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Moisture correction calculations in ACI-recommended concrete mix design

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The ACI–recommended method of mix design is commonly practiced in the United States, and is taught in university curricula. Though immense effort might have gone into preparing the method over many decades, there is an obvious arithmetical error in computing and recommending the starting point of the moisture to be added to the mix. The error is on the liberal side, in that more water is recommended to be added than the exact calculations warrant. While it is realized that mix design is an approximate science, the starting point is based on theoretical science that can be made accurate. The error has gone unnoticed without remark. This paper points out where the error is, and proposes a reasonable remedy.

Introduction

This article observes and illustrates that the calculations for moisture correction provided in the guidelines for Portland Cement Association's (PCA) *Designing and Proportioning Normal Concrete Mixtures,* as well as those in the recommendations of ACI 211, are flawed owing to a simple calculation.[1] The PCA process is commonly used all over the United States and many parts of the world, and therefore, the observation of an error comes with some surprise. Nevertheless, the error throws off the proper use of the proposed tables in ACI 211. In practical mix delivery, additional water is invariably added at the batch plant or construction site, over and above the recommendations of the ACI method, thus indicating that original mix designs yield stiff mixes. However, it is evident that the recommended design tables are based on a partially false premise. But, that said, it is entirely feasible to make improvements to the design recommendations.

The Portland Cement Association's (PCA) guidebook titled *Design and Control of Concrete Mixtures*, Kosmatka et al. (2002), is in its 14th edition now, having been in use for over 75 years.[2] The book is used by United States' practitioners as their primary reference, and by universities as a textbook for their concrete mix design classes. Consequently, the PCA guidelines are extremely popular, not to mention they are easy to use and apply. The PCA method is essentially similar to the ACI method, with PCA adapting charts and tables of ACI, such as ACI 318, ACI 211.1 and ACI 211.3. Nawy (2001), Waddell and Dobrowolski (1993), Derucher et al. (1998), and Mindess et al. (2003), and many others, make reference to the ACI and PCA concrete mix design method.[3,4,5,6]

However, the author discovers that the calculation technique recommended for moisture correction in the various manuals, guidebooks, and other books based on the ACI procedure is technically flawed. This does not mean that the whole design methodology should be scrapped. Only, that the error leads to wetter mixes, while using a "proper" calculation leads to stiffer mixes. Twenty-four student trial tests conducted for various mix strengths and environmental conditions revealed this to be true. Nevertheless, it is quite straightforward to see, as is described in the paper, that the error favors more water to be added to the concrete mix. For practicing engineers and students, this may be just as well, since workability with stiff mixes is obviously burdensome and undesirable. Moreover, it is quite reasonable to assume that the error went unnoticed for all these decades because the mixes were coming out wet and workable in the laboratory and batch plant, so no one complained.

For a calculation flaw of this nature, tests and trials are not necessary for illustrating the error, since the error is in the theory. However, trials and tests help to observe the extent of decrease in slump experienced by following "proper" calculations, as was evident from instructor supervised student trials. This paper explains where the flaw lies, provides examples, and suggests what can be done by way of rectification. There is no literature or precedence on this topic. Perhaps, no one has noticed the error, or if noticed, has not published. The central part of this paper is in the section titled "Moisture Correction Calculations – PCA Reference."

Charts and tables in concrete mix design

The charts mentioned in Table 1 are among those commonly used in mix designing by the ACI/PCA mix design technology. The essential chart for determining moisture use is chart no. 5 of Table 1, *Approximate Mixing Water and Target Air Content Requirements for Different Slumps and Nominal Maximum Sizes of Aggregate.*

Table 1. General charts for mix design recommended by ACI and PCA

Chart No.	Reference table	ACI reference
1	Maximum w/c material ratios and minimum design strengths for various exposure conditions	ACI 318
2	Requirements for concrete exposed to sulphates in soil or water	ACI 318
3	Relationship between w/c material ratio and compressive strength of concrete	ACI 211.1 and 211.3
4	Bulk volume of coarse aggregate per unit volume of concrete	ACI 211.1
5	Approximate mixing water and target air content requirements for different slumps and nominal maximum sizes of aggregate	ACI 211.1 and ACI 318
6	Recommended slumps for various types of construction	ACI 211.1
7	Minimum requirements of cementing materials for concrete used in flatwork	ACI 302
8	Cementitious materials requirements for concrete exposed to deicing chemicals	ACI 318

Moisture correction calculations – PCA reference

The mistake in the PCA guide observed by the author is one of simple arithmetic, but of considerable consequence to how mix design can be logically understood and performed. Take the example of Kosmatka et al (2002) of the Portland Cement Association, pp. 163-165, using the Absolute Volume Method of mix designing. Their empirical requirements for coarse and fine aggregate, both ovendry, are 1674 lb (759 kg) and 1236 lb (560 kg), respectively; the amount of water indicated for the special conditions is 270 lb (122 kg). These empirical requirements using the design charts of Table 1 are satisfactory, so far. The moisture conditions of the aggregates in the sample considered are:

Aggregate type	Specific gravity	Total moisture	Moisture absorption	Moisture available for mixing
Coarse aggregate	2.68	2%	0.5%	1.5%
Fine aggregate	2.64	6%	0.7%	5.3%

Now, weight correction for moisture requires that we batch the following quantities of coarse and fine aggregate, mentioned correctly by Kosmatka et al. as

Coarse Aggregate (CAgg): 1674 x 1.02
= 1707 lb (774 kg)

Fine Aggregate (FAgg): 1236 x 1.06
= 1310 lb (594 kg)

So far, so good! However, the mistake creeps in at this junction. If we are to batch 1707 lb (774 kg) of CAgg and 1310 lb (594 kg) of FAgg, the surface moisture that will be available to the mix will be directly related to the amounts we batch. Now, 1.5% of the CAgg of 1707 lb (774 kg) is surface moisture, while 0.5% is absorbed by the aggregate as moisture based on its absorptivity and is not available for mixing. Similarly, 5.3% of the FAgg is available for mixing, while 0.7% is absorbed owing to its absorptivity. It is easy to see that the weight of the water – absorbed and free – comes from the total amount batched at the weight station. Hence, the logical amounts of mixing water to be excluded from the mix should be as follows:

CAgg: 1707 x 0.015 = 25.6 lb (11 kg)

FAgg: 1310 x 0.053 = 69.43 lb (31 kg)

Therefore, the actual amount of water to be added to the mix should be

270 – 25.6 – 69.43 = 174.97 lb (79 kg)

However, Kosmatka et al. make the error of stating that the amounts of water to be excluded should be

CAgg: 1674 x 0.015 = 25.11 lb (11 kg)

FAgg: 1236 x 0.053 = 65.51 lb (29 kg)

Resulting in a recommendation for the amount of water to be added to be

270 – (1674 x 0.015) - (1236 x 0.053) = 270 - 25.1 - 65.51 = 179.38 lb (81 kg)

Hence, there is a difference of 4.41 lbs (2 kg) of water between what Kosmatka et al calculate and what is the correct calculation. ***Kosmatka's calculation makes the mix wetter and more workable. This difference is the root cause of the difficulties encountered in accurate mix designing.*** This is an error of iteration that ignores the fact that when you increase the amount of CAgg from 1674 lb (759 kg) to 1707 lbs (774 kg), you bring in extra surface water as a basic component of those additional 33 lbs (14 kg). The extra amount of free moisture available as a result of those additional 33 lbs (14 kg) is 33 x 0.015 = 0.495 lb (0.224 kg). The same reasoning goes for FAgg, where we can see that on increasing the weight of FAgg from 1236 lb (560 kg) to 1310 lb (594 kg), we add 74 x 0.053 = 3.92 lb (1.77 kg) of free moisture for mixing. As a consequence of increasing the batched weights of CAgg and FAgg, we have an additional 4.41 lb (2 kg) of free moisture available for mixing. The reader will see that this 4.41 lb (2 kg) is directly equal to the difference of 179.38 lb (81 kg) of water to be added, calculated by Kosmatka et al, and the 174.97 lb (78 kg) of water calculated by the author.

The fact of the matter is that the weight measured at the batch plant is not for ovendry aggregates. If it were to be so, the recommendations of Kosmatka et al (2002) could be acceptable. However, were it to be so, concrete companies would have to go to great lengths to ovendry their aggregates for mass consumption, an exercise that would be costly and time consuming. Consequently, ovendrying is NOT done in practice. ***Hence, Kosmatka et al (2002) ignore the practical dimensions of the problem.***

Laboratory tests

Tests performed by groups of students in 24 class exercises for varying concrete mixes as lab exercises, gave extremely stiff mixes of 0-0.5" slump for the author-recommended version of calculations, compared to the PCA expectation of slump of 1-4" (refer chart no. 6 of Table 1). The actual average of all those exercises was 0.15", with half the exercises yielding no slump at all. Upon commensurately adding the extra water (which would be 4.41 lbs (2 kg) in this example), the slumps increased considerably enough to make a difference between a somewhat workable mix and non-workable mix. Slumps increased by an average amount of 0.6" for the 24 exercises, and only two exercises eventually yielded 0.25" slump.

This confirms the theoretical underpinnings of the problem. While the ACI and PCA mix designing methods recommend multiple iterations for adding water at the batch plant, and further recommend the initial amount of water to be added only as an entry point, this initial amount of water does not satisfy the practical dimensions that arise from weigh batching the fine and coarse aggregates.

Moisture correction calculations – ACI reference

This error has been perpetuated by other authors and researchers. Mindess (2003), referring to the ACI Method of mix design, pp. 236-239, makes the same assumption as Kosmatka et al. Basically, the incremental weight of water owing to the incremental weight of aggregates is ignored in the same manner. A summary of his calculations versus what they should be are given in the following Tables 2 through 4:

Table 2. Aggregate properties

Aggregate type	Specific gravity	Total moisture	Moisture absorption	Moisture available for mixing
Coarse aggregate	2.68	1.5%	1.0%	0.5%
Fine aggregate	2.63	5.5%	1.3%	4.2%

Table 3. Aggregate weight calculations

Aggre-gate type	Weight recomm. OD, lb (kg)	Weight SSD, lb (kg)	Weight batched, lb (kg)	Incremental weight, lb (kg)	Incremental free moisture, lb (kg)
CAgg	1701 (771)	1718[3] (779)	1727[1] (783)	26[5] (11)	0.13[6] (0.06)
FAgg	1097 (497)	1111[4] (503)	1158[2] (525)	61 (27)	2.56 (1.16)

Wt. of Water = 305 lb (138 kg); OD = Ovendry; SSD = Saturated Surface Dry

[1] = 1701 (OD) x 1.015; = 1718 (SSD) x 1.005

[2] = 1097 (OD) x 1.055 = 1157.3 ~ 1158; = 1111 (SSD) x 1.042 = 1157.6 ~ 1158

[3] = 1701 (OD) x 1.01 [4] = 1097 (OD) x 1.013 = 1111.2 ~ 1111

[5] = 1727 – 1701 = 26 [6] = 26 * 0.005 = 0.13 lb

Table 4. Moisture deduction approach

	Moisture deduction, lb (kg)	Final weight of water added, lb (kg)
Mindess (2003)	1718 x 0.005 + 1111 x 0.042 = 55.25 (25)	305 – 55.25 = 249.75 ~ 250 (113)
Author	1727 x 0.005 + 1158 x 0.042 = 57.27 (26)	305 – 57.27 = 247.7 (112)

Thus, it is seen that there is a difference of over 2 lb (0.907 kg) in the amount of extra water to be added, which equals the total incremental free moisture found in Table 3 (excluding multiple rounding errors). The one difference between Kosmatka et al (2002) and Mindess et al (2003) is that the former takes the ovendry weights as the basis for making moisture correction values, while the latter takes saturated surface dry weights as the basis for making moisture correction values. In that regard, the cumulative error of Mindess et al is less than that of Kosmatka et al. ***However, they both fail to account for all the additional incremental moisture that comes as a result of the incremental weight increase for batching.***

Moisture correction calculations – No slump concrete, ACI 211.3R-97

ACI guidelines for the design of no-slump concrete, ACI 211.3R-97, makes the same mistake in moisture correction ("Guide," 1997). On page 7 of their guide, they provide an example: The dry weights calculated for coarse and fine aggregate, and their moisture properties are provided in Table 5.

Table 5. Weight requirements and moisture properties of aggregates

Aggregate type	Dry weight	Total moisture	Moisture absorption	Moisture available for mixing
Coarse aggregate	2403 lb (1089 kg)	1.0%	0.5%	0.5%
Fine aggregate	914 lb (414 kg)	5.0%	0.7%	4.3%

Recommended water content = 243 lb (110 kg)

On this basis, the amount batched should be as follows, and ACI and author are in agreement with this:

CAgg: 2403 x 1.01 = 2427.03 lb (1100 kg)

FAgg: 914 x 1.05 = 959.7 lb (435 kg)

Of these weights, 0.5% is free moisture for CAgg, and 4.3% is free moisture for FAgg. The real calculations, then, should be as follows:

Free moisture from CAgg = 2427.03 x 0.005
= 12.13 lb (5.5 kg)

Free moisture from FAgg = 959.7 x 0.043
= 41.26 lb (18 kg)

Total free moisture = 53.39 lb (24 kg)

Therefore, water to be added = 243-53.39
= 189.61 lb (86 kg)

However, ACI 211.3R-97 gives the following calculations for the total free moisture:

Free moisture from CAgg = 2403 x 0.005
= 12.01 lb (5.44 kg) [~ 12 lb (5 kg) as used by ACI]

Free moisture from FAgg = 914 x 0.043
= 39.30 lb (17 kg) [~ 39 lb (17 kg) as used by ACI]

Total free moisture
= 51.31 lb (23 kg) [~ 51 lb (23 kg) as used by ACI]

Therefore, water to be added
= 243 - 51.31 = 191.69 lb (87 kg)

Hence, the ACI calculations recommend that 2.08 lb (0.9 kg) of more water should be added, in contrast to what the calculations actually indicate. Considering that their recommendation is for no-slump concrete, they are not recommending a mix relatively dry enough.

Observations and discussion

Though mix design is an approximate science – one that is engineered rather than follow a perfect technique – it is nevertheless better to base one's charts and tables on calculations as accurate as possible rather than have to increase the level of approximation and trial batches necessary. We observe that the PCA-method of moisture correction exemplified by Kosmatka *et al*; the ACI-method of mix design exemplified by Mindess et al; and ACI 211.3R-1997 for no-slump concrete are all partially flawed on the matter of moisture correction. ***This flaw arises from a defect in ACI 211 itself, which fails to give due recognition in free moisture correction***

to the incremental aggregates added during design for the moisture carried by the aggregates. While this error might be 'small', it does not excuse the error, especially given that small differences in moisture added have a significant effect on slump. PCA has apparently perpetuated the error of ACI.

Such an error may possibly be managed and contained on industrial sites, since mix designing is an approximate science, anyway. However, such a difference can be troublesome to researchers hunting for accurate answers, and to students, who, while learning concrete mix designing, expect logical rigor.

Analogy

A simple analogy should suffice to explain the reason behind the flaw: a sponge having weight z_0, for instance, can hold n% of its own weight in water. A same type of sponge of size 1.1 x z_0 will still hold n% of its weight in water, thereby holding 1.1 times more water than sponge of size z_0. So it is with porous aggregates. The arithmetic and rationale is as simple as this – probably high school level – but ACI and PCA and thousands of engineers over many decades in USA seem to have either missed this point, or thought the flaw to be of no consequence, or overlooked it deliberately in order to not make any waves.

Query and discussion

A general query and discussion on this matter was conducted between Steven Kosmatka, the author of the PCA book on concrete mix designing, and the author. In reference to the author's suggestion to him that the moisture correction should be made in relation to the total amount batched, Steven Kosmatka (2003) replied that the moisture correction should be made in relation to the dry weights. His reply was

> "The book has the correct calculation — 270 - (1674 x 0.015) - (1236 x 0.053) = 179. Always make the moisture adjustments relative to the dry weights. If not, the base value continually fluctuates."

There is nothing wrong in making moisture adjustments relative to the dry weights, provided the commensurate moisture adjustments are also made. The commensurate moisture adjustments, regrettably, are not made in the PCA book. Moreover, in practical batching, oven dry aggregates are NOT made available.

In contrast, Mindess at al make their adjustment relative to the SSD weights. The answer for making adjustments based on OD weights and SSD weights should be the same. However, the main issue is whether the moisture correction is based on the quantity you weigh at the batch station to put into the mix, or whether you base the moisture correction on a prior number. ***Hard reality says that you go by the facts of what you are actually batching.*** Moreover, for scientific rigor, there is no fear of having the base value of the ovendry weight or base value of moisture correction to fluctuate, since the main issue is the surface moisture present in batched aggregate.

Again, Kosmatka (2003) writes correctly that -

> "if one wants a correct answer for the amount of moisture to be added, one must consider how much one is batching, consider the moisture content in the batched amounts, and make corrections accordingly. The rationale is that one must subtract the moisture contained in the aggregates we are eventually batching."

But then makes the mistake of further claiming that

> "This is exactly what the book calculation does."

Thus, the PCA book misinforms the users, because the book does not do what PCA proposes. This oversight has perpetuated for 75 years.

For the sake of expediency and convenience, many a technique can be justified, for which basic ratio mix designs have often come in handy. However, the author does not believe that the emphasis of the profession is toward rough-and-ready techniques just to make things work, but that there is an emphasis on steadily increasing exactness whenever possible. The elaborate mix design method of ACI, and the enormous effort put into its development, is proof that the profession seeks accuracy and reliability.

Making revisions to design tables: Suggestions

What is the remedy for this problem? If we want to retain the integrity of arithmetic, the science of Archimedes, and simple science, then it is incumbent upon us to make some changes in the mix design charts of ACI. Since the main parameter being affected through the moisture correction calculations is the total amount of water to be added, perhaps some changes should be brought about to chart no. 5 of Table 1, *Approximate Mixing Water and Target Air Content Requirements for Different Slumps and Nominal Maximum Sizes of Aggregate*. Since the correct moisture correction calculations will demand that less water be added, the easiest thing to do if we want to retain the total set of the mix design charts and techniques is to increase the recommended water content in above chart.

How much should the water recommendations be increased by? Considering that the water amounts in the above chart are in round numbers in multiples of five, and since the correction amount we are talking about is small – to the magnitude of four or five pounds, depending on the conditions and circumstances -- it may be reasonable, as an empirical recommendation, to increase all water content values in above chart by five pounds each.

Further studies

It might be more effective to conduct a study to see if there are more precise answers for the amount by which the water quantities in above chart should be increased. Such a study could consider various scenarios and conditions, and different types of aggregates having different moisture content and absorption. But, further discussion on this is beyond the scope of this paper.

Conclusions

The observations and arguments reveal that the calculations for moisture correction in the ACI and PCA recommendations, are unfortunately mistaken, albeit by a small amount. Using "corrected" calculations results in stiff mixes, considerably more than designed for. Using the erroneous calculations pose an ethical dilemma to the conscientious engineer, since they compromise standards in basic physics and mathematics.

The conflict is between continuing to use the ACI and PCA-recommended mix design along with the recommended tables and charts for mix design that are based on a false premise, or to use the proper calculations and revise the tables and charts. Said another way, shall we continue as normal and bury our face in the sand and insist we don't see anything wrong, or shall we accept the error for the betterment and enhancement of our profession, and thus take steps to improve our manuals and guides. For the author, the only ethical choice is the latter. The major – and simplest – improvement would be made to the recommended water content of the ACI 211.1 chart titled *Approximate Mixing Water and Target Air Content Requirements for Different Slumps and Nominal Maximum Sizes of Aggregate.* Correspondingly, the recommended method for moisture correction should be rectified to make the moisture correction based on the actual ***batched amount*** of aggregates.

(Note: Original calculations are all in lbs. Conversions from lb to kg have generally been rounded down to the whole numbers.)

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