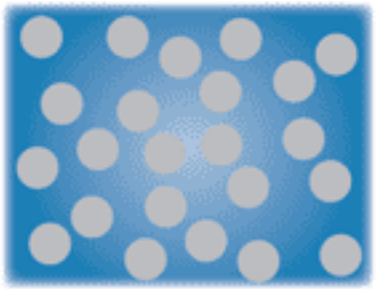


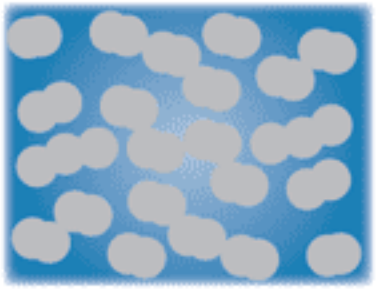
Hydration is the result of a chemical reaction that occurs between the cement and water. Initially the cement grains are dispersed throughout the system and are separated by water (Fig. 1 at right). During this stage of hydration, which typically occurs in the first 15 minutes, a rapid exothermic chemical reaction takes place, which produces a considerable amount of heat. Following this initial reaction, the hydration process enters a dormant period of any where from two to four hours. This dormant period allows for the transportation and placement of the concrete.

Rather than adding additional water to increase the concrete's workability, water-reducing admixtures can improve the dispersion of the cement particles to increase the workability.



Following the dormant period, the cement will continue to hydrate, producing reaction products that will begin to fill the voids between the cement particles (Fig. 2 at right). The formation of reaction products ultimately creates the binding material between aggregates. A basic mix will typically reach its initial set after about four hours of hydration. At this time, concrete is no longer workable and will typically have a compressive strength of about 500 psi. The cement will continue to hydrate, producing additional reaction products that will fill the voids provided by the initial mix water. As long as there is available room for the reaction products to form and water present to further hydration, the hydration reaction will persist and the concrete will continue to gain strength. However, once the available water has been exhausted or the voids have been filled, the hydration of the cement will cease and the strength gain of the concrete will plateau.

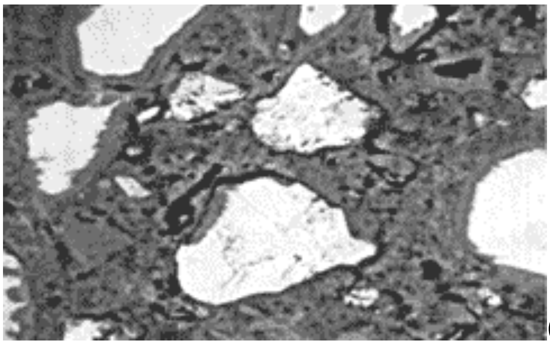




In theory, 100 percent hydration of cement can be achieved when enough water has been provided to react with the available cement and enough space has been provided by the initial mix water for the hydration products to form. Although 100 percent cement hydration does not actually occur, we will proceed as if it does. Roughly 1.1 unit volumes of water are required to completely hydrate 1 unit volume of cement, meaning that 1 cubic foot of cement will produce 2.1 cubic feet of hydration product formed from the available cement and water. This translates to a w/c ratio of 0.36. However, in order to achieve complete hydration, all the pores within the system must be completely filled with water throughout the hydration reaction. If a w/c ratio of 0.36 were used, the pores would not remain full during the entire reaction; thus to achieve 100 percent hydration, a w/c ratio of 0.42 is required.

Some concretes are produced with w/c ratios lower than 0.2 and as high as 0.7, although these ratios are not recommended for quality concrete. Concretes with higher water-to-cement ratios ultimately contain more water than is required for complete hydration of the available cement. This additional water creates additional voids known as capillary pores. As the w/c ratio increases, so does the capillary porosity, and it has a strong influence on the strength and permeability of the concrete as illustrated in the following graphs. A concrete with a high porosity will not provide a watertight structure and will likely deteriorate at an accelerated rate when exposed to severe freeze-thaw conditions or a corrosive environment.

Because of this effect, both the American Concrete Institute (ACI) and the National Precast Concrete Association have established maximum w/c ratio limits for various applications. The “NPCA Quality Control Manual for Precast Products” sets a maximum w/c ratio of 0.45 for concrete exposed to freezing and thawing and a maximum limit of 0.40 for concrete that will be exposed to deicer salts, brackish water or seawater. A maximum w/c ratio of 0.48 is set for watertight products containing fresh water. In order to produce concrete with a lower water-to-cement ratio, chemical admixtures can reduce the required amount of mixing water and still obtain the desired fresh properties to facilitate the placement and consolidation of the concrete.



One of the key parameters in producing high-strength concrete is the use of a low w/c ratio. As explained earlier, this means that not all of the cement will hydrate because of the lack of available space within the system for hydration products to form and because of the lack of free water available to hydrate all of the cement (Fig. 3 at right). This is why moisture curing of high-strength concrete is extremely important.

Aggregate moisture corrections

Aggregates are not completely solid but rather contain a certain level of porosity. Pores may be located in the center of the aggregate, while others may actually connect to the surface of the aggregate. When calculating the bulk specific gravity of an aggregate, take both the volume of the aggregate and all its pores into consideration. These pores will likely contain a certain level of moisture that will affect the performance of the concrete if appropriate corrections are not made to account for the actual moisture content of the aggregates. There are four different moisture conditions for aggregates, two of which may be achieved in a laboratory, while the other two occur naturally on a daily basis in aggregate stockpiles.

Oven-dry (OD): This is achieved under laboratory conditions when the aggregate is heated to 220 F (105 C) for an extended period. Under this condition, all moisture is removed from the aggregate's pores.

Air-dry (AD): The surface of the aggregate is dry and the internal pores may be partially filled with water. This condition may occur on a hot summer day or in an arid region. The aggregates will likely absorb water from the mix, which may affect the workability of the concrete unless proper adjustments are made to the aggregate and water batch weights.

Saturated surface-dry (SSD): This is achieved under laboratory conditions when all the pores are completely filled with water but no free water remains on the surface of the aggregate. Aggregates in this condition will not contribute free water nor absorb water from the mix.

Damp or Wet: All the pores are completely filled with water and the surface of the aggregate contains free water. Aggregates in a stockpile will typically be in this condition, meaning additional water will be added to the mix unless proper adjustments are made to the aggregate and water batch weights.

Aggregate mixture proportions are developed using either the oven-dry or saturated surface-dry condition. It is important to know this information when adjusting mix designs to account for actual aggregate moisture contents. Mix designs are typically developed using the oven-dry condition, but some may be developed using the saturated surface-dry condition. According to Ken Hover of Cornell University, one advantage of designing a mix based on SSD conditions is that the total weight of the batched materials will be the same before and after aggregate moisture corrections. Corrections to aggregate batch weights can be made using a correction factor, while the batch water weight is easily calculated by subtracting the weight of the cement and adjusted aggregates from the original design weight of all materials.

The actual aggregate moisture content and the absorption value of the aggregates must be known in order to accurately adjust the batch weights. The aggregate supplier should be able to provide you with the absorption value for each aggregate; otherwise they may be calculated following the procedures in ASTM C127 for coarse aggregates and ASTM C128 fine aggregates.

$$A = \frac{W_{SSD} - W_{OD}}{W_{OD}} \times 100\%$$

A = Absorption

W SSD = Weight saturated surface-dry aggregate

W OD= Weight oven-dry aggregate

The moisture content for each aggregate must also be calculated. Aggregate moisture contents will vary throughout a stockpile, with wetter aggregates located near the bottom of the pile. It is extremely important to calculate the aggregate moisture content at least once a day and perhaps more frequently when producing self-consolidating concrete (SCC), which is more sensitive to changes in aggregate moisture contents. Some batching systems are equipped with probes that read the moisture content of aggregates while being discharged from the hopper. These systems are typically tied directly into the batch computer and will automatically adjust the batch weights for correct proportions and w/c ratio. For batching systems without moisture meters or probes, the aggregate moisture content must be determined manually.

ASTM C566, "Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying," should be followed when determining the aggregate moisture content. Take a representative sample from the aggregate stockpile, avoiding the first few inches as this material is probably dry and not representative of the entire lot. Take the samples in accordance with the procedures established in ASTM D75, "Standard Practice for Sampling Aggregates," except for the sample size.

Weigh the collected sample and record it prior to drying. Use a hot plate, microwave oven or some other means of drying. Note that very rapid heating may cause some particles to explode, resulting in the loss of particles, which may render your calculations inaccurate. The sample is considered dry when further heating would cause less than 0.1 percent additional loss in mass. Allow the sample to cool to avoid damaging the scale. Weigh the sample to the nearest 0.1 percent. Calculate the total aggregate moisture content (MC) using the follow equation:

$$MC = \frac{W_{initial} - W_{OD}}{W_{OD}} \times 100\%$$

MC = Moisture Content

W initial = Weight of the sample prior to drying

W OD = Weight of the sample after drying

By using the moisture content and absorption of the aggregates, you can adjust the batch weights to account for the actual moisture condition. If the moisture content is higher than the aggregate's absorption value, the aggregates will contribute free water to the mix. If the moisture content is below the absorption value, the aggregates will absorb a portion of the mix water.

For mix designs based on raw materials in an oven-dry condition, make the following adjustments.

Calculate the adjusted coarse aggregate (CA BW) and fine aggregate (FA BW) batch weights using the following equation for each material:

$$AGG_{BW} = AGG_{DW} \times (1 + \frac{MC\%}{100\%}$$

AGG BW = Weight of adjusted aggregate to be batched (calculate for CA BW and FA BW)

AGG DW = Mix design weight of aggregate (CA DW and FA DW)

MC = Moisture content as a percentage (MC CA and MC FA)

Calculate the adjusted water batch weight (W BW) using the following equation:

$$W_{BW} = W_{DW} - (CA_{DW} \times \frac{MC_{CA} - A_{CA}}{100\%}) - (FA_{DW} \times \frac{MC_{FA} - A_{FA}}{100\%})$$

W BW= Weight of water to be batched after adjustment

W DW= Mix design weight of water

CA DW = Mix design weight of coarse aggregate

MC CA = Moisture content of coarse aggregate as a percentage

A CA = Absorption of coarse aggregate as a percentage

FA DW = Mix design weight of fine aggregate

MC FA = Moisture content of fine aggregate as a percentage

A FA = Absorption of fine aggregate as a percentage

For mix designs based on raw materials in a saturated surface-dry condition, make the following adjustments.

Calculate coarse aggregate (CA BW) and fine aggregate (FA BW) batch weights by multiplying each aggregate design weight (AGG DW) by its respective correction factor (CF) using the following equation:

$$CF = \frac{(100\% + MC\%)}{(100\% + A\%)}$$

CF = Correction factor must be calculated for each aggregate (CF CA and CF FA)

MC = Moisture content of aggregate as a percentage (MC CA and MC FA)

A = Absorption of aggregate as a percentage (A CA and A FA)

$$AGG_{BW} = AGG_{DW} \times CF$$

AGG BW = Weight of adjusted aggregate to be batched (calculate for CA BW and FA BW)

AGG DW = Mix design weight of aggregate (CA DW and FA DW)

CF = Correction factor must be calculated for each aggregate (CF CA and CF FA)

Determine the amount of batch water by subtracting the sum of the corrected batch weights (cement, CA BW and FA BW) from the sum of all the initial design weights, including the water. This concept is illustrated below.

$$W_{BW} = \sum C_{DW}, CA_{DW}, FA_{DW}, W_{DW} - \sum C_{DW}, CA_{BW}, FA_{BW}$$

W BW= Weight of water to be batched after adjustment

$C_{DW} = C_{BW}$; The weight of the cement does not change form the initial design

CA_{DW} = Mix design weight of coarse aggregate

FA_{DW} = Mix design weight of fine aggregate

CA_{BW} = Adjusted batch weight of coarse aggregate

FA_{BW} = Adjusted batch weight of fine aggregate
The following examples show to adjust how mix design weights to account for aggregates of varying moisture contents.

Example 1: Adjusting Mix Designs Based on Oven-Dry Conditions

The following information is provided for the initial mix design:

- Cement = 650 lbs
- Coarse Aggregate (OD) = 1,836 lbs
    - Absorption = 0.5%
    - Moisture Content = 2.0%
- Fine Aggregate (OD) = 1,243 lbs
    - Absorption = 0.7%
    - Moisture Content = 5.20%
- Water = 315 lbs

Calculate the adjusted aggregate batch weights

$$CA_{BW} = 1{,}836lbs \times (1 + \frac{2.0\%}{100\%}) = 1{,}836lbs \times 1.02 = 1{,}872.72lbs \approx 1{,}873lbs$$

$$FA_{BW} = 1{,}243lbs \times (1 + \frac{5.20\%}{100\%}) = 1{,}243lbs \times 1.052 = 1{,}307.64lbs \approx 1{,}308lbs$$

Calculate the adjusted water batch weight:

$$W_{BW} = 315lbs - (1{,}836lbs \times \frac{2.0\% - 0.5\%}{100\%}) - (1{,}243lbs \times \frac{5.2\% - 0.7\%}{100\%}) = 231.53lbs \approx 231lbs$$

The new batch weights are as follows:

- Cement = 650 lbs
- Coarse Aggregate = 1,873 lbs
- Fine Aggregate = 1,308 lbs

- Water = 231 lbs

Example 2: Adjusting Mix Designs Based on Saturated Surface-Dry Conditions

The following information is provided for the initial mix design:

- Cement = 650 lbs
- Coarse Aggregate (SSD) = 1,610 lbs
    - Absorption = 0.5%
    - Moisture Content = 1.8%
- Fine Aggregate (SSD) = 1,245 lbs
    - Absorption = 0.7%
    - Moisture Content = 4.8%
- Water = 310 lbs

Total weight of materials = $650lbs + 1{,}610lbs + 1{,}245lbs + 310lbs = 3{,}815lbs$

Calculate the adjusted aggregate batch weights

$$CA_{BW} = CA_{DW} \times CA_{CF} = 1{,}610lbs \times \frac{(100\% + 1.8\%)}{(100\% + 0.5\%)} = 1630.83lbs \approx 1631lbs$$

$$FA_{BW} = FA_{DW} \times FA_{CF} = 1{,}245lbs \times \frac{(100\% + 4.8\%)}{(100\% + 0.7\%)} = 1{,}295.69lbs \approx 1{,}296lbs$$

Calculate the adjusted water batch weight

$$W_{BW} = \sum C_{DW}, CA_{DW}, FA_{DW}, W_{DW} - \sum C_{DW}, CA_{BW}, FA_{BW}$$

$$W_{BW} = 3{,}815lbs - (650lbs + 1{,}631lbs + 1{,}296lbs) = 237lbs$$

The new batch weights are as follows:

- Cement = 650 lbs
- Coarse Aggregate = 1,631 lbs
- Fine Aggregate = 1,296 lbs
- Water = 237 lbs

What would happen if the design batch weights in the above examples were used without making corrections to account for the actual aggregate moisture contents? The w/c ratio in the first example would have changed from roughly 0.48 to 0.61, and the w/c ratio in the second example would have changed from roughly 0.48 to 0.59. This would mean that the 28-day compressive strength of each mix would likely be reduced by 1,000 psi, not to mention that the w/c ratios may no longer comply with the limits established by the authority having jurisdiction.

Whether you are using your own batch plant with automated moisture probes or purchasing ready-mixed concrete, it is extremely important that all individuals involved with the batching, mixing and casting of concrete understand the importance of maintaining the specified water-to-cement ratio. All additional water added to a mix should be measured and accounted for by adjusting mix proportions to ensure the maximum water-to-cement ratio is not exceeded. Having tight control on the w/c ratio will remove one of the many variables that influence the strength and durability of finished products.