HIGH PERFORMANCE CONCRETE AND DRILLED SHAFT CONSTRUCTION

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ABSTRACT: Drilled shaft foundations on major bridge projects often require the use of underwater placement of large volumes of concrete through densely placed rebar, with the cage often made even more congested with the placement of additional tubes for post-construction integrity testing. Such conditions represent the most difficult circumstances for constructors in terms of concrete placement to achieve a shaft which is free of defects or anomalies in the integrity testing. The concept of “high performance” for drilled shaft concrete is that the mixture should address the most critical performance requirements related to workability. This paper describes the important considerations in concrete mixture design for drilled shaft construction including the use of admixtures and mixture components associated with self-consolidating concrete (SCC). Some case histories of difficulties associated with concrete are also described.

INTRODUCTION

Large diameter drilled shafts are becoming increasingly popular on major bridge projects due to increased availability of drilling equipment and skilled contractors and inherent advantages of high capacity shafts in supporting axial and lateral loads. Shaft diameters of up to 4 m (13 ft) and lengths of up to 80 m (260 ft) are no longer unusual. These shafts often require the use of underwater placement of large volumes of concrete through densely placed rebar, with the cage usually made even more congested with the placement of additional tubes for post-construction integrity testing. Such conditions represent the most difficult circumstances for constructors in terms of concrete placement to achieve a shaft which is free of defects or anomalies in the integrity testing.

This paper provides an overview of the most important characteristics of concrete mixture design and construction practices for drilled shaft construction. In drilled shaft applications, the most critical performance requirements for concrete are related to workability and thus the concept of “high performance” material emphasizes the construction aspects of the mixture in addition to hardened properties required to meet
structural design requirements. Important components of a good mixture design and installation plan include requirements for workability for the duration of the concrete placement operations, passing ability, resistance to bleeding, and low heat of hydration. Strength requirements and aggregate properties that are consistent with these considerations are important, as are concrete placement techniques used by the contractor. If any single important issue is not adequately addressed in the mixture design and placement procedures, placement difficulties and/or anomalies in integrity test measurements can result.

WORKABILITY AND PASSING ABILITY

Concrete workability levels for large diameter drilled shafts must address issues relating to underwater placement via tremie, congested reinforcing cages, concrete pumping operations, and filling ability from a single point tremie discharge into a large diameter hole. In order to flow laterally from the discharge point and fill the shaft without entrapment of drilling fluids or laitance from the underwater surface of the fluid concrete, the concrete must flow smoothly through the reinforcing cage under its own buoyant weight without “piling up” near the tremie. A mixture with the desired workability will not result in more than a few inches of difference in height between the top of the concrete surface near the tremie and the concrete on the outside of the reinforcement as shown on Figure 1.

![Figure 1 Concrete Flow in Under Tremie Placement](image)

Figure 1 Concrete Flow in Under Tremie Placement

The inability of the concrete to flow laterally can lead to entrapment of laitance (the contaminated concrete on the top of the rising column of concrete) and encapsulation of pockets of low strength as described by Brown (2004) and illustrated on Figure 2. The photos in Figure 2 were each taken from drilled shafts cast into removable steel liners in a
lake (left is from Texas, right is from Pennsylvania), and the soft pockets of trapped laitance were exposed upon removal of the form. Yao and Gerwick (2004) describe the desirability of underwater concrete to flow laterally in a “bulged” flow pattern with a relatively flat, smooth top surface rather than as a “layered” flow pattern which can result in steeply sloped and rugged top surface that increase the exposure of concrete surfaces to water.

Figure 2 Exposure of Trapped Laitance Attributed to Inadequate Workability

Deese and Mullins (2005) and Camp et al. (2002) describe relative differences in concrete levels within and outside the reinforcement that are attributed to the inability of the concrete to readily pass through the cage. Even if the concrete has adequate workability, the aggregate size and shape must be such that the mixture passes readily through the reinforcement. Figure 3 is a photo of a mixture which is workable (as evidenced by the shovel that was easily placed into the concrete), but which exhibited a measured difference in concrete level between the inside and outside of the reinforcing cage of over 1 m (4 ft) due to the close spacing (75 mm opening) of the transverse reinforcing. Note also that structural designers sometimes include a requirement (especially for single column shaft foundations in seismically active regions) that the upper portion of the shaft contain a second inner longitudinal steel cage within the shaft designed to extend up into the column and thus avoid a lap splice at the column/ shaft joint. This detail creates a condition in which the drilled shaft concrete must flow through two concentric cages.

Workable concrete for tremie placement in drilled shafts must be a flowable, cohesive, self consolidating mixture that is easily placed without external vibration. Although the use of the term “self-consolidating concrete” or SCC has been used in recent years with reference to mixtures with ultra workability in conventional concrete applications, drilled shaft concrete has always been intended as a self consolidating mixture. Traditionally, drilled shafts have been constructed using slump as the sole indication of workability. Alternative methods to describe workability may have application in large diameter drilled shafts.
Concrete slump ranging from 175 to 225 mm (7 to 9 inches) has been found to provide adequate workability for drilled shafts up to 2.5 m (8 ft) in diameter if the reinforcing cage has openings not less than 150 mm (6 inches). For mixtures requiring greater workability, the use of slump flow and/or the L-box (or J-Ring) tests may be more suitable for assessing the properties of the fresh concrete. Figure 4 provides an illustration of these control tests, now in routine use for SCC mixtures. The slump flow is a simple test performed with a conventional slump cone, but measurements are performed on the diameter of the resulting fluid concrete mixture rather than the height of the cone. Based on some initial field trials of drilled shaft construction using SCC-type mixtures (Brown et al. 2005), slump flow requirements in the range of 450 to 600 mm (18 to 24 inches) appear suitable for drilled shaft construction.
Concrete mixtures can be designed with high workability by using suitable aggregates and gradation and the proper dosage of water reducing admixtures. Some of the key components for high workability drilled shaft mixtures are as follows:

- Rounded gravel aggregate sources are much preferred over crushed stone in these mixtures. Coarse aggregates with a No. 67 or No. 78 gradation have performed better than a No. 57 in terms of workability.
- In general, an increase in the sand content in proportion to coarse aggregate will provide increased workability and passing ability with less tendency for segregation; a sand to total aggregate ratio (by volume) from 0.44 to 0.50 has been found to work well in drilled shaft mixtures.
- Water reducing admixtures in current use, include polycarboxylate-based materials. Many contractors have a reluctance to use “super plasticizers” as they are sometimes called because of experiences with flash set. However, these bad experiences were typically encountered with the older naphthalene-based water reducers and given the wide range of newer products available nowadays, a water reducer combined with proper hydration control admixtures can extend the workability as needed for practically all drilled shaft applications. It must be noted that hydration control is highly temperature dependent, as will be discussed subsequently.

**WORKABILITY RETENTION**

For large diameter shafts which can often require 300 to 500 m$^3$ (400 to 650 yd$^3$) of tremie-placed underwater concrete, retention of workability is critical. The dosage of retarding or hydration control admixtures must be selected to ensure that the concrete retains adequate workability to allow the tremie placement to be completed. Loss of workability will lead to difficulties in maintaining flow through the tremie, with attendant flaws in the shaft as described above and illustrated in Figure 5.

![Figure 5 Effects of Loss of Workability During Concrete Placement](image-url)
Difficulties with tremie placement associated with loss of workability are illustrated from a project record of over-water placement of concrete on a bridge project, shown on Figure 6. In this particular instance, there were difficulties and delays in loading the delivery barge (denoted as “traveling hopper”) and the mixture had sufficient retarder to maintain workability for only about 4 to 5 hours. Approximately 5½ hours after the first concrete was batched, the concrete became stuck in the tremie and the crane operator had difficulty lifting the tremie (which then suffered a failure of the rigging). When the tremie was finally pulled free, concrete was unable to flow freely from the tremie and flow was resumed only after jigging the tremie up and down (see figure 5). Subsequent integrity test results revealed poor quality concrete at the elevation corresponding to this event and expensive shaft repairs were required.

![Figure 6 Placement Difficulties Associated with Loss of Concrete Workability](image)

**RESISTANCE TO BLEEDING**

For drilled shafts with such high workability requirements, a mixture with low bleeding is necessary. Mixture characteristics relating to bleeding are also closely related to those affecting segregation, and a concrete mixture with a very high workability requirement is more susceptible to bleeding and/or segregation concerns. Ground conditions also play a role; low permeability cohesive soils are more conducive to bleeding concerns than sandy soils which allow excess water in the mixture to escape.
The worst conditions for bleeding occur when there is a long steel casing that prevents excess water in the concrete from escaping into the surrounding soil.

The hydrostatic pressure of fresh concrete in a shaft that is 60 m (197 ft) or more in length is substantial and can contribute to bleed water channels along the longitudinal reinforcement or permanent casing. Often, bleed water tends to follow the location of the tremie pipe in the fresh concrete, leading to bleed water channels in the center of the shaft. Bleed water channels within the shaft or near integrity test tube locations can result in anomalies in integrity test results (most often consisting of crosshole sonic logging or gamma-gamma testing). One such example is shown on Figure 7; this core was taken from a shaft that exhibited low CSL velocities within this range (S&ME 2004).

![Figure 7 Crack Within Drilled Shaft Revealed by Coring](image)

Another illustration of internal bleed saw (Brown et al, 2005). The lower part of this photo is a cut which is transverse to the shaft axis and about 4m (13 ft) from the top of the 1.8m (6 ft) diameter shaft. The upper part of the photo is a cut through the center of the shaft parallel to the shaft axis. The cracks appear to correspond to the path of the tremie pipe. These internal bleed water cracks or channels may or may not have any detrimental effect on the performance of the drilled shaft, but anomalous low velocity zones revealed by CSL testing can result in expensive water channels is shown on Figure 8 from an exhumed shaft that had been cut using a wire and consuming delays while the nature of the anomaly is investigated.

Where bleed water results in channels adjacent to a removable liner, surface irregularities can result as shown in the photo of Figure 9. Although these irregularities may be shallow, they reduce the effectiveness of the concrete cover over the reinforcing and can lead to future durability problems. Even where concrete will not be exposed, excessive bleeding can result in weak concrete near the top of the shaft which will require time-consuming chipping with hand tools to ensure a sound connection to the pile cap or column.
Low bleeding can be obtained by using more cementitious materials and by using viscosity-modifying admixtures (aka, anti-washout admixtures). ASTM C 232 is an available test method to assess potential bleeding in a concrete mixture, and drilled shaft concrete should exhibit little to no bleeding in this test. This test method is unable to subject the concrete to high pressure conditions present in deep shafts, however. Considerations of workability dictate that there is water in a mixture that exceeds the amount of water needed to hydrate the cementitious materials. Reduction in the water-to-cementitious materials ratio will reduce bleeding, but mixtures that are exceptionally high in cement content can have other problems related to heat of hydration and set time. The total cementitious content can be increased without increasing net portland cement content by using more fly ash or ground-granulated blast furnace (GGBF) slag. Viscosity
modifying admixtures (VMA) can be effective at binding up free water prior to setting of the concrete.

When high dosages of fly ash or GGBF slag are used, the strength development will be slower when compared to mixtures with only portland cement. However, when cured, these mixtures may exhibit higher long-term strengths. In these cases it is advisable to test the specified compressive strength at 56 or 91 days in lieu of the normal 28 day specified strength for conventional concrete.

CONTROL OF TEMPERATURE

Control of temperature is very important for drilled shaft concrete in order to control setting time and the heat of hydration. Excessive concrete placement temperatures will accelerate the rate of hydration significantly and reduce the concrete’s workability. This effect is nonlinear and rate of hydration increases dramatically with temperature in excess of 70°F. The measurements presented on Figure 10 demonstrate the effect of initial temperature on the heat generated within the concrete as a function of time. This generated heat produces more rapid setting in the mixture and a significantly higher heat of hydration in mass concrete.

![Figure 10: The effect of different initial mixture temperatures on the temperature development during adiabatic conditions (Schindler 2002)](image)

Besides the concern about setting time, high heat of hydration is a potential concern for drilled shaft concrete. Shafts larger than about 1.2 m (4 ft) diameter have characteristics of mass concrete in which the heat of hydration can feed on itself and generate large temperatures within the shaft. Recent measurements in Florida (Mullins, 2006) have shown temperatures within the interior of 3 m (10 ft) diameter shafts as high as 180°F. Concrete members made with plain portland cement that reach temperatures above 158°F may exhibit delayed ettringite formation (DEF). DEF can significantly reduce long term durability of the hardened concrete. The temperature development of
an in-place mixture within an actual shaft can be evaluated on test specimens by using adiabatic or semi-adiabatic calortimery (Schindler and Folliard 2005).

In-place temperatures can be controlled by: 1) limiting the total cementitious materials content, 2) controlling the fresh concrete placement temperature, and 3) proper selection of the cementitious material types.

The amount of total cementitious materials has implications relative to design compressive strength. However, concrete design stresses are often quite low in drilled shafts and so it is prudent that the mixture design requirements not exceed the actual performance requirements for design. Because of concerns for setting time and heat of hydration, the use additional portland cement to accommodate an unnecessarily high strength requirement can have other implications on mixture performance. When it comes to cement content, more is not always better!

The data from Figure 10 demonstrate the benefits of controlling the fresh concrete placement temperature in terms of controlling heat of hydration. Temperature controls at the batch plant can be achieved by substituting some of the mixing water with ice, or with liquid nitrogen thermal probes that are used to cool the concrete in the truck.

The use of Type II cement and high dosages of either Class F fly ash or GGBF slag are often the best options to control heat of hydration. Concrete mixtures with high dosages of fly ash or GGBF slag will tend to generate less heat of hydration and are also less prone to DEF; temperatures up to about 178°F can be tolerated without significant concerns of DEF.

SUMMARY

Drilled shaft concrete for large diameter shafts requires careful consideration of the special concrete requirements for this application. The authors propose that the concept of “high performance concrete” should be applied to drilled shaft mixtures to incorporate critical performance requirements related to workability. Specific performance requirements that are particular to drilled shaft applications are described, including workability for the duration of the placement operation, passing ability, resistance to bleeding, and low heat of hydration. Some of these requirements have common characteristics with those associated with “self-consolidating concrete” or SCC, but many are specific to drilled shaft applications. This paper has included an overview of many strategies that might be employed to achieve a concrete mixture that is well-suited to drilled shafts, including:

- Use rounded gravel aggregates rather than crushed stone
- Use No. 67 or 78 aggregate gradation rather than No. 57
- Use sand to total aggregate ratio in the range of 0.44 to 0.50
- Use water reducing and hydration control admixtures
- Use fly ash and/or slag to increase cementitious materials content and reduce the portland cement content
- Use 56 day or 90 day strength specifications in lieu of 28 day for concretes with high dosage of fly ash or GGBF slag
- Use viscosity modifying admixtures (VMA) as needed to help control bleeding

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Consider the temperature of the mixture when selecting admixture dosages to meet workability requirements and delay setting time and use adiabatic or semi-adiabatic curing of specimens to evaluate temperature development of in-place mixtures.

- Control the fresh concrete placement temperature to less than 80°F (and preferably 75°F).
- Utilize Type II cement along with fly ash or slag to control heat of hydration and reduce potential for delayed ettringite formation.

Of course these suggestions are general guidelines with varying degrees of relevance to each specific project. Perhaps the most important guideline is that each drilled shaft project should have a specific mixture developed to meet the requirements for that project. Fresh concrete performance grades, as proposed for hardened properties (Goodspeed, Vanikar, and Cook 1996) should be established for drilled shaft concretes. By preselecting the required performance grade for each fresh property, this will enable designers, contactors, and concrete suppliers to communicate the specific unique requirements of the concrete placement before bidding of the project costs. A single mixture design cannot be simply transferred from one locale to another without consideration of the specific source materials and project requirements.

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REFERENCES


