CONCRETE DEFECTS IN BORED PILES AS A RESULT OF INSUFFICIENT APPLICATIONS OF CHEMICAL ADMIXTURES

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SUMMARY

Concrete typically consists of aggregates, binders, water and air. Depending on the size and shape of the aggregates, the void structure of the concrete matrix can vary considerably. When external pressure is applied to the fresh concrete matrix (such as during and after the placement of fresh concrete in deep excavations like bored piles or diaphragm walls), the void space of the aggregates is reduced and excess water (or cement paste) might be driven from the concrete matrix, typically rising upwards along drainage paths such as reinforcement cages or steel liners, leaving behind voids, channels or areas of poor quality concrete. This phenomenon is known as concrete bleeding or channelling.

The repair and remediation of such damage, which can be located several metres below the pile cut-off level, can be time consuming and expensive.

The lack of fines in the fresh concrete matrix in combination with too much water has been identified as the main trigger for concrete bleeding in deep excavations like bored piles. However, a lack of fines in combination with insufficient (too little) water content is likely to affect the workability of the fresh concrete, causing reduced flow, passing-ability and filling-ability. Such reduced workability performance could cause defects related to insufficient concrete flow, such as mattressing or inclusions of soil or debris in the cover zone of the pile.

Recommendations for the design of tremie concrete mixes, mainly based on practical experience, have been published to assist practitioners to optimise concrete flow and to minimise concrete bleeding in deep excavations by providing performance criteria for fresh concrete; however, these publications do not always provide enough guidance with respect to the potential influence of fines and chemical admixtures on fresh concrete performance.

In recent years, the insufficient application of chemical admixtures in tremie concrete has contributed to defects such as mattressing or segregation-induced concrete bleeding in bored piles and diaphragm walls. Despite very low water levels in various mix designs providing a very stable mix, concrete has segregated prior to setting, and excess paste has been forced from the fresh concrete matrix to rise to the surface along drainage paths inside the fresh concrete.

In other occasions, defects due to insufficient lateral fresh concrete flow and workability have been observed, as the fresh concrete could not pass completely through reinforcement bars and fill the void space behind, leaving a hollow space.
This paper discusses concrete defects in deep foundations with a particular focus on the insufficient application of chemical admixtures and associated effects on the workability and stability of the fresh concrete for deep foundations such as bored piles and diaphragm walls.

INTRODUCTION

The placement of tremie concrete for bored piles or diaphragm walls is a ‘blind’ process. The excavation of the pile or trench is often carried out under the support of water or drilling fluids (e.g., bentonite or polymer) to stabilise the open excavation. Prior to placement of the fresh concrete using the tremie method, the excavation have to be cleaned to ensure that the base is free of debris and fines from the drilling process and the site walls are free of smear.

The placement of tremie concrete is a complex process, and it is important to ensure that the fresh concrete does not mix with the fluid inside the open excavation. As highlighted by several authors (e.g., Beckhaus et al. 2011; Larisch et al. 2013, Larisch 2016), the workability and rheology of fresh tremie concrete is critically important for the outcome and quality of the finished pile or diaphragm wall panel.

Mattressing, as shown in Figure 1, is the most common defect based on lack of concrete workability (Joint EFFC/DFI Concrete Task Group 2018). Defects caused by mattressing typically indicate insufficient flow and fill-ability of the fresh tremie concrete during placement. If the viscosity of the concrete is too high during placement, it will not easily pass through obstacles such as reinforcement bars and is unable to fill the voids behind. Such obstacles can split the fresh concrete matrix, leaving behind a thin channel of de-bonded concrete. If placement occurs under water or drilling fluids, such fluids can enter the thin channel and prevent the concrete from re-bonding, creating a permanent separation layer. Consequently, mattressing can severely affect the durability performance of a reinforced concrete pile or diaphragm wall panel as indicated in Figure 1.

Other defects in deep foundation elements made of cast-in-place concrete relate to inadequate stability of the fresh concrete: the ability to retain water inside the fresh concrete matrix, especially if hydrostatic pressure is applied to the fresh concrete prior to setting. Typical defects related to stability issues of fresh concrete are bleeding channels or voids inside the hardened concrete matrix or along reinforcement bars or steel liners of the deep foundation elements, as shown in Figure 1.

Figure 1. Defects due to mattressing (Joint EFFC/DFI Concrete Task Group 2018) on a bored pile (left) and diaphragm wall panel (centre), and bleeding channels observed on a bored pile (right)
The rectification of defects caused by insufficient concrete workability and/or stability can be technically challenging, time consuming and expensive. Mattressing observed on retaining structures can be repaired without great difficulty on the wall facing the excavation by applying shotcrete. The discovery, exposure and remediation of mattressing defects on the buried face of the wall can be extremely difficult. In the author’s experience, such defects are primarily remediated by cathodic protection or additional structural strengthening of the wall.

Bleeding channels and voids can affect the durability and structural performance of the deep foundation element. The remediation of stability-related fresh concrete issues can also be difficult, as channels and voids can reach 10 m or more below surface levels. In some instances, bleeding channels and voids are so severe that the replacement of the affected piles is necessary, resulting in substantial additional costs and program implications.

The correct use and application of chemical admixtures has the potential to enhance the workability of fresh concrete and to improve its water retention capability and overall stability. However, if applied incorrectly, chemical admixtures have the potential to significantly decrease the required workability of fresh concrete or result in segregation and bleeding, causing potential issues and defects in deep foundations like bored piles.

**Workability and Stability Requirements of Tremie Concrete**

Tremie concrete for deep foundations requires distinct rheological characteristics with respect to yielding, viscosity and slump retention times to achieve the necessary performance criteria for workability and stability. If the concrete is placed under submerged or wet conditions, it must displace the water or drilling fluid inside the excavation, pass through the space between reinforcement bars with ease, and fill the voids behind, to ensure reinforcement bonding and sufficient concrete cover. In addition, the fresh concrete must be self-levelling to avoid inclusions in the cover zone and self-compacting to ensure optimal density and permeability.

Fresh concrete placed inside a deep foundation element is subject to significant hydraulic pressure, exerted by the self-weight of the fresh concrete. This provides compaction to the fresh concrete inside the excavation (the self-consolidation ability of tremie concrete). This pressure is about 0.25 bar per metre depth, and pushes excess water or cement paste out of the fresh concrete matrix. Consequently, the fresh concrete matrix changes its rheological performance after the loss of the initially batched water and cement paste and may become ‘stiffer’ with reduced workability performance or higher viscosities.

These important fresh concrete attributes need to be specified, measured and quantified, so that suitable mixes can be developed and performance under externally applied pressure estimated reliably prior to placement. Additional test methods to determine concrete workability (besides the slump test), such as the L-box test, spread test and T500 time, are required to evaluate the workability performance of fresh tremie concrete (Joint EFFC/DFI Concrete Task Group 2018; Concrete Institute of Australia 2012) as the slump test only measures the lateral collapse of the fresh concrete after lifting the cone. The slump test does not provide information about flow behaviour, yield stress or viscosity of the fresh concrete.

The required viscosity of fresh tremie concrete can be estimated by the L-box test and spread tests with subsequent T500 times. Low T500 times (usually around <5 seconds) indicate low concrete viscosity and are not just favourable but required for sufficient lateral tremie concrete flow and fill-ability. However, these tests are only an indicative and qualitative assessment as the criteria stipulated in best practice guidelines are based on experimental research. Further studies and rheological measurements of tremie concrete are urgently required for a better theoretical understanding of this complex topic.
Yield stress (control of segregation under pressure) can be increased by reducing the total water content (depending on the fines content, general grading characteristics and shape of the particles) and the selection of more ‘favourable’ grading curves, especially with respect to the optimal fines content. The filtration press (Joint EFFC/DFI Concrete Task Group 2018; Concrete Institute of Australia 2012) can be used to assess the stability of fresh tremie concrete mixed in the laboratory and/or on site. However, high yield stresses have the potential affect the workability and flow of fresh tremie concrete.

Concrete Flow During a Tremie Pour

It is important to understand the basic flow patterns of tremie concrete inside a pile or diaphragm wall excavation. There are currently two different theories on tremie concrete flow inside a deep excavation (Joint EFFC/DFI Concrete Task Group 2018): (i) plug flow and (ii) bulging flow (see Figure 2). The flow pattern largely depends on the rheology of the fresh concrete which is placed for a particular pile or panel.

The placement of the first load/batch of concrete is similar in both theories. Initially, the tremie pipe is filled with water or drilling fluid as it is lowered down into the excavation. The separator (e.g., rubber ball or vermiculite plug) is installed through the hopper before the first charge of tremie concrete is discharged into the hopper. As the tremie concrete flows down the tremie pipe, divided from the drilling fluid or water by the tremie separator, the base of the pile or diaphragm wall excavation experiences some flushing from the fluid displaced from inside the tremie pipe. This fluid flushes debris and remaining fines from the base, dispersing them temporarily a few metres above the pile base. As the fresh concrete reaches the bottom of the tremie pipe, it hits the clean base of the excavation, spreading outwards from thecentre of the bottom of the tremie pipe (which is located about 300–500 mm above the bottom of the excavation) towards the edges of the deep excavation. When it reaches the borehole/panel walls, the fresh concrete starts to flow upwards, pushing through the reinforcement cage and along the borehole wall. The debris and fines that were dispersed temporarily from the base settle on top of the fresh concrete from this first batch. This is one reason why numerous tremie concrete guidelines (Joint EFFC/DFI Concrete Task Group 2018, Concrete Institute of Australia 2012) recommend trimming back this contaminated layer of concrete after the tremie pour.

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**Figure 2.** Concrete flow inside a deep foundation using the tremie method. After placement of the initial batch (left), concrete might flow using plug flow (centre) or bulging flow (right).
Plug Flow

The theory of plug flow assumes that the initial plug of concrete rises upwards as a result of pressure applied by the fresh concrete, entering the excavation through the tremie pipe underneath, during placement. No fresh concrete blends with the initial plug, but rather, pushes it upwards. As the tremie pipe is lifted regularly, maintaining its minimum embedment into the fresh concrete of at least 2m (Joint EFFC/DFI Concrete Task Group 2018), the initial batch of concrete always stays on top of the fresh concrete and the contaminated layer of debris stays on top of the plug. This theory assumes that the concrete plug closes up after shearing during the upwards movement and that it does not mix with fresh concrete from below. Plug flow is likely to occur when using very fluid, self-leveling concrete mixes with low-to-moderate yield stresses and low viscosity. Such mixes are very close to self-compacting concrete (SCC), as shown in Figure 3. In addition, boundary conditions with low shear resistance, such as smooth borehole walls and pile sections without or very light reinforcement cages, support plug flow.

Bulging Flow

Bulging flow occurs when the initial concrete plug is sheared off by the reinforcement bars and pushed towards the sides of the excavation during the upwards movement as a result of shear resistance. Bulging flow assumes that the older concrete is displaced vertically and laterally and is placed along the borehole wall and reinforcement cage. Fresh concrete from the ongoing tremie placement is pushed through the centre of the fresh concrete column, along the tremie pipe (which forms a path of low resistance), and, as a result, relatively fresh tremie concrete can be found close to or directly at the surface of the completed pile or diaphragm wall panel.

Bulging flow occurs if the concrete shows moderate-to-high viscosity, when passing-ability and fill-ability is limited. High yield stresses typically also support bulging flow patterns.

In the author’s opinion, the type of fresh concrete flow inside a deep excavation strongly depends on the rheology of the fresh concrete. Tremie concrete, designed closer to SCC characteristics, might exhibit plug flow, whereas concrete designed closer to normal class concrete is likely to exhibit bulging flow.

As the initial plug of fresh concrete (including the contaminated layer of debris and fines on top of its surface) is pushed and placed along the borehole wall during bulging flow, contaminated concrete can sometimes be found inside the concrete cover zone or along the reinforcement cage, which has the potential to cause defects due to inclusions and related durability issues.

Consequently, tremie concrete should be designed with the aim of exhibiting plug rather than bulging flow to avoid deposits of contaminated concrete along the borehole wall (cover zone) and/or reinforcement cage. Spread testing is therefore more suitable than slump testing.

In the author’s experience, based on numerous observations of concrete pours and analysis of a large variety of defects in concrete piles, a combination of both flow patterns is likely to occur in most applications, and, depending on the consistency of the concrete supply, different batches might exhibit different flow patterns.

During bulging flow, the deposit of debris from the contaminated layer is likely to occur independently of the selected pile diameter. Thinner layers of contaminated concrete might deposit at larger depths. Issues inside the concrete cover zones are typically not detected by state-of-the art pile integrity testing methods, such as cross-hole-sonic logging or low-strain integrity testing (Larisch 2011). The recent development of new pile integrity testing methods, such as thermal integrity profiling (TIP), which is based on the hydration temperature of the deep foundation element, could help to detect such defects in the future.
Grading Curves and Particle Packing

The performance of tremie concrete, especially for deep piles or diaphragm walls in excess of 30 m depth, is more sensitive to the characteristics of the raw materials than normal class concrete.

Optimised packing densities of the aggregates and the addition of well-graded sand can minimise the void content. This is important for improved workability of the fresh tremie concrete, as the quantity of cement paste required to fill the voids between the aggregate particles is minimised, leaving more of the binder content (cement paste) available for wetting and lubricating the aggregates (for example, by reducing inter-particle friction) and consequently improving the fresh concrete workability. However, too much cement paste is likely to be squeezed out under pressure, when the aggregate matrix is compressed, and the void content is reduced. It is important to find the 'optimal' amount of cement paste required to fill and lubricate the aggregate matrix. The ‘Bauer filtration press’ can aid to assess the amount of excess paste/water forced out of the matrix by applying pressure to the fresh concrete.

In general, fines increase the surface area of the fresh concrete matrix, and water or cement paste can 'bond' with this increased surface area. This is important to reduce the total surface area of the aggregates to allow for the lowest possible design water percentage, while maintaining sufficient fines to assist in water retention within the microstructure.

Therefore, the choice of suitable aggregates and their packing density and grading curves is vital for the successful design of well-performing tremie concrete mixes. If those data points are not available, the fines content of particles < 600 microns should be at least 25% of the total aggregate content as a starting point for laboratory trials to ensure increased resistance to bleeding under pressure. In some cases, this value might need to be increased to 30% of the total aggregate volume, subject to laboratory testing and required performance criteria (Larisch 2019).

The fines content of natural aggregates and sands strongly depends on the local availability. Therefore, trials should be carried out for new tremie mixes to assess the potential risk of bleeding under pressure, especially when aggregates with low fines content are used. Gaps in the grading curves usually indicate a discontinuity in particle size distribution, which could indicate an increased risk of segregation under pressure and associated bleeding under pressure. Such gaps could be filled by adding other coarse materials or fillers to ensure optimal packing density for a particular concrete mix design.

Chemical admixtures can help enhance fresh concrete performance and properties but should not be used to mask a poorly graded mix designs.

Chemical Admixtures

As discussed previously, fresh tremie concrete requires a certain amount of energy (yield stress) to start moving before it resists this movement (viscosity) after initiation. These two key rheological parameters (yield stress and viscosity) vary across concrete types and applications, as shown in Figure 3.

Tremie concrete requires low viscosity for good filling-ability at low-to-moderately high cohesion, which is represented by a higher yield stress value, to control segregation and bleeding under pressure. Therefore, it is important to ensure that tremie concrete is designed with higher viscosity and lower yield stress than normal class concrete but lower viscosity and higher yield stress than 'standard' SCC mix designs.
Figure 3 shows the impact of chemical admixtures and other additives with respect to the rheology of any concrete mix design. The graph is used to assess the influence of such admixtures and additives for tremie concrete applications.

**Time**

Time develops the setting and hardening of fresh concrete, and consequently, the plastic viscosity will mildly increase, whereas the yield stress will grow until setting occurs.

**Silica Fume or Micro Silica**

Silica fume or micro silica is not a chemical admixture but a supplementary cementitious material. In various international and national guidelines, the replacement of other supplementary cementitious materials such as ground granulated blast-furnace slag or fly ash with silica fume is permitted and mandatory or indicative quantities for replacement are provided. It is important to note that silica fume, because of its very fine particle sizes, has a significantly higher surface area than cement, slag or fly ash. Therefore, replacement quantities are typical lower for similar applications. The use of micro silica in fresh concrete initially reduces the plastic viscosity before it increases both, the yield stress and viscosity.

Tremie concrete with silica fume is very stable, but workability and flow are typically reduced compared with the use of fly ash or slag. This needs to be considered when designing tremie concrete with silica fume, and laboratory tests are required to assess whether basic requirements, such as low T500 times and sufficient L-box flow and filling-ability, for fresh tremie concrete are met.

**Air (Air-entraining Admixtures)**

The addition of air into fresh concrete mixes has only marginal effects on the yield stress (stability) if no external pressure is applied (hence, not applicable to tremie concrete). Added air has the potential to reduce the viscosity of the fresh concrete, making it more workable.

As air-entraining admixtures improve workability, fill-ability and concrete flow, the additional air inside the fresh concrete matrix provides space for excess water or cement paste during batching; the volume of this additional water/paste can vary between 5–20/l/m³ depending on the air content. Therefore, air-entraining admixtures are beneficial to reduce concrete bleeding...
if no external pressure is applied. However, because of the applied hydrostatic pressure during and right after the placement of tremie concrete, the air content in such concrete can be reduced to about 1% if particle packing is optimised. Consequently, the excess, water and/or cement paste kept inside the additional air voids during batching is pushed out of the fresh concrete matrix and travels along drainage paths such as reinforcement cages towards the surface, potentially creating bleeding channels and voids (Larisch 2019). In addition, any entrapped air must travel upwards through the fresh concrete matrix and might become ‘trapped’ in layers of stiffer concrete, potentially causing voids, air pockets or other potential defects. Such defects can be large or small and insignificant in terms of the overall strength and durability performance, and it is not possible with current state-of-the-art non-destructive testing methods to detect small or medium-sized air pockets or other defects. Concrete coring would be required to find such pockets, and it is often impossible to distinguish between air pockets and bleed water pockets.

Air-entrawing admixtures are not recommended for tremie concrete.

Water

In general, the addition of water reduces the yield stress (cohesiveness and stability) of a tremie concrete mix and reduces viscosity at the same time. The latter potentially improves the workability of the fresh concrete during testing. As the addition of water reduces the plastic viscosity of fresh concrete but increases the risk of bleeding under pressure. Conversely, concrete workability after concrete bleeding under pressure is significantly reduced, and the addition of water does not necessarily improve the workability of tremie concrete during and after placement.

Prior to the development of efficient high-range water reducers (HRWR), the addition of water was not uncommon to achieve the required workability characteristics for tremie concrete. In the author’s personal experience, a few decades ago, some tremie concrete mixes were designed using a strength class above the project requirements, and additional water was added to improve workability with the side effect to ‘dilute’ the concrete. Standard concrete mixes were designed with slump values around 120–140mm and additional water added to achieve slump values around 200–220mm. With the addition of the extra water, concrete bleeding in bored piles started to occur more frequently as the stability of the fresh concrete started to become insufficient. This method should not be used any longer; it does not reflect industry best practice. The use of water-reducing (WR) admixtures and HRWR is highly recommended when designing tremie concrete mixes.

Water-reducing Admixtures

WR and HRWR admixtures are generally referred to as plasticisers and superplasticisers. Their main goal is the reduction of the water content in a concrete mix to increase strength and durability and hence workability. Figure 3 suggests that WR admixtures have no or very little impact on the viscosity of fresh concrete but can assist to significantly reduce the yield stress (cohesiveness and stability) of a concrete mix.

Superplasticisers’ main function is to absorb onto the positively charged cement particles, where they repel others through electrostatic repulsion and steric hindrance, thereby releasing the trapped water. The result of this dispersion can be utilised to reduce the energy to the initiate flow of the concrete. However, if too much water is dispersed into the fresh concrete, the mix might become unstable. In normal class concrete (and tremie concrete), the yield stress counteracts sedimentation forces of the larger grains and prevents them from sinking (Wallevik 2003). If the yield value of the tremie concrete is too low to prevent the aggregates from sinking, segregation of the concrete is likely to occur. Therefore, overdosing tremie concrete with WR or HRWR admixtures can cause segregation of fresh tremie concrete.
Segregation Due to Overdosing WR or HRWR Admixtures

If the dosage of WR or HRWR admixtures is too high, the amount of design water might be insufficient to react with all admixtures; thus, a portion of the WR/ HRWR will stay ‘dormant’. These ‘dormant’ admixtures may react with water released into the fresh concrete by segregation or bleeding under pressure or with water entering from the surrounding soil matrix.

During the tremie pour, individual concrete batches are placed in layers, one on top of the other, as described previously, regardless of whether the flow pattern follows a plug or bulging flow pattern. If one layer of fresh concrete contains a higher water content (with a high likelihood of bleeding under pressure), and if this layer is ‘sandwiched’ between layers with lower water contents (with a low likelihood of bleeding under pressure), the layer with the higher water content could release bleed water into the layers with low water contents. This bleed water could then react with the ‘dormant’ chemical admixtures, which might cause segregation and release more water into the fresh concrete matrix, potentially starting more segregation and release of water. The released water typically moves upwards and usually travels along reinforcement bars or steel casings (Larisch 2019). The whole mechanism strongly depends on how much bleed water travels upwards and ‘activates’ the ‘dormant’ chemical admixtures in the layers above. Sometimes, the process only affects a few layers within the pile, ending or slowing down when it moves closer to the surface as the hydrostatic pressure becomes less, and a smaller amount of water is released out of the fresh concrete.

Over-dosing WR admixtures can significantly increase the air content in fresh concrete.

Viscosity-modifying Admixtures and Other Anti-washout Admixtures

Viscosity-modifying admixtures (VMAs) can be used to improve the rheology of the fresh concrete and increase its stability and resistance to bleeding under pressure. VMAs were developed for underwater concrete and their main purpose is to increase the cohesiveness (yield stress) of the concrete to prevent washout of fines and increase viscosity. VMAs and other anti-washout admixtures are very useful in reducing bleeding under pressure.

However, tremie concrete requires low viscosity with relatively low-to-moderate yield stress; with increasing viscosity, the ability to flow and fill voids is reduced. Thus, VMAs should be dosed up very carefully and must be subject to laboratory trials before being used in tremie mix designs. Overdosing VMAs can significantly impact the workability of fresh tremie concrete, which might be reflected by high T500 times or inability of the mix to reach the end of the L-box. ‘Mattressing’ is a typical defect caused by insufficient fresh concrete workability.

Natural minerals are also a proven product to improve the rheology of tremie concrete if dosed correctly. Minor adjustments to the concrete mix design might further improve their impact.

Retarders and Hydration Stabilisers

The function of retarding admixtures is to delay the end of the dormant period and the start of the setting/hardening time of the fresh concrete, which is typically achieved by ending the rapid set of the tricalcium aluminate. The admixture anions and molecules are adsorbed onto the surface of the cement particles, hindering or slowing further cement hydration.

Retarders are required to maintain the required concrete workability criteria over the extended period needed to place concrete for a bored pile or diaphragm wall panel. Such requirements are typically 2–4 hours for standard applications but can extend to 10 hours or more for special applications (Larisch 2019). Slump retention is primarily linked to concrete stability and the conservation of yield stress at low-to-moderate levels. Changes in yield stress will affect the viscosity and the ability of the fresh concrete to fill the deep excavation.
In the author’s experience, retardation admixtures are most efficient and suitable for retardation times of 3–4 hours. Longer slump or spread retardation times can be achieved more reliably and efficiently with hydration stabilisers.

It is important to highlight that overdosing retardation or hydration stabilising admixtures might create unfavourable side effects, such as greatly increased (and uncontrolled) set times. In the author’s professional experience, such set times could be in excess of 24 hours, which might risk the integrity of the concrete matrix, as segregation or ‘bleeding under pressure’ could be prolonged and bleed water or cement paste may be observed to escape at the surface level a long time after the concrete pour has been completed.

Laboratory trials to prove slump retention performance are strongly recommended prior to concrete placement on site, and it is important to model the boundary conditions inside a deep excavation where no external energy is applied to the fresh concrete during placement.

The ‘Bucket Test’

The ‘bucket test’ is non-standardised fresh concrete test to assess the performance of the slump retention of a concrete mix without applying external energy. Tremie concrete inside an excavation does not experience external energy via re-mixing or stirring; therefore, those conditions need to be simulated accordingly.

The suggestion is to fill a number of buckets with fresh concrete right after batching. The number of buckets to be filled should be equal to the specified slump retention time calculated in ‘hours’ (e.g., for four hours’ slump retention, four buckets are required). The buckets should be closed with a lid and put aside in a cool and shady area. The first bucket is opened after one hour and the concrete is poured (without stirring) on a spread board or clean and level surface. Workability is assessed visually, and if the concrete still flows, slump retention should be suitable for one hour, subject to the experience and skill of the tester. The concrete could be filled in a slump cone and a slump or spread test could be carried out to obtain the spread and T500 time.

This procedure should be repeated until the last bucket has been assessed or the concrete becomes ‘unworkable’ (see Figure 4). This test can be modified to suit project-specific needs (e.g., 60- or 30-minute intervals).

![Figure 4. The non-standardised ‘bucket test’ indicates the slump retention time of resting concrete mixes and provides an estimate of how long the fresh concrete remains ‘workable’ (left) and when it becomes ‘unworkable’ (right)](image-url)
CONCLUSIONS

If applied correctly, chemical admixtures can largely improve the rheology performance of fresh tremie concrete. However, insufficient applications can also reduce workability and stability performance, with associated defects and non-conformances.

Concrete defects such as mattressing or inclusion of debris or fines can be the result of insufficient tremie concrete workability. Bleeding channels and segregation are typical indications of unsuitable stability performance of the fresh mix during placement.

The structure of a high-performing tremie concrete mix should yield a robust balance between rheological attributes based on optimal packing density, material grading and chemical reactivity of the constituents. Tremie concrete requires low-to-moderate yield stresses for stability and cohesion in combination with low viscosity to ensure workability and fill-ability.

The rheology of the fresh concrete plays an important role with respect to the flow behaviour inside the deep excavation during placement—the time-dependant rheology, hydrostatic pressure conditions and local reinforcement details greatly influence those patterns.

More viscous concrete might tend to show bulging flow behaviour during concrete placement using the tremie method, as the concrete might ‘stick’ to the reinforcement cage and borehole wall, whereas less viscous concrete with more favourable flow characteristics may follow a plug flow pattern. The latter is likely to push the layer of contaminated concrete (located on top of the first batch of tremie concrete) to the surface, without depositing contaminants like debris and fines along the reinforcement cage and borehole wall. Therefore, tremie concrete should be designed that has rheological behaviour closer to SCC than normal class concrete to ensure plug flow behaviour, such that the contaminated layer is pushed to the surface rather than laterally into the reinforcement cage and borehole wall (bulging flow).

The flow of tremie concrete inside an excavation needs to be understood in more detail; the flow patterns described in recent tremie concrete guidelines (Joint EFFC/DFI Concrete Task Group 2018) and published by Larisch et al. (2013) are only an attempt to better understand this process. Further site trials in combination with advanced numerical modelling are required.

The main defects caused by insufficient concrete workability in bored piles and diaphragm walls are mainly related to mattressing and inclusions of debris at the reinforcement cage and along the borehole wall. Typically, such defects are related to concrete mixes with insufficient viscosity, resulting in bulging flow.

Bleeding channels, voids and segregation issues can be related to stability problems of the fresh tremie concrete and insufficient yield stresses of the fresh concrete mix. Bleeding under pressure can change the rheology of the fresh concrete because of the reduction of water, which can create issues related to workability performance, as described above.

The use of WR and HRWR can significantly enhance concrete workability and reduce the amount of water needed to achieve the required workability, which greatly reduces the risk of bleeding under pressure. The dosage of such admixtures needs to be monitored carefully, as overdosing WR or HRWR can cause segregation of fresh concrete, and the released water has the potential to create defects as a result of bleeding under pressure or further segregation. Typically, bleeding channels or weak concrete inside the cover zone are indicators of insufficient stability, segregation and bleeding under pressure.

VMAs and anti-washout admixtures can improve concrete stability, but overdosings those admixtures may affect concrete viscosity, leading to insufficient flow and fill-ability characteristics of the fresh concrete, which may result in mattressing through insufficient flow.
Retarders should be used for slump retention times up to 4 hours and hydration stabilisers for applications in excess of 4 hours. Retardation admixtures must be applied with great care as overdosage might extend set times to 24 hours or more, which exposes the concrete to potential issues because of segregation or bleeding under pressure. Laboratory tests that model the boundary conditions inside a deep foundation should be considered.

Air-entraining admixtures can improve fresh concrete workability and reduce general bleeding. Unfortunately, such admixtures are unsuitable for tremie concrete applications as the additional air is likely to encapsulate additional water or cement paste, which will be pushed out when external pressure (due to the self-weight of the fresh concrete) is applied. Overdosing WR admixtures can significantly increase the air content in fresh concrete.

The replacement of fly ash or grounded granular blast-furnace slag with silica fume should always be verified by laboratory tests to confirm that the required workability of the tremie concrete is still provided. Silica fume significantly increases the yield stress and viscosity of the fresh concrete, which can cause issues with workability and the ability to flow through reinforcement cages and fill voids inside the pile excavation. Mattressing can occur when silica fume is added to a tremie mix without sufficient adjustment of the concrete mix design.

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