Machine-Learning-Aided Concrete Mixture Optimization

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TRADITIONAL CONCRETE MIXTURE DESIGN METHODS

CHAPTER 1

CONVENTIONAL CONCRETE PROPORTIONING DESIGN METHODS

1.1 Standards for the design of ordinary concrete proportions in China

Concrete ratio refers to the proportional relationship between the number of constituent materials in concrete. There are two commonly used methods of expression: one is to express the mass of each material in each $1m^3$ concrete, such as 300 kg of cement, 180 kg of water, 720 kg of sand, 1200 kg of stone, the total mass of each $1\,m^3$ concrete is 2400 kg; the other method of expression is to express the ratio of the mass of each material to each other (with the mass of cement as 1), the above example will be converted into Mass ratio: cement: sand: stone = 1:2.4:4, water-cement ratio = 0.60(JGJ 55-2011).

Basic requirements for concrete proportioning design

The task of designing concrete proportion is to choose raw materials according to the technical properties of raw materials and construction conditions, reasonable selection of raw materials, and to determine the amount of each component material to meet the technical and economic indicators required by the project. Specifically, the basic requirements of concrete mix ratio design are:

a. Meet the strength level of concrete structure design;
b. To meet the construction requirements of the ease of concrete mix;
c. To meet the durability requirements of concrete structure design indicators (such as frost resistance, impermeability grade and erosion resistance, etc.);
d. Optimize cement usage and reduce concrete costs.

Three parameters in concrete proportion design

Concrete proportion design, in essence, is to determine the cement, water, sand and stone, the four basic components of the three proportional relationship between the amount of material. That is, the proportional relationship between water and cement, commonly used water-cement ratio; sand and stone proportional relationship, commonly used sand rate; cement paste and aggregate proportional relationship, commonly used unit water consumption ($1m^3$ concrete water consumption) to reflect. Water-cement ratio, sand rate, unit water consumption is the three important parameters of the concrete ratio, because these three parameters have a close relationship with the performance of the concrete, in the ratio design to determine the correct determination of these three parameters, you can make the concrete to meet the above design requirements.

Basic information on concrete proportioning design

Before the design of concrete proportion, first of all, we should master the basic information related to the performance of raw materials, concrete technical requirements and construction conditions and management level, mainly:

a) The technical properties of raw materials, including cement varieties and actual strength, density; sand, stone type, apparent density, bulk density and moisture content; sand grading and coarseness and fineness; stone grading and maximum particle size: mixing water quality and water source; admixture varieties, properties and appropriate dosage.
b) The technical requirements of concrete include the requirements of ease of use, strength level and durability requirements (such as frost resistance, impermeability, abrasion resistance and other performance requirements).
c) Construction conditions and management level include mixing and vibration mode, component type, minimum clear distance between reinforcement bars, construction organization and construction season, construction management level, etc.

Steps in concrete proportion design

Concrete proportion design includes preliminary proportion calculation, trial mix and adjustment steps.

1. Calculation of the preliminary proportion

According to the selection of raw material properties and technical requirements of concrete for the preliminary proportion of the calculation, in order to derive for the test with the proportion.

(1) Determination of formulation strength ($f_{cu,0}$)

In order for the concrete strength to have the required guarantee, it is necessary to formulate it at a strength higher than the designed strength class value.

Since $m_{fcu} = f_{cu,k} - t\sigma$

Let the formulated strength $f_{cu,0} = m_{fcu}$, then $f_{cu,0} = f_{cu,k} - t\sigma$ or $C_v = \frac{\sigma}{m_{fcu}}$, then $f_{cu,0} = \frac{f_{cu,k}}{1+tC_v}$

Where, $f_{cu,0}$ is the formulated concrete strength in MPa; $f_{cu,k}$ is the designed standard value of concrete cubic compressive strength in MPa; σ is the standard deviation of concrete strength in MPa; C_v is the coefficient of variation of concrete strength; And *t is* Probability degree.

When the concrete strength class required by the design is known, the formulated strength of the concrete can then be determined by the following formula:

$$f_{cu,0} = f_{cu,k} - t\sigma \tag{1.1}$$

According to the 'concrete structure engineering construction specification' and 'ordinary concrete proportion design regulations' (JGJ55-2000):

$$f_{cu,0} \geq f_{cu,k} + 1.645\sigma \tag{1.2}$$

That is, the guarantee rate of concrete strength is 95 per cent, corresponding to t = -1.645. The standard deviation of concrete strength σ shall be determined according to the following provisions based on the statistical information of the construction unit:

When the construction unit has recent concrete strength information of the same species, the standard deviation of concrete strength σ shall be calculated according to the following formula:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} f_{cu,i}^2 - n m_{fcu}^2}{n-1}} \tag{1.3}$$

Where, $f_{cu,i}$ represents the concrete strength of the i-th group of specimens for the same type of concrete, in MPa ; m_{fcu} statistical cycle of the same species of concrete strength of the average of denotes the average concrete strength across n groups, MPa ; n is the total number of specimen groups, with n≥25.

When the concrete strength grade C20, C25, its strength standard deviation calculated value is less than 2.5 MPa, the standard deviation used to calculate the strength of the preparation should be taken not less than 2.5 MPa; when the strength grade is equal to or greater than the C30 level, its strength standard deviation calculated value is less than 3.0 MPa, the standard deviation used to calculate the strength of the preparation should be not less than 3.0 MPa.

When the construction unit does not have recent information on the strength of the same variety of concrete, the standard deviation σ of its concrete strength can be taken according to Table 1.1.

Note: ‘the same species of concrete’ refers to the same strength level of concrete and the same production process and proportion of concrete is basically the same.

Table1.1 σ (MPa)

Concrete strength class	<C20	C20～C35	> C35
σ	4.0	5.0	6.0

The strength of the concrete preparation shall be increased appropriately in the following cases:

1) When there is a significant difference between the field conditions and the test conditions;
2) Important projects and special requirements for concrete;
3) C30 and above strength grade concrete, project acceptance may be non-statistical method of assessment.

(2) Preliminary determination of water/cement ratio (W/C)

According to the measured actual strength of cement f_{ce} (or the selected cement strength grade), the type of coarse aggregate and the required concrete formulation strength ($f_{cu,0}$), the required value of water-cement ratio is calculated according to the formula for concrete strength (applicable to concrete strength grade less than C60):

$$\frac{W}{C} = \frac{Af_{ce}}{f_{cu,0}+A\cdot B\cdot f_{ce}} \quad (1.4)$$

In order to ensure the necessary durability of concrete, the water-cement ratio shall also not be greater than the specified maximum value of water-cement ratio, if the calculated water-cement ratio is greater than the specified maximum value of water-cement ratio, the specified maximum value of water-cement ratio shall be taken.

(3) Selection of water consumption per 1 m^3 of concrete (W_0)

The amount of water consumption is mainly selected according to the required slump value of concrete and the type and specification of aggregate used. Therefore, the type of project and construction conditions should be considered first, according to the specification to determine the appropriate slump value, and then determine the amount of water per 1 m^3 concrete. Calculation of water consumption for flowable and large flowable concrete (slump greater than 90 mm) is shown in Section II of this chapter.

Alternatively, the water consumption per unit can be roughly estimated by the following formula:

$$W_0 = \frac{10}{3}(T + K) \quad (1.5)$$

Where W_0——per lm^3concrete water consumption, kg; T—slump of concrete mix, cm; K—coefficient, taken from the type of coarse aggregate and the largest particle size, can refer to Table 1.2.

Table 1.2 K value in the formula for calculating water consumption per unit of concrete

ratio	crushed stone				pebbles			
	Maximum particle size(mm)							
	10	20	40	80	10	20	40	80
K	57.5	53.0	48.5	44.0	54.5	50.0	45.5	41.0

Note: 1. When volcanic ash silicate cement is used, add 4.5-6.0.
2. When fine sand is used, increase by 3.0.

(4) Calculation of unit cement use for concrete (C_0)

The amount of cement used (C_0) can be found from the selected amount of water used per 1m^3 of concrete (W_0) and the resulting value of the grey to water ratio (C/W):

$$C_0 = \frac{C}{W} \times W_0 \tag{1.6}$$

(5) Selection of reasonable sand rate value (S_p)

Reasonable sand rate value should be determined mainly according to the characteristics of concrete mix slump, cohesion and water retention. A reasonable sand rate should generally be found out through tests.

Alternatively, the sand rate can be determined on the basis of the principle of filling the stone voids with sand with a slight surplus to set aside the stones. According to this principle can be listed in the sand rate formula is as follows:

$$S_p = \frac{S}{S+G}; V_{os} = V_{og} \bullet P'$$

$$S_p = \beta \frac{S}{S+G} = \beta \frac{\rho'_{os} \cdot V_{os}}{\rho'_{os} \cdot V_{os} + \rho'_{og} \cdot V_{og}}$$

$$= \beta \frac{\rho'_{os} \cdot V_{og} \cdot P'}{\rho'_{os} \cdot V_{og} \cdot P' + \rho'_{og} \cdot V_{og}} = \beta \frac{\rho'_{os} \cdot P'}{\rho'_{os} \cdot P' + \rho'_{og}} \tag{1.7}$$

Where, S_p is the sand rate (%); S and G represent the amount of sand and stone per 1m³ of concrete, respectively, in kg; V_{os} *and* V_{og} denote the volume of sand and stone stacked per 1m³ of concrete, respectively, in m³; ρ'_{os} *and* ρ'_{og} denote sand and stone density, in kg/m³. P' is the stone void ratio, in %; β is mortar residual coefficient, also known as dialling off coefficient, generally take 1.1 ~ 1.4.

(6) Calculation of the amount of coarse and fine aggregates (G_0) and (S_0)

The amount of coarse and fine aggregates can be obtained by the volumetric method or by assuming the apparent density method.

1) Volumetric method assumes that the volume of the concrete mix is equal to the sum of the absolute volume of the constituent materials and the

volume of air contained in the concrete mix. Therefore, in the calculation of 1m³ concrete mix of the amount of each material, can be listed in the following formula:

$$\frac{C_0}{\rho_c}+\frac{G_0}{\rho_{og}}+\frac{S_0}{\rho_{os}}+\frac{W_0}{\rho_w}+10\alpha=1000L \quad (1.8)$$

Also based on the known sand rate the following equation can be listed:

$$\frac{S_0}{S_0+G_0}\times 100\% = S_p \quad (1.9)$$

Where, C_0 is cement dosage for 1m³ concrete, in kg; G_0 is amount of coarse aggregate for 1m³ concrete; S_0 is amount of fine aggregate for 1m³ concrete, in kg; W_0 is water consumption of 1m³ concrete, in kg; ρ_c is density of cement, in g/cm³; ρ_{og} is apparent density of coarse aggregate, in g/cm³; ρ_{os} is apparent density of fine aggregate,in g/cm³; ρ_w is density of water, in g/cm; α is percentage of air content of concrete (%), α can be taken as 1 when air-entraining admixtures are not used; S_p is sand ratio, in percent.

The amount of coarse and fine aggregates can be found from the above two relational equations.

In the above equation, ρ_c is taken as 2.9-3.1, ρ_w = 1.0; ρ_{og} and ρ_{os} should be measured by test, ρ_{oh} can be determined according to the accumulated test data, and in the absence of data can be selected within the range of 2400-2450kg/m³ according to the approximate density of aggregates, particle size, and the strength grade of concrete.

Through the above six steps can be water, cement, sand and stone dosage of all out, to get a preliminary proportion for trial mix.

Note: The above concrete proportion formula and table, are dry state aggregate as a benchmark (dry state aggregate refers to the moisture content of less than 0.5% of the fine aggregate or moisture content of less than 0.2% of the coarse aggregate), such as the need for saturated surface of dry aggregate as a benchmark for the calculation, it should be modified accordingly.

2. Trial mixing, adjustment and determination of mixing ratio

(1) Trial mixing and adjustment of mixing ratio

The amount of each material is calculated with the help of some empirical formulas and data, or the use of empirical information, and thus may not be able to meet the actual situation, in the project, the project should be used in the actual use of raw materials. Concrete mixing, transport methods should also be the same as the production of the same method, through the test mix adjustment, until the concrete mixture of the ease of compliance with the requirements, and then put forward for the test of concrete strength of the benchmark ratio. The following describes the method of adjusting the compatibility:

Weigh the materials according to the preliminary mix ratio for test mixing. After thoroughly mixing the concrete, measure the slump and check its cohesion and water retention properties. If the slump does not meet the requirements, or if cohesion and water retention are insufficient, adjust the water content or sand rate as needed, keeping the water-cement ratio constant. When the slump is lower than the design requirements, the water-cement ratio can remain unchanged by increasing the amount of cement paste appropriately. If the slump is too high, increase the aggregate while maintaining the sand rate. If sand is insufficient, leading to poor cohesion and water retention, increase the sand rate accordingly; conversely, if there is excessive sand, reduce the sand rate. After each adjustment, perform a test mix until the mixture meets the specified requirements. Once test mix adjustments are complete, measure the apparent density of the concrete mix (ρ_{oh}).

The value of the water-cement ratio of the benchmark concrete mix ratio derived from the ease of adjustment test is not necessarily selected appropriately, and the result is that the strength does not necessarily meet the requirements. Therefore, the strength of the concrete should be tested. Generally use three different ratios, one of which is the benchmark ratio, the other two ratios of the water-cement ratio value, should be compared to the benchmark ratios were increased and reduced by 0.05, its water consumption should be the same as the benchmark ratios, the value of the sand rate can be increased or reduced by 1%. Each mix to make a group (three) test blocks, standard curing 28d test pressure (in the production of concrete strength test blocks, but also need to test the compatibility of the concrete mix and determine the apparent density, and the results as a representative of the performance of this mix of concrete mix).

Note: in the conditions of the unit can be produced at the same time a group or several groups of test blocks for rapid testing or earlier age test pressure, in order to set out in advance of the concrete ratio for construction use, but later still must be based on the results of the standard curing 28d test, adjust the ratio.

(2) Determination of mixing ratio

The concrete strength at each value of grey-water ratio derived from the test is used as a graphical method or calculated to find the value of grey-water ratio corresponding to $f_{cu,0}$. And determine the amount of material per cubic metre of concrete according to the following principles:

Water Consumption (W)-Take the value of water consumption in the base mix and adjust it appropriately according to the slump (or Vibro consistency) value measured during the fabrication of strength specimens;

Cement Consumption (C)-Take the value of water consumption multiplied by the value of the grey-water ratio determined by testing and necessary to achieve $f_{cu,0}$;

Amount of coarse and fine aggregates (G) and (S) - take the amount of coarse and fine aggregates in the base mix and make appropriate adjustments according to the determined value of the water-cement ratio.

(3) The correction of the apparent density of concrete

Fit ratio after trial mixing, adjustment to determine, but also according to the measured apparent density of concrete ($\rho_{oh,0}$) to make the necessary corrections, the steps are:

Calculate the calculated apparent density value of concrete ($\rho_{oh,1}$):

$$\rho_{oh,1} = C + W + S + G \quad (1.12)$$

The measured apparent density value of the concrete ($\rho_{oh,0}$) was divided by the $\rho_{oh,1}$ meter to obtain the correction factor δ, i.e:

$$\delta = \frac{\rho_{oh0}}{\rho_{oh1}} \quad (1.13)$$

When the absolute value of the difference between $\rho_{oh,0}$ and $\rho_{oh,1}$ does not exceed 2% of $\rho_{oh,1}$, the ratio determined from the above, that is, to determine the design ratio; if the difference between the two is more than 2%, it is necessary to have determined the ratio of the concrete in each item of the amount of material are multiplied by the correction factor δ, that is, the final design ratio.

In addition, the usual simple practice is through the test pressure, selected both to meet the concrete strength requirements, the cement dosage is less than the required proportion, and then make the correction of the apparent density of concrete.

If there are special requirements for concrete, such as impermeable concrete with impermeable grade not less than P6, frost-resistant concrete with frost-resistant grade not less than F50, high-strength concrete, mass concrete, etc., the design of the concrete proportion should be in accordance with the 'ordinary concrete proportion design regulations' (JGJ55-2000) relevant provisions.

3. Construction mix ratio

The design ratio is based on the dry material, while the sand and stone materials stored at the site contain a certain amount of moisture. Therefore, the actual weighing of materials on site should be corrected according to the site of sand, stone water content, the corrected ratio, called construction ratio. Site storage of sand, stone water content often changes, should be amended at any time according to the changes.

Assuming that the water content of sand measured at the site is W_s, the water content of stone is W_g, then the above design ratio is converted to construction ratio, the weighing of materials should be:

$$C' = C(kg) \tag{1.14}$$

$$S' = S(1 + W_s)(kg) \tag{1.15}$$

$$G' = G(1 + W_g)(kg) \tag{1.16}$$

$$W' = W - S \cdot W_s - G \cdot W_g(kg) \tag{1.17}$$

1.2 ACI Standard for Plain Concrete Proportioning Design

The first step in the preparation of concrete with certain performance requirements is the selection of the component materials, and the second step is the design of the proportioning process to ensure that the proper combination of the component materials can be achieved. Although there are sound technical principles that can be used to guide the design of the proportioning process, the process of concrete proportioning is not entirely scientific for a variety of reasons. Nonetheless, since the composition of concrete greatly affects the cost and performance of a product, it is important for engineers responsible for developing or approving concrete proportions to be familiar with the basic principles of proportioning and the methods commonly used.

1.2.1 Specific principles of concrete proportion design

In describing the specific principles of concrete proportioning, we need to bear in mind that the fundamental purpose of proportioning is to strike a reasonable balance between workability, strength, durability and economy.

(1) Workability

Workability refers to some properties of fresh concrete such as consistency and cohesion. Consistency is a measure of how wet or dry the concrete is and is usually assessed using slump (i.e. the wetter the mix, the greater the slump). The amount of water used is a key factor in cost, so it is important to note that slump is almost directly proportional to the amount of water used in concrete for a given set of materials. With slump held constant, the water requirement of a mix usually decreases (1) when aggregates are well graded and the maximum particle size increases, (2) when the content of angular and rough-surfaced particles in the aggregates decreases, (3) when the amount of air-entraining agent in the concrete mix is increased, and (4) when fly ash partially replaces cement.

Cohesion is an indicator for assessing the concrete's placing and smoothing properties, which are usually evaluated using smoothing performance and visual resistance to segregation. During concrete trial mixing, if cohesion is poor, it can be improved by one or more of the following methods: (1) increasing the sand/coarse aggregate ratio; (2) using fly ash to partially replace cement or sand; and (3) increasing the cement paste/aggregate ratio. Obviously, due to the low density of fly ash, it can increase the volume ratio of cement paste to aggregate without increasing the amount of cement, water, or sand used in the concrete.

Since the slump of fresh concrete is a measure of the fluidity of the concrete mix at the time of placing, and since the slump test is simple and can be quantitatively determined, most methods of mix design use slump as a rough indicator of workability. It is generally assumed that concrete mixes containing sufficient quantities of cement (with or without mineral admixtures) and well-graded aggregates have good cohesive properties. It is important to note that a series of laboratory trial mixes are usually required before conclusions can be drawn about the workability to meet the requirements of a given project. Due to differences in equipment, further adjustments to the mix may be necessary after field trial mixes have been conducted or after experience has been gained with a large number of concrete mixes.

(2) Strength

The strength specified by the designer should be considered as the minimum required strength in view of structural safety. Therefore, in order to take into account the variability in concrete materials, mixing methods, transport and placing, as well as the curing and testing of concrete specimens, the American Concrete Institute's Technical Standard 318 requires, based on statistical principles, that there should be a certain amount of richness in the strength design. In other words, based on the variability of the test results, the test mix average strength obtained by selecting the mix must be higher than the specified strength value. A detailed description of how to determine that the trial mix average strength is based on the specified strength is given in the appendix at the end of this chapter. It is important to note that the strengths used in the proportioning calculations are the trial-mean strengths and not the strengths specified in the design.

Although there are other factors that can affect the strength of concrete, the relevant charts used in proportioning design assume that the strength of concrete depends only on the water-cement ratio and air content. For a given set of materials and conditions, a more accurate relationship between strength and water-cement ratio can be determined from past experience or trial mixes. Depending on the water content state of the aggregates, the amount of water in the mix as well as the amounts of sand and coarse aggregate must also be corrected to ensure that the water-cement ratio in the concrete mix is accurate.

(3) Durability

When concrete is subjected to general environmental conditions, durability does not usually need to be specifically considered in the proportioning procedure, since strength itself is regarded as one of the indicators of general durability. However, in the presence of special environmental conditions that may shorten the service life of the concrete, the durability of the concrete requires special consideration in the proportioning design. For example, all concrete exposed to freeze-thaw cycling conditions needs to be air-entrained. For concrete exposed to chemically aggressive environments such as de-icing salts, acidic solutions, and sulphate solutions, water reducers and mineral admixtures need to be added during formulation. Under these conditions, although higher water-cement ratios may satisfy the strength requirements, lower water-cement ratios are usually specified to take into account the effects of the exposure environment.

1.2.2 Concrete proportioning steps

Most countries have a variety of methods for designing concrete ratios. The use of mathematical calculations to determine a proportion to meet a given set of performance requirements is usually not very effective due to the wide variation in the properties of the raw materials. It is therefore understandable why there are many empirical proportioning methods based on extensive test data and local material development.The method recommended by ACI Committee 211 is more prevalent in the United States and many other countries around the world. The basic principles regarding this method are described below.

The mass method is generally considered to be less accurate, but it does not require specific gravity and apparent density data for the raw concrete materials; the absolute volumetric method is considered to be more accurate. Both methods consist of the following nine consecutive steps, the first six of which are identical. The following background data should be collected, to the extent possible, before starting the proportioning calculations:

i. Sieve analysis results and fineness modulus of coarse and fine aggregates;
ii. The compacted dry bulk weight of the coarse aggregate;
iii. Apparent specific gravity or apparent density of the material;
iv. Water absorption capacity or free water volume of aggregate;
v. Variation of mixing water volume with slump, air content and aggregate gradation;
vi. The relationship between strength and water-cement ratio under conditions where there is a combination of cement and aggregate;
vii. Project specifications [e.g., maximum water-cement ratio, minimum air content, minimum slump, maximum aggregate size, and early strength (generally specified as 28 d strength value)].

Whether the properties of concrete are pre-specified by the specification or determined by the proportion designer, the proportion of each raw material in the concrete mix can be calculated using the following steps

Step 1: Select Slump

If the slump is not specified, a suitable slump value can be selected from Table 1.3. A drier, stiffer mix should be selected whenever possible, provided it is easy to pour, compact and does not segregate. Typical slumps for pumped concrete mixes can be designed for 100 mm to 150 mm.

Table 1.3 Recommended slump values for various types of structures

Structure type	Slump (mm)	
	maximum values	minimum value
Reinforced concrete foundation walls and foundations	75	25
Vegetative concrete foundations, caissons and substructure walls	75	25

Beams and reinforced concrete walls	100	25
column	100	25
Pavements and slabs	75	25
mass concrete	50	25

Note: (1) The slump should be increased by 25mm if the vibrator is not used and other methods of pounding are used.
Source: The American Concrete Institute.

Step 2: Select the maximum aggregate size

For a well-graded coarse aggregate of the same volume, the larger the maximum size, the smaller the aggregate void ratio, and thus the larger maximum size reduces the amount of mortar used in the concrete mix. In general, the maximum size of coarse aggregate should be the maximum that can be obtained economically and that is compatible with the structural dimensions. ACI specifies that the maximum aggregate size should not exceed 1/5 of the minimum spacing of the forms, 1/3 of the thickness of the concrete slab, and 3/4 of the minimum clear spacing of the reinforcing bars.

Step 3: Estimation of mix water volume and air content

According to ACI recommendations, the amount of water in the mix per unit volume of concrete at a given slump depends primarily on the maximum particle size of the aggregate and whether the mix is air-entraining or not. Tables 1.5 show the mix water volumes for two series of non-air-entraining concrete and air-entraining concrete, respectively. The data in the table also gives the expected air introduction for non-air-entraining concrete and also gives recommended values for air content for air-entraining concrete with frost resistance needs. ACI also gives guidelines for the reduction in water volume due to the use of light-rounded aggregates and water-reducing agents.

Table 1.4 Approximate water and air content required for different slumps and maximum nominal size of aggregates

Water consumption of aggregates at specified maximum nominal grain size (kg/m^3)								
Slump (mm)	9.5	12.5	19	25	37.5	50	75	150

Non-air-entraining concrete								
25-50	207	199	190	179	166	154	130	113
75-100	228	216	205	193	181	169	145	124
150-175	243	228	216	202	190	178	160	-
Approximate air residue in non-air-entraining concrete (%)	3	2.5	2	1.5	1	0.5	0.3	0.2
air-entrained concrete								
25-50	181	175	168	160	150	142	122	107
75-100	202	193	184	175	165	157	133	119
150-175	216	205	197	184	174	166	154	-
Average value of recommended gas content in the environment (%)	-	-	-	-	-	-	-	-
Water consumption of aggregates at the specified maximum nominal grain size(kg/m^3)								
Slump (mm)	9.5	12.5	19	25	37.5	50	75	150
air-entrained concrete								
benign environment	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0

Medium environment	6.0	5.5	5.0	4.5	4.5	4.0	3.5	3.0
hostile environment	7.5	7.0	6.0	6.0	5.5	5.0	4.5	4.0

i. The mixing water content for air-entraining concrete is based on the total air content of a typical 'medium environment' as shown in the table.
ii. The slump of concrete containing aggregates larger than 37.5 mm is determined by removing particles larger than 37.5 mm with a wet sieve.
iii. For large-aggregate concrete, the aggregate with a particle size greater than 37.5 mm is removed by wet sieving prior to the air content test, and the expected air content of concrete with a maximum aggregate size of less than 37.5 mm should correspond to the number in the 37.5 mm column. However, the air content corresponding to the largest particle size should be used as the total air content for preliminary proportioning calculations.
iv. The introduction of gas when using large particle size aggregates for low cement content concrete is not necessarily detrimental to the strength of the concrete. In most cases, the reduction in the amount of mixing water is sufficient to improve the water-cement ratio and compensate for the loss of strength caused by the introduction of gas. Therefore, in general, consideration should be given to using the recommended gas content for extreme conditions for concrete with large maximum nominal aggregate size, even if there is little or no exposure to wet and freezing conditions.

Step 4: Selection of water-cement ratio

The use of different aggregates and cement varieties at the same water-cement ratio will result in concrete with different strengths. Therefore, using the actual materials used to establish an accurate strength to water-cement ratio relationship is the most desirable method. In the absence of such data, concrete formulated with ASTMI type silicate cement can be used and the data in Table 1.5 can be referred to for trial mixing of concrete. In addition to meeting strength requirements, the water-cement ratios obtained from Table 1.5 may need to be reduced when durability is required (see Table 1.7). For example, a maximum water-cement ratio of 0.5 (0.45 for thin sections) is permitted for structures subjected to freezing in wet environments, and a maximum water-cement ratio of 0.45 (0.4 for thin sections) is permitted for structures exposed to seawater or sulphate water attack.

Table 1.5 Relationship between water-cement ratio and compressive strength of concrete

28d compressive strength (MPa)	Non-air entraining concrete	air-entrained concrete
40	0.42	—
35	0.47	0.39
30	0.54	0.45
25	0.61	0.52
20	0.69	0.60
15	0.79	0.70

i. The estimated average strength value, the air content of concrete does not exceed the values listed in Table 1.4. When the water-cement ratio is unchanged, the strength will decrease when the air content increases. Strength tests were conducted using φ 6×12in. (φ152×305mm) cylindrical specimens, cured in a fog chamber at 73.4±3°F (23±1.7)°C for 28d, and tested in accordance with ASTM C31.9(b), 'Method for Site Fabrication and Curing of Concrete Compressive and Flexural Specimens.

Table 1.6 Recommended maximum water-cement ratio for plain concrete subjected to sulphate attack

Environment	Water-soluble sulphate in soil① (SO_4), (% by mass)	Sulphate in water① (SO_4), (ppm)	Requirements for cementitious materials	Maximum water-gel ratio②
0	0.00～0.10	0～150	—	—
1	0.10～0.20	150～1500	Type II or equivalent	0.50
2	0.20～2.00	1500～10000	V or equivalent	0.45
3	>2.00	>10000	V-shaped + volcanic ash or slag	0.40

i. The relationship between sulphate expressed as SO4 and sulphate expressed as SO3 in the chemical analysis of cement is SO3 × 1.2 = SO4.
ii. In addition to sulphate, if chloride ions or other aggressive media are present, a lower water-cement ratio is necessary to reduce the potential corrosion of buried parts.

Source: ACI Committee 201, Report 201.2R-08: Guide to Durable Concrete, ACI Manual of Concrete Practice, Part 1, Concrete Institute, Farmington Hills, MI. 2008.

Step 5: Calculate the amount of cement

The cement dosage can be obtained by dividing the amount of mixing water obtained in step 3 by the water-cement ratio.

Step 6: Estimating the amount of coarse aggregate

Economic benefits can be realised by maximising the volume of coarse aggregate (based on the dry-compacted state) per unit volume of concrete. Numerous test data have shown that in properly graded materials, the finer the grain size of the sand and the larger the grain size of the coarse aggregate, the greater the percentage of volume of coarse aggregate allowed, resulting in satisfactory concrete workability. By referring to the data in Table 1.7, the volume of coarse aggregate per unit volume of concrete can be estimated, which can be based on the maximum particle size of the coarse aggregate and the fineness modulus of the fine aggregate. The dry weight of the coarse aggregate is then obtained by multiplying this volume by the experimentally determined compacted dry weight.

Table 1.7 Volume of coarse aggregate per unit volume of concrete

Maximum aggregate size (mm)	Dry pounding volume of coarse aggregate per unit volume of concrete for different fineness modulus sands①			
	2.4	2.6	2.8	3.00
9.5	0.50	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
19	0.66	0.64	0.62	0.60
25	0.71	0.69	0.67	0.65
37.5	0.75	0.73	0.71	0.69
50	0.78	0.76	0.74	0.72

75	0.82	0.80	0.78	0.76
150	0.87	0.85	0.83	0.81

i. Volume is based on the dry-pounded condition specified in ASTM C29 Aggregate Unit Mass, and the data in the table are based on the preparation of concrete whose compatibility is suitable for general reinforced concrete structures. For concretes with lesser ease, such as concrete pavements, the volume of coarse aggregate can be increased by about 10 per cent. For concretes with greater ease, such as those that are sometimes required for pumping, the volume of coarse aggregate can be reduced by about 10 per cent.

Source: The American Concrete Institute.

Step 7: Estimating the amount of fine aggregate

After completing step 6, all the components of the concrete mix have been estimated except for the fine aggregates. The quantity of fine aggregates can be obtained by the subtraction method, either by the 'mass method' or by the 'absolute volume method'.

The mass method assumes that the capacity of the fresh concrete is already known empirically, and the amount of fine aggregate can simply be obtained by subtracting the total weight of water, cement and coarse aggregate from the capacity of the concrete. If reliable estimates of the concrete mass are not available, an initial estimate of the mass of a concrete mix of medium strength, medium slump, and aggregate specific gravity of about 2.7 can be found in Table 1.8. Experience has shown that even a rough estimate of the bulk weight will fully satisfy the requirements of the test mix.

If the absolute volume method is used, the volume of fine aggregate required is equal to the unit volume of concrete minus the sum of the volumes occupied by the known constituents (i.e., water, air, cement, and coarse aggregate). This volume is then multiplied by the apparent density of the fine aggregate, which is the mass of the fine aggregate.

Table 1.8 Preliminary Estimates of Fresh Concrete Bulk Weights

Maximum aggregate size (mm)	Preliminary estimate of concrete mass① (kg/m^3)	
	Non-air-entraining concrete	air-entrained concrete
9.5	2280	2200
12.5	2310	2230
19	2345	2275
25	2380	2290

37.5	2410	2350
50	2445	2345
75	2490	2405
150	2530	2435

The data presented are for concrete with a medium cement dosage (330 kg/m3) and medium slump with an aggregate specific gravity of 2.7. Water use is shown in Table 1.8 for slumps of 75 to 100 mm. If necessary, the following adjustments can be made after obtaining the necessary data: for every 5 kg increase in water consumption (Table 1.9 for slumps from 75 to 100 mm), the capacity of the concrete should be reduced by 8 kg/m3 and vice versa. Cement dosage in 330 kg/m3 on the basis of every increase or decrease of 20 kg, the concrete weight should be correspondingly increased or decreased by 3 kg/m^3; Aggregate specific gravity of 2.7 on the basis of every increase or decrease of 0.1, the concrete weight is also increased or decreased by 60 kg/m^3.

Step 8: Adjustment of Aggregate Water Content

Generally, the aggregates on the yard are wet, and if the moisture content is not corrected, the actual water-cement ratio of the trial mix will be higher than the value selected in Step 4, and the weight of the aggregates in the saturated surface-dry state (SSD) will be lower than the values estimated in Steps 6 and 7. We assume from the outset that the mix proportions determined from Step 1 to Step 7 are based on the saturated surface dry state. Therefore, during the trial mixing process, the amount of mixing water should be reduced accordingly and the amount of aggregate should be increased accordingly, depending on the amount of free water in the aggregate. This is shown in the example below.

Step 9: Trial mix adjustment

The theoretical calculations above make a number of assumptions, so the actual material ratios used must be tested and adjusted in the laboratory by trial mixing with a small amount of concrete (e.g. 7.6 litres). The slump, workability (freedom from segregation), bulk weight and air content of the freshly mixed concrete should be determined and the strength of hardened concrete specimens cured under standard conditions should be determined at a specified age. After several trial mixes, when the concrete mix meets the workability and strength requirements, the laboratory trial mix can be enlarged for construction mixes.

1.3 References

[1] Ministry of Housing and Urban-Rural Development of the People's Republic of China. 2011. Code for Design of Ordinary Concrete Mix Proportion JGJ 55-2011 [S]. Beijing: China Architecture & Building Press.

SECTION 2

PREDICTING CONCRETE PROPERTIES USING MACHINE LEARNING

CHAPTER 2

DATA PREPROCESSING METHODS

Before constructing an efficient machine learning model, it is essential to obtain high-quality data, as the quality of data directly impacts model performance. Data collected from the real world is often complex and unprocessed, containing various defects and incomplete information. To ensure the smooth progress of subsequent data analysis and modeling processes, data preprocessing becomes an indispensable step. The aim of this process is to enhance data quality, making it more suitable for algorithms such as data mining and machine learning (Mat Roni and Geri Djajadikerta, 2021).

Data collected from the real world usually contains a lot of errors, invalid, missing and other noisy data, which seriously interferes with the process and results of data processing. Data preprocessing is the process of cleaning and repairing the original collected data to make it well suited for data mining algorithms such as machine learning (Mat Roni and Geri Djajadikerta, 2021). It is the first and crucial step in creating a machine learning model, which improves the accuracy and efficiency of the machine learning model.

2.1 Missing value processing

Machine learning methods are used to analyze and process large amounts of historical data and experience accumulated during the decision-making process in order to obtain knowledge that is useful for decision-making. In most cases, the process of data collection is not always accurate, stable and reliable, for example, there are registration omissions and writing errors in manual data collection, sensing drift, network or system failures, and power outages and omissions in sensor data collection, and data collected from nature often contain a certain degree of missing data. The data analysis process based on machine learning technology requires high data quality, and most models cannot support the mining processing of data containing missing values, and the selection of an inappropriate missing value completion method will also significantly reduce the accuracy of the data