

Will More Cement in Your Mixture Hurt You?

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Abstract

An old rule of thumb states that if you need more strength in a concrete mixture, just throw more cement at it. Sometimes that helped, sometimes not. Today many engineers realize that there are many other variables in a mixture that effect strength as much as, or more than, cement content. They also realize that increased cement content in a concrete mixture can lead to a number of effects that may reduce the life of the pavement. Many properties of concrete are adversely affected by over-cementing the mixture. These are discussed to help the reader understand why optimizing the cement content will help produce an efficient mixture that will meet the project requirements. By first determining the voids in the aggregate portion of the concrete mixture and then increasing that volume by an amount necessary for workability, a volume of paste can be determined that will approximate the optimum cementitious content to both maximize strength and also provide a workable mixture. Also discussed are the effects of increasing the cement content in a concrete mixture, including durability, strength, heat generation, shrinkage, set time, workability, CO₂ footprint, as well as cost.

Introduction

For the purposes of this paper, mixture design is considered the process of determining required and specifiable characteristics of a concrete mixture (how should the concrete perform). Mixture proportioning is the process of determining the quantities of concrete ingredients required to meet the requirements of the design (Taylor, 2006).

Both of these activities will impact how much cement is contained in a given mixture. A prescriptive specification may call for a fixed binder content, and/or materials characteristics may require a certain amount of cement for the mixture to achieve needed workability and mechanical limits.

While European practitioners are familiar with the idea of adjusting cementitious content based on the needs of the mixture and materials available, there is still a common perception in the USA that system performance is primarily controlled by this variable. It is not uncommon, then, for specifications to require minimum binder contents that are well in excess of those really needed.

This paper discusses how to think about mixture proportioning without being tied to a fixed binder content, and illustrates how excess cement may, indeed be detrimental.

Research Significance

This paper intends to start discussion of an alternative methodology for proportioning concrete mixtures. This approach to proportioning would lead to more sustainable mixtures while not compromising performance.

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Background

In US practice, most proportioning methodologies were developed before water reducing admixtures, or supplementary cementitious materials were commonplace. The approaches were then, aimed at achieving workability, without sacrificing strength. The approaches were also aimed at typical structural concrete: about 100mm slump and a target strength of about 30 MPa at 28 days.

Today we work with a dizzying array of new materials; to make concrete with workability from zero slump to self-consolidating concrete; seeking 30 MPa psi at 4 hours, or 120 MPa psi at 28 days. The basic rules of concrete technology have not changed, but the demands are more stringent, the windows of acceptable variability are tighter, and yet the of spectrum incoming variables is wider than ever.

Many engineers will affirm that adding cement to a mixture will increase strength. This is true, if cement is added and the water content is held constant. However, in an age when water-reducing admixtures are the norm, it is possible to reduce water content while holding cement content constant, and thereby reduce water / cementitious materials ratio (w/cm) without decreasing workability. Therefore, this popular rule of thumb is no longer necessarily valid. Unfortunately, the rule is so tightly embedded in our heads it is tough to grasp an alternative way to think about it. This paper invites readers to discard their preconceived notions on mixture proportioning, and to think through, from first principals, what we really need in a mixture, and how much.

First, let us look at how proportioning has been conducted historically.

Absolute Volume Method of Mixture Proportioning The absolute volume approach proceeds through the following steps (different versions may vary slightly, but the fundamentals are similar):

1. Choose the slump
2. Choose the coarse aggregate size
3. Choose the water content of mixture based on the above
4. Choose the air content
5. Use the w/c ratio to calculate binder content
6. Calculate the coarse aggregate volume based on subtracting the fineness modulus (FM) of sand from a fudge factor
7. Fill the remaining volume with sand

The logic behind using the FM of the sand is not unreasonable. Workability of a mixture is controlled by several factors including:

- Angularity of the coarse aggregate
- Rheology of the mortar
- Amount of mortar separating the coarse aggregate particles (aggregate gradation)

The finer the sand, the thinner that separating layer can be, while still lubricating the mixture (Figure 1). Therefore, increasing FM means that less sand and more rock can be used.

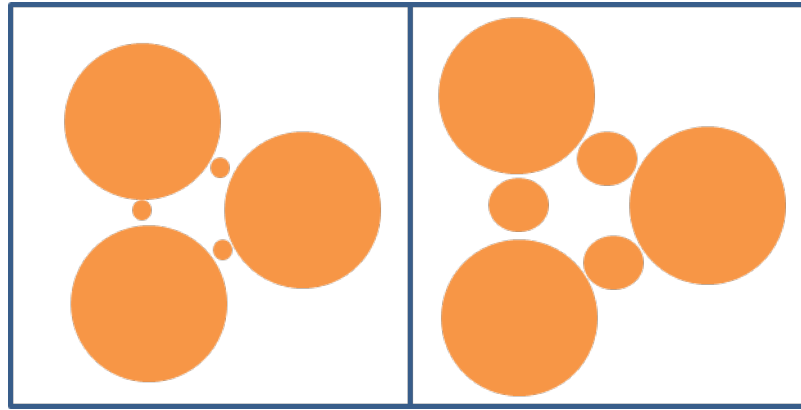


Figure 1. Larger sand particles force coarse aggregate particles apart, reducing how much coarse aggregate can be used in a mixture.

There is little iteration in this method as formally written. Variables such as aggregate texture, and SCM and admixture dosages are not easily accommodated. The tables used in many published methods also assume a reasonably workable mixture and a limited range of strength requirements. Let us therefore investigate what is really needed out of a mixture and how do we achieve that with the materials we have.

What we really want The contractor is primarily concerned about

- Workability – meaning the ability to place and finish the concrete without segregation while using the equipment intended.
- Cost – because that is the key to winning the bid and getting the job in a low-bid environment.
- Strength – if it is the basis of payment.

The owner is primarily concerned about

- Reliability – is the finished product going to last as long as intended.
- Cost – because agency budgets are shrinking while demands are growing. However, they are also concerned with obtaining value for the money spent – not a system that will deteriorate prematurely.

These interests however, may be in tension, meaning that specifications have to be detailed and complex and they have to be enforced using quality assurance programs that include close inspection of the whole construction process.

The critical performance metrics for concrete used in most paving projects will likely include:

- Workability – the ability to be spread and consolidated without tearing or excessive edge slump
- Setting time
- Strength, because fatigue life is a function of strength. It is interesting however, that some State DOT's do not use strength in their daily acceptance protocols.
- Potential durability
- Permeability –assessed using an electrical conductivity or resistivity test
- Resistance to freezing weather
- Chemical effects such as alkali silica reaction (ASR)
- Risk of cracking as influenced by shrinkage, strength development and heat of hydration

How to get the required performance The primary factor that controls performance of a hardened mixture is the w/cm. This is because a limited amount of water is required to react with the cement, and any excess results in increased capillary voids, which decrease strength and increase permeability. In addition, the more total water there is in a mixture, the more there is to evaporate, thereby increasing shrinkage. Reducing water is therefore a good thing – within limits.

On the other hand, insufficient water in the mixture will lead to poor workability. A minimum amount of paste is required to get between the aggregate particles and lubricate the mixture, even when WRA's are used (Figure 2). Therefore, to ensure effective consolidation, a minimum amount of water is needed. In addition, if there is not enough water to hydrate all of the cement, the system will be at greater risk of so-called autogenous shrinkage. This normally becomes significant at w/cm below about 0.40 (Taylor, 2006).

Most other factors controlling mixture performance do so by influencing one of the above – w/cm for performance and water content for workability. This includes the aggregate system, paste quality and paste volume as discussed below.

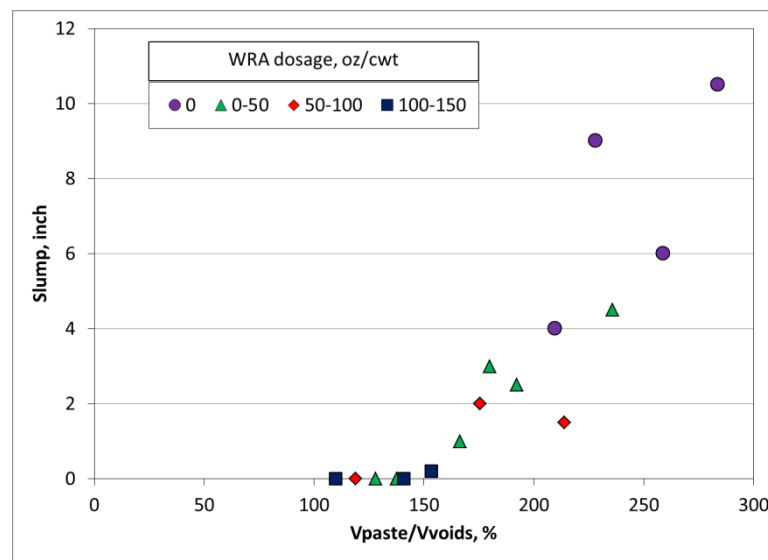


Figure 2. A plot of slump as a function of the ratio of volume of paste to volume of voids between the aggregates for a plain portland cement mixture. Regardless of the admixture dosage, it is impossible to achieve workability if there is insufficient paste in the mixture. The minimum required for the aggregate system used in this work is about 1.5 times more paste than voids. (Based on Yurdakul, 2010) (1in=25.4mm)

How Does the Cementitious Content of a Concrete Mixture Affect Performance?

The amount of cementitious material in a concrete mixture will affect many properties, both plastic and hardened. In most cases, increasing the amount of cement may result in a negative effect. Reducing the cementitious content (within limits) will, for most applications, result in a more durable pavement or structure. These affected properties are discussed below.

Workability Workability is a critical property for concrete paving because smoothness and longevity are both strongly influenced by the ability to extrude the mixture to the correct grade, fully consolidate it and to prevent edge slump. Ideally, a mixture should flow readily under vibration and be stable when not worked. Unfortunately, no test exists that adequately measures these needs in the field and many paving contractors resort to using a visual judgment to assess a load of concrete as it is delivered.

Increasing the amount of cementitious material in the mixture can make the mixture more workable but increasing fine powder content may cause the mixture to become sticky and harder to work and finish.

Set Time Set time affects concrete performance because it will strongly influence the saw cutting window and is tied to initial strength gain. If setting is too slow, the risk of plastic shrinkage cracking increases, and drying cracking may still occur even though the system is too soft for conventional sawing to commence. Setting that is too rapid increases the risk that the sawing crew will not be able to keep up, leading to random cracking in the slab.

The set time of a concrete mixture is controlled by the hydration process, which in turn is affected by:

- The chemistry of the system: increasing alkalis will shorten setting times
- w/cm: decreasing w/cm means that particles are closer together, shortening the time it takes for hydration products to interlock
- Temperature: increasing temperature accelerates hydration

Increasing cement content will increase the heat of hydration, which in turn may indirectly accelerate reactions, and so shorten set times.

Heat Generation As discussed below, the peak temperature has a significant influence on the amount of shrinkage the concrete experiences, particularly in the first day. In addition, concrete that hydrates faster will generally have a coarser microstructure and lower ability to resist fluid transport and therefore poorer potential durability. Reducing the heat therefore will reduce the cracking potential and positively affect durability.

The chemical reactions that occur as a part of the hydration process will accelerate with increased temperature. In turn, hydration is an exothermic process, releasing heat into the mixture and raising temperatures. Factors that increase heat generation include:

- Increasing cementitious content
- Higher initial temperatures
- Faster reacting systems (e.g. high alkali content; low SCM dosage)

Shrinkage Concrete shrinkage results from several different mechanisms (Taylor, 2006).

One of these is thermal shrinkage. The higher the cement content, the higher the hydration temperature will be at the time of set, and the peak temperature shortly thereafter. Therefore, the temperature drop and stresses will increase when the system cools. The greater the difference between peak temperature and the ambient temperature as the system cools determines the thermal stresses induced in the concrete slab. Therefore lowering that maximum temperature will reduce those stresses.

Shrinkage is also caused by the loss of moisture. For a given water cement ratio, the more cementitious material in the mixture, the greater the amount of water in the concrete (Figure 3). As that water leaves the pavement, shrinkage stresses are induced. Therefore reducing the cementitious content will also reduce the concrete shrinkage.

Autogenous shrinkage also induces stresses when the resulting hydration products occupy less space than the original material.

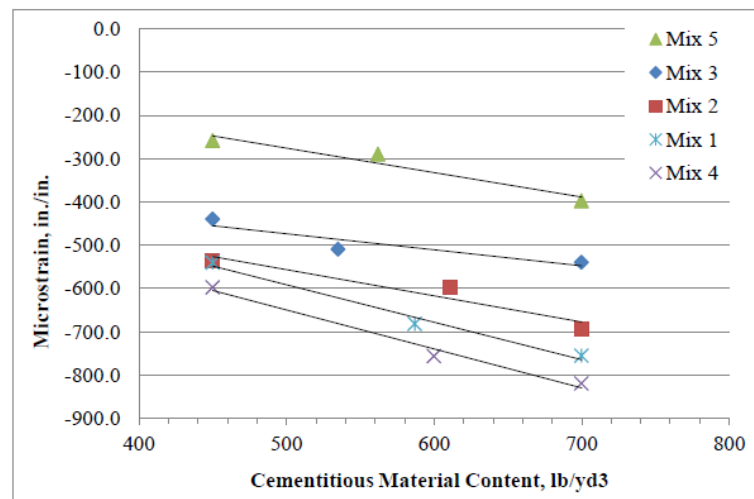


Figure 3. Increasing paste content increases drying shrinkage for a variety of cementitious systems. (Wang, 2010) (1in=25.4mm)

Strength Strength is primarily controlled by the w/cm, therefore increasing cement content at a fixed w/cm does not increase strength once sufficient paste is provided to the mixture to fill all of the voids between aggregate particles and to coat all of the aggregate particles (Figure 4).

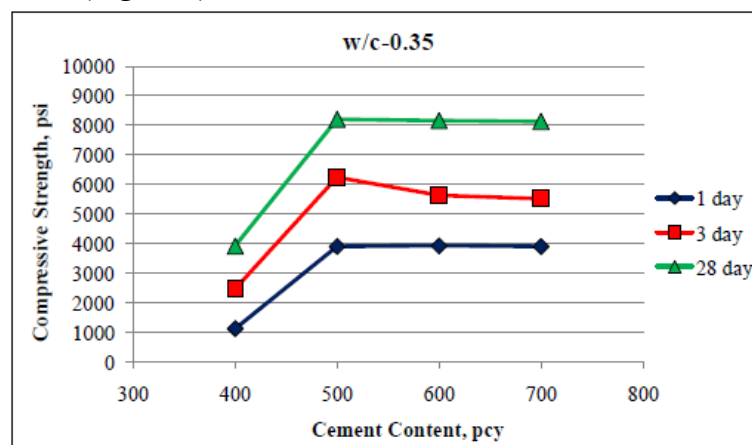


Figure 4. Once sufficient paste is provided to the mixture, any additional amount does not contribute to added strength for a given w/c. (Yurdakul, 2010) (1in=25.4mm)

Durability It is a commonly held that adding cement will increase strength and thereby improve durability. However, increasing the cement content may only increase strength to a point, beyond which little gain is realized. Also, a higher strength mixture does not assure increased durability. Often increased cement content can actually compromise potential durability, for instance, cracking caused by excessive heat reduces durability and decreased workability will create numerous problems during paving. Increased paste content may increase permeability, because paste is normally more permeable than aggregate (Figure 5).

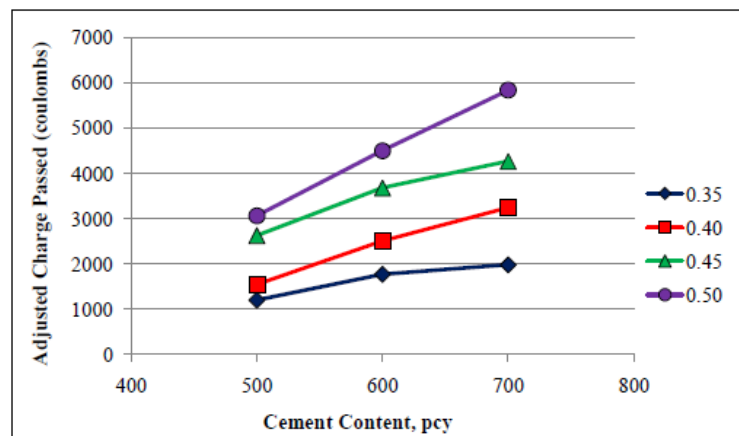


Figure 5. Added cement increases rapid chloride penetrability for a given w/c. (Yurdakul, 2010) (1in=25.4mm)

Alkali silica reaction (ASR) involves alkali from the cementitious material. As that amount of cementitious material increases, there are more alkalis in the mixture to react with susceptible aggregates.

CO₂ footprint Today the sustainability of concrete pavement construction is becoming increasingly important. The CO₂ produced during the production of cement is a significant part of concrete's effect on the environment. Any mixture containing more cement than is needed to meet the project specific needs increases the environmental impact and cost of the mixture.

Cost Cement is the most expensive component in a concrete mixture, therefore reducing the cementitious content will reduce the cost of the concrete.

Proposed Mixture Proportioning Procedure

The following discussion covers a suggested approach to mixture proportioning based on that reported for self-consolidating concrete by Koehler (2007). It builds on the principals discussed above. It should be noted that it is an iterative approach, because decisions made at one stage may influence factors already considered.

Step 1: Choose an Aggregate System The first step is to work on the aggregate system. The aim is to combine the available aggregates to obtain a maximum density (within limits). It is assumed that the aggregates being proportioned are of acceptable quality in terms of durability and contaminants.

Combined gradation. Adjusting the combinations of aggregates available will allow development of a system with a maximum, or close to maximum, amount of aggregate in the mixture. Increasing aggregate content in the mixture, will reduce the amount of paste needed to fill the spaces. This is desirable because the paste is the most expensive part of the mixture, and the most prone to temperature and drying shrinkage effects.

For two-aggregate mixtures, it is easy to measure and plot the consolidated bulk density of aggregate blends with incremental changes in coarse and fine proportions. Then read off the desired peak combination. For systems containing more than two aggregates one approach would be to use numerical modeling such as used in Compass© (FHWA, 2010) (Figure 6).

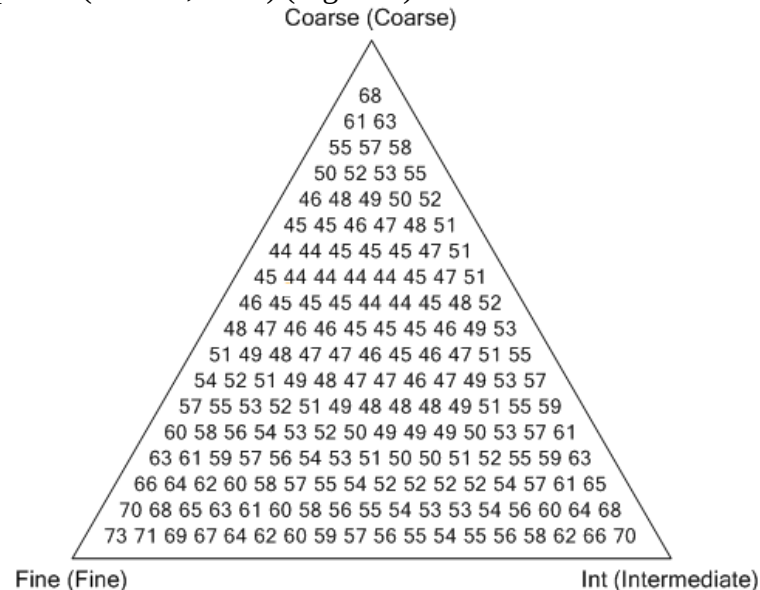


Figure 6. Plot from Compass© showing calculated void space between aggregates depending on the blend of given coarse, fine and intermediate materials.

An alternative is to look at the plots recommended by Shilstone (Shilstone, 1990). The workability factor chart was developed for paving applications and recommends that mixtures fall within Zone 2. A plot of the power 45 curve will also indicate which combination is closest to the “ideal” line (Taylor, 2006).

The aggregate grading can also affect performance as follows:

- Segregation is largely controlled by whether the system is gap graded or not. Preventing two adjacent low points in a haystack curve will help to reduce the risk (Figure 7).
- Bleeding is directly controlled by the amount of fine material or dust in the mixture. Increasing powder, including cementitious materials, content will reduce the risk of excessive bleeding. On the other hand, a mixture that does not bleed at all is at great risk of plastic shrinkage cracking.



Figure 7. Haystack plot showing two low points at #16 and #30 sieves, indicating a high risk of segregation (Taylor, 2006). (1in=25.4mm)

Determine the void space. Having selected the aggregate system, determine the volume of void space between the aggregates. This can be done by weighing a full container of the consolidated combined aggregates at SSD, then adding water to fill the container and weighing it again. This information will be used in Step 3.

Assess texture and shape effects on rheology. The actual amount of paste needed for both hardened properties and workability will vary based on whether the aggregate is rounded or angular, and on the amount of fines. In other countries it is common to report the so-called water demand of a sand – i.e. the amount of water required in a mixture to achieve a given slump at a given cement content (Fulton, 2001). This variable is primarily controlled by the amount and form of dust and fines in the sand. Further work is needed to develop this approach and to quantify the effects of the coarse aggregate and is underway at present.

Step 2: Choose a Paste System The characteristics of the paste system will primarily control the long-term performance of the concrete and influence the workability. The factors that can be adjusted in a paste are the percentage of supplementary cementitious materials, the w/cm, and the air content and the type.

Cementitious blend. The use of SCM's along with cement in a concrete mixture is a common practice today. SCM's can be added at the cement plant or the batch plant, and can be used alone or in ternary blends. They improve the properties of concrete in many ways. However, as with most things, they will have side effects, and those changes must be understood. Many of those changes will be a benefit, but in certain situations they can be a negative. Below is a discussion of the effects that SCM's have on various concrete properties.

- Workability: Fly ash and slag cement generally improve workability.
- Stickiness: As cementitious contents of a mixture exceed that which is needed for workability, the mixture can become more sticky and inhibit the workability of the concrete. Fly ash also can create a more sticky mixture. During moderate and cooler weather, though, stickiness is not a common concern.

- **Set Time:** Pozzolans take part in a secondary reaction with the calcium hydroxide that is produced in the cement hydration process. The reaction is normally slow, which is why the introduction of SCM's into a mixture will normally retard the setting time. In hot weather conditions, this can be a significant benefit for paving, but in cold weather can increase the risk of cracking.
- **Strength:** The pozzolanic reaction of SCM's utilizes the calcium hydroxide from the cement reaction to produce additional calcium silicate hydrate (CSH). Therefore, the use of SCM's in the mixture will lead to reduced strength gain at early ages, but increased strength in the long term. This effect is very marked in low alkali mixtures. These needs must be balanced when considering constructability factors such as early cracking risk.
- **Permeability:** As with strength, the increase in CSH in the hydration reaction products, due to the addition of SCM's, will also decrease the permeability of the concrete over time.
- **Durability:** SCMs are effective at reducing alkali silica reaction and sulfate attack when used at appropriate dosages.
- **Environmental impact:** Because SCM's are by-products from other industrial processes, their use will reduce the environmental impact by reducing the volume of material needing to be landfilled, and by reducing the amount of cement required in a mixture along with its environmental burden.
- **Incompatibility:** The amount of sulfate in a cementitious system depends on the chemistry of the cementitious materials, and strongly affects initial setting and early strength development. Adding high calcium fly ash at the batch plant may increase the risk of flash or false set. A potential solution is to use cementitious blends prepared at the cement plant in which the sulfate balance is controlled at the point of manufacture.

In summary, careful and appropriate use of supplementary cementitious materials can lead to an improved performance, and improved sustainability. Typical ranges in pavement mixtures are 15 to 25% Class F fly ash, 15 to 40% Class C fly ash or slag cement.

Water/cementitious ratio. The amount of water in the mixture controls the following properties of a mixture:

- **Workability** – increasing water increases workability. Too little water, however, may be insufficient to achieve a base workability even with the use of water reducing admixtures.
- **Strength** – decreasing w/cm increases strength and improves other hardened properties (Figure 8).
- **Permeability** – decreasing w/cm improves impermeability.
- **Cracking risk** – reducing water content reduces the drying shrinkage, but below w/cm of about 0.40 can increase autogenous shrinkage.

For concrete paving, there is therefore a balance that must be maintained between a low w/cm for hardened properties and high enough water content for workability. Each mixture is unique because of the ingredients within it and finding that balance is an art.

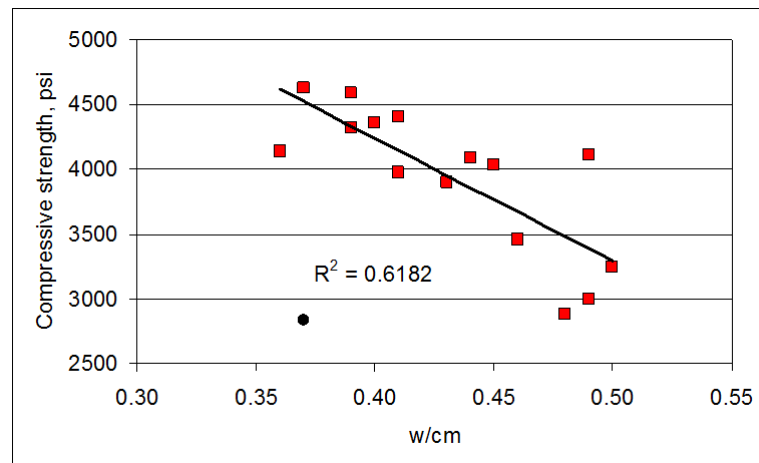


Figure 8. Plot of strength at 28 days vs. w/cm data from 16 sites around country, with a variety of cementitious systems and aggregates. Despite the range of materials, there is still a clear trend in the relationship. (Fick, 2008) (1in=25.4mm)

Chemical Admixtures. Once sufficient water is in a mixture to provide a certain amount of workability, slump can be significantly modified by the addition of water reducing admixtures. The effects of these chemical on segregation must be monitored and dealt with, possibly by adjusting the amount of fine material in the mixture.

If Type A water reducing admixtures are used, there is a potential for uncontrolled setting in hot weather with certain fly ashes. However, if high range admixtures are used, care must be taken to prevent overdose and making the mixture too fluid. Modern high range products will likely also affect the air void system.

Accelerators and retarders can be used to modify setting times. Note that accelerators will not influence strength beyond a few days. Indeed, retarders will help slow a system down and improve microstructure, leading to better potential performance in the long term.

Dosages of all admixtures will need to be adjusted continually because of the effects of changes in aggregate moisture and weather. The proportions developed initially should only be considered guidelines.

Air content. It is the air system that protects the concrete from freeze/thaw damage. The small air bubbles, along with a close spacing relative to each other, provide the space for expansion as the water within the concrete freezes. What is desired then is a large number of small bubbles in the hardened concrete.

Certain fly ashes exhibit a high loss-on-ignition, which is mostly unburnt carbon in the material. This carbon will absorb the air-entering agent and can make it difficult to generate and control the needed air void system.

Increasing workability makes it easier to entrain air, but it also makes it easier to lose air with excessive handling and vibration.

Air content is normally expressed as a percentage of the volume of concrete, although it is the paste that needs to be protected. A common rule of thumb is that air volume should be about 9% of the volume of mortar (Kleiger, 1952). Note that this value is approximate, and should not be used as a pass / fail acceptance parameter.

Step 3: Choose paste volume Factors that lead to decisions regarding the amount of paste needed in a mixture are addressed next.

As discussed above, it is critical that all of the voids between the aggregates be filled with paste. Some additional amount is needed to coat the particles to help glue them together, and to separate and lubricate them in the fresh state for workability. All performance characteristics of a mixture drop off very rapidly if there is insufficient paste. Initial research has shown that the volume of paste should be about 150% of the void space to achieve satisfactory hardened properties (Figure 2).

The same work also showed that a paste volume of about 125% of the void space was needed to achieve satisfactory workability regardless of the paste system used. These data were from a single aggregate combination so needs might vary for other systems. Factors that will influence this decision will include the quality of the paste and effects of the aggregate shape and smoothness. Data are still being developed to quantify these effects.

Step 4: Iterate Repeat steps 1 to 3 to ensure that everything is in balance and to take into account the interactions between the decisions made.

Step 5: Conduct trial batches and adjust The final step in any concrete mixture proportioning exercise is to prepare trial batches and assess the properties of the proposed mixture. The properties to be looked at include both fresh and hardened properties. Adjustments can be made to admixture dosage and water content, or cementitious materials quantity, depending on the problem observed.

Most incompatibilities can only be discovered when temperatures are high and chemical reactions are accelerated. Therefore, at least one trial batch should be prepared with the concrete temperature near 90 degrees, or near the expected maximum ambient temperature during the paving period.

Worked Example A set of proportions were developed using the guidelines in ACI 211, and based on the approach described above. Common input parameters were a fixed target slump of 1 inch, w/cm of 0.45, fly ash content of 20% and the aggregates discussed in Yurdakul (2010).

The theoretical proportions from the methods are shown in Table 1 along with typical proportions used in everyday practice based on DOT requirements.

Table 1. Mix Proportions from different sources

	ACI Method	Proposed Method	Typical Usage
Cement, kg/m ³	295	250	270
Fly ash, kg/m ³	75	60	65
Water, kg/m ³	165	140	150
Coarse, kg/m ³	1650	1090	915
Fine, kg/m ³	110	790	915

It is clear that the ACI method leads to much higher cementitious contents than required in practice, while the proposed method would result in further savings in cost and environmental impact, without compromising performance.

Closing

The aim of this paper is to help the reader think about mixture proportioning as more than just applying a list of rules, but to be aware of the interactions between the materials, their dosages, and their effects and side effects on the mixture. Such an approach may be more challenging, but in the long term can lead to savings, because recipe based mixtures will never be the most efficient. It is acknowledged that there may be increased risk as proportions are less conservative, and that risk may be transferred from the owner to the contractor. On the other hand, with risk comes the potential for reward.

The art will be in finding an effective way to specify and accept concrete performance.

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