Concrete is the premier and the most widely used construction material in the world for various types of civil engineering works. During the construction of bridges, dams or any other structure where the foundation part of the structure lies underwater, one has to opt for underwater construction. Underwater concrete has been in use for a long time. Technological progress has mainly been made through the development of improved methods for concrete placement and better equipment. Improvements have been made as regards the design of the mix proportions, the implementation methods, and the quality of the admixtures itself. Superior features include: underwater anti-washout property, self-compacting property, and self leveling property. Anti-washout underwater concrete offers superior performance when the concrete is in fresh state. By adding an anti-washout admixture to concrete, its viscosity is increased and its resistance to segregation under the washing action of concrete can be enhanced. When concrete is placed under water, it induces concrete to deteriorate uniformity. Therefore it is important that we should follow proper mix design, concrete production and placement and quality control. This article presents a brief overview of the characteristics of antiwashout underwater concrete and discusses the
Tremie method, which is the most common method used for underwater concrete placement.

Characteristics of Antiwashout Underwater Concrete

Antiwashout underwater concretes have slightly different properties than ordinary hydraulic cement concrete because of the effect of the admixture. Fresh antiwashout concrete can be characterized by the following properties:

Flowability

Underwater concrete must be so placed in the formwork that it will require no further handling or compaction. The mix therefore should be plastic, cohesive and have good flowability. The mix should also be richer than it is for concrete placed in air, usually no less than 7 bags of cement per cubic yard. Cohesiveness and flow properties can be greatly improved by using admixtures. A retarder and 4 percent entrained air are generally recommended as the combination that ensures more uniform concrete strength across the form, retards the initial set and internal heat development, and reduces laitance. Because of the increased viscosity of antiwashout underwater concrete, the slump transformation takes place over several minutes. The slump is ultimately 8 to 10 in. To have a better understanding of the flowability of this type of concrete, a slump-flow value or a spread value determined by the German Standard DIN 1048 is more suitable than a slump value. The relationship of these values is demonstrated in Figure 4. Table 1 provides criteria for the relationship between flowability and conditions of execution.

Air Content

Mortar and concrete mixed with cellulose ether have greatly increased air content; therefore, such antiwashout admixtures contain an air-detraining admixture to reduce the air content of the concrete to between 3 and 5%. From a petrographic standpoint, the bubble-spacing factor of concrete containing the antiwashout admixture is about the same as concrete without the admixture, but the freezing and thawing resistance tends to be somewhat low.

Bleeding

Concrete containing the antiwashout admixture retains more of the mixing water. Since the normal amount of admixture used is more than double the amount required to prevent bleeding, very little, if any, bleeding occurs in antiwashout underwater concrete. This lack of bleeding is responsible for the small reduction in quality of the concrete and increases the need for reinforcing steel.

Setting Time

The use of antiwashout cellulose admixtures affects the setting time of underwater concrete. When a cellulose antiwashout admixture is used, the setting time (ASTM C 191, 2007) is greatly extended; therefore, the antiwashout admixture contains an accelerating admixture. The most common accelerating admixture amounts are adjusted to result in a final setting time of from 5 to 12 hours. Antiwashout admixtures containing acrylic have no effect on the setting time. When an air-entraining, water-reducing admixture is added to the antiwashout admixture, the setting time is slightly extended, but the increase in setting time for the normal admixture amounts is less than 5 hours. Specialty admixtures can extend the setting time for underwater antiwashout concrete by 30 hours or more.

Mixtures for underwater placements

Concrete must be proportioned for very workable concrete if it is to be placed underwater. The slump should be controlled at approximately 7 in. Normally, the hydraulic-cement content should be around seven bags per cubic yard. The maximum size aggregate should be 1-1/2 to 2 in., and the fine aggregate (fine) content should be around 45% of the total aggregate content. The concrete should be air entrained at about 6 to 7%. Any application that improves the workability of concrete should be considered. This includes pozzolans, natural aggregates in lieu

<table>
<thead>
<tr>
<th>Slump Flow Value (cm)</th>
<th>Softness</th>
<th>Conditions for Applications</th>
<th>Conditions for Execution</th>
</tr>
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<tbody>
<tr>
<td>40</td>
<td>Hard consistency</td>
<td>When it is desired to keep the flow small, such as the execution of a slanted path</td>
<td>Concrete pump pressure transmission boundary</td>
</tr>
<tr>
<td>45</td>
<td>Medium consistency</td>
<td>General case</td>
<td>Less than 50-m concrete pump pressure transmission distance</td>
</tr>
<tr>
<td>50</td>
<td>Medium soft consistency</td>
<td>When excellent filling capability is needed</td>
<td>Concrete pump pressure transmission distance of 50–200 m</td>
</tr>
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Fig. 1: Relationship of slump, slump-flow value, and spread value

Table 1: Criteria of relationship between flowability and conditions of execution
of crushed stone, and use of chemical admixtures to extend the setting time and permit additional water reduction. The fine aggregate proportion should be higher than it is under normal conditions: approximately 45 percent of the total aggregate. Coarse aggregate should be gravel rather than crushed rock; the maximum size being about 3/4 inch. In the case of large mass placings, aggregate up to 1 1/2 inches in diameter can be used.

**Underwater Dispersion Resistance**

The dispersion resistance of concrete during an underwater placement operation is evaluated by such tests as the cementitious materials outflow rate, the change of water permeation rate, the turbidity of the water, the change of pH value, and the change of composition. The rate of dispersion is decreased as the quantity of antiwashout admixture in the underwater concrete is increased.

**Underwater Concrete Placement Method**

There are mainly five methods for placing concrete under water which are listed below:

- Tremie method
- Pump method
- Hydrovalve method
- Toggle bags
- Bags work

Among these five methods Tremie method is the most common method used for underwater concrete placement.

**The Tremie Method**

The most common method of handling concrete under water is by Tremie. A Tremie consists essentially of a vertical steel pipeline, topped by a hopper and is long enough to reach from a working platform above water to the lowest point of the underwater form work. By this technique the steel pipeline, with a watertight seal at its tip, is placed at the bottom of the form work. Depending upon depth, the pipe is filled or partially filled with concrete. Then the pipe is gently raised about 6 inches to release the concrete letting it rise up around the tube. The major objective is to see that the mix flows as continuously and steadily as possible against the pressure of the water until the form is full. The lower end of the pipe must remain submerged in the concrete at all times to maintain its seal under water. By this procedure the concrete is forced and consolidated into place under its own weight.

Tremie pipe should be heavy and rigid enough to withstand external water pressure while remaining perfectly stable during the placing operations. Smooth, seamless pipe is preferable for maximum flow with a diameter of not less than 6 inches and not more than 12 inches. The pipe is normally assembled in long sections, depending on size, mass and depth of the placing. Some form of rubber packing ring is necessary at the joints to seal them properly or else the cement paste may be washed from the mix. The bottom end of the Tremie must be smooth and without flanges, so it can be withdrawn cleanly leaving no voids. In proper Tremie placing, a closure is used to seal the pipe prior to placing the concrete. The simplest type of closure has a flat rubber gasket wooden or steel plate which butts against the end of the pipe. The plate should be 2 inches larger in diameter than the pipe. A single or double wire attached cent rally to the plate passes through the pipe to be attached to the hopper. As the Tremie is lowered to the bottom of the form, water pressure holds the plate tightly in position. Then the pipe and hopper are filled. The plate-retaining wire is released if it is single, or withdrawn if it is double, and the Tremie is raised about 4 to 6 inches from the bottom of the form, allowing the concrete to flow into place.

These closures are usually in the form of cones, plugs or dishes of concrete or steel that fit tightly within the pipe. They are attached to the hopper by wire and are lowered down the pipe to allow the hopper to be charged continuously. After the Tremie is filled, the valve is released and the pipe is raised to allow the concrete to flow. An effective plug can be provided by forcing an inflatable rubber ball into the top of the pipe. The ball is pushed downward by the weight of the concrete. Using a ball for the plug offers the advantage that it will pop to the surface on leaving the pipe. A Tremie hopper should always be partially
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filled with concrete to keep its seal. Loss of a Tremie seal causes segregation and the forming of a gravel plug in the bottom of the pipe. Loading should be slow and steady. The hopper size depends on the mix’s rate of delivery, the volume of concrete being placed, and the rate at which Tremie action is maintained. Maximum center-to-center distance recommended for Tremie pipes varies with the size, depth and configuration of the placing, but the average figure is about 15 feet. The Tremie should be close to the congested form work and reinforcement. For very large jobs, the formwork is either divided or filled in sections or several Tremies are used. The first load of concrete discharged into a Tremie should be especially rich in mortar. This provides a lubricating coating through the pipe which eases the flow of subsequent loads. At the time of closure release, placing begins with the pipe end suspended 4 to 6 inches from the bottom of the form. The initial outrush of concrete will create a protective barrier to prevent the entry of water from the end of the pipe.

The pipe should remain in this position until a thickness of concrete ranging from 3 feet to 4 feet 6 inches has been built up in the form. The raising action of the Tremie can then begin, delivering new loads of concrete into the hopper until the form is full. The depth of pipe submersion necessary before lifting can begin depends on the depth of the water, the plasticity of the mix, and the concrete’s rate of delivery into the hopper. Three to five feet is a reasonable average under most conditions. The deeper the pipe end is submerged initially, the flatter the surface of the concrete will be. The main concern is to place new concrete with the least possible disturbance to the concrete already in place, while maintaining the top surface as level as the job allows. Slow, steady raising of the Tremie is essential.

Under no circumstances should the concrete be allowed to rush out quickly, or water may enter at the pipe ends. If the seal is lost, surges of concrete in contact with water will cause segregation, washing-out of fines and excessive laitance. The rate of placing for most jobs should be considered on the basis of at least 12 to 15 inches per hour. Once placing has begun, it should proceed continuously until the form is full. For this reason a breakdown in mix supply is quite serious when placing concrete under water. Reserve equipment should always be on hand to assure on-the-job continuity. Adequate provision must be made for lowering the Tremie into the form and raising it as placing proceeds. Most large scale handling is done by crane or derrick and smaller jobs by scaffold mounted hoists. Stoppages during Tremie placing can cause considerable difficulty and every effort should be made to foresee and avoid them. The main causes of stoppages are: pipe diameter too small as the mix gradually forms a bridge across the pipe walls; delays in delivery because the mix inside the pipe begins to stiffen; mix too harsh or too stiff making plastic flow impossible; poor aggregate grading and, in particular, insufficient fines, the lubricating coating on the pipe walls is broken and sticking follows.

Stoppages sometimes can be avoided by applying vibration or shock blows to the Tremie pipe. However, great care is needed to avoid losing the seal between the concrete in the form and that in the pipe. By raising the Tremie above the surface, the concrete below the stoppage will fall out and be replaced by water, usually freeing the flow in the process. Using a rubber ball valve offers the best situation in which to replace a lost seal. Recharging of the hopper can be resumed over the ball while the pipe end is inserted about 18 inches below the level of the concrete in the form. A slow pressure is then applied to the ball forcing the water out of the pipe. A sudden out-surge of water should be guarded against as it will wash away fines and lead to segregation under the pipe. Pressure at the end of the pipe is usually sufficient to deform the ball and force it clear.

Case Study 1: Lake Okeechobee S65e Structure Tailwater Weir

The American Bridge completed two 2,700CY [2,065m³] underwater concrete pours, meeting a major milestone on this $14.3M, 5 month emergency project for the South Florida Water Management District near Okeechobee, Florida. The concrete was placed by Tremie using four concrete pumps in two 18 hour continuous pours during the weekends of June 21-22 and July 12-13, at rates up to 230CY (175m³) per hour. As a result of the success of these two pours, the project is now expected to finish on or ahead of the August 16 completion date.

The emergency weir is a tail water structure located about 4,500’ (1,370m) downstream of the S65E control structure and lock – the last structure on the Kissimmee River before its discharge into Lake Okeechobee 8½ miles below. The project is necessitated by record low water levels in the 730-square-mile Lake Okeechobee. Low water in the lake results in the potential of unprecedented head differentials above and below the structure, as the wet season returns and river flow increases. This exposes the structure to possible flotation and sliding during excessive hydrostatic head, and to scouring induced by high velocity and hydraulic jump during openings.
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Case Study 2: Bandra Worli Sea Link, India

The Bandra Worli Sea Link Project in Mumbai, completed in the end of 2008, provides a much faster means to commute from the island city to the western suburbs of Mumbai with Worli and central Mumbai. As a crucial passage and landmark structure in the city, the 5.6-kilometer Bandra Worli Sea Link spans the Mahim Bay, part of the Arabian Sea, and has eight lanes and two cable-stayed bridges with prestressed concrete viaduct approaches. The harsh environment in the Arabian Sea and the complex design of the sea link has generated unique requirements for concrete applications.

Four-hour slump retention

In the construction of the bridge sub-structure, concrete used in the pile cap and piers was cast on the job site in the sea. The concrete was produced on shore and then transported by sea barge and placed in-situ. This process can take up to four hours, depending upon the roughness of the sea. Sometimes, strong winds and tidal variations even make it harder to supply and apply materials in the open sea.

Special precast elements

Bandra Worli Sea Link project has 9 approach bridge modules. Each approach module comprises two independent carriageways. The deck of the carriageways consists of triple cell precast box girders supported on piers founded on an independent substructure. The cable-stayed main bridge has two similar precast triple cell boxes. The precast segments for the bridge are cast at a central precasting yard using the short line method. The concrete for the segments is supplied by the batching plant and is pumped into each mould. Thus the concrete had to achieve 25 MPa strength within 24 hours without steam curing.

Consistent strength for high-volume fly ash concrete

The last but very important requirement was to enable the usage of high-volume fly ash concrete (HVFAC) for Tremie seal concreting, which was done under the pile cap. HVFAC technology allows large volumes of fly ash to replace Portland cement in various concrete applications, thereby providing the multiple benefits of reduced CO2 emissions, improved cost-benefit ratios for infrastructure development, and reduced environmental impacts related to the disposal of fly ash. In this case, the fly ash contents were up to 50% of the total binder. As specified by the customer, the compressive strength requirement for Tremie seal concrete was 30 MPa after 28 days. As the concrete was placed underwater, cohesive strength with good workability was needed in order to be placed with the Tremie pipe or pump. Knowing the challenging requirement of the customer, BASF Construction Chemicals India aptly provided integrated solutions to address it.

Consistent strength for high-volume fly ash concrete

In general, CUBIC METERS grade concrete made with Portland cement only will require a cement content of around 400 kg per cubic meters. With the high content of fly ash, Tremie seal concrete in this project consumed Portland cement of just 180 kg per cubic meters. This would result in a saving of 0.22 tonnes of CO2 for each cubic meters of concrete for the Tremie seal. The total Tremie seal concrete for the project was 20,000 cubic meters and reduced approximately 4,400 tonnes of CO2.

Conclusion

For in-the-wet construction of navigation structures, underwater concrete construction is a critical component underwater concrete construction can be accomplished with the same degree of reliability as above water construction. If it is not carried out properly, with the proper concrete mixture and placement, it can result in a major overrun in construction cost and schedule. The essential difference between underwater concrete and conventional concrete is in the workability requirements. The underwater concrete must flow laterally and compact itself under its own buoyant weight, while conventional concrete is compacted with mechanical vibration. The antwashout underwater concrete is being considered for use in many underwater structures and other large-scale projects. Under current conditions, several problems remain, such as: (1) differences in performance of the more than ten kinds of admixtures currently being marketed, (2) differences in mixing methods and placement methods used by various contractors, and (3) inappropriateness of the antwashout concrete for use in above-water structures due to its drying shrinkage and poor resistance to freezing and thawing. It is recommended, therefore, that the engineer and contractor fully understand the quality of the antwashout underwater concrete and the procedures involved in the placement of this relatively new and innovative material.

References

- Sam X.Yao, and Ben C. Genwick, Under Ground Concrete-Mix Design And Construction Practices.
- Jagadish R., Underwater concrete.

Fig. 5: Tremie Technology used in Bandra Worli Sea Link, India