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Primary firm secant pile concrete specification

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The minimum compressive strength of concrete at age 28 d is the main performance criterion for the acceptability of an approved mix design. In secant pile wall construction, it is necessary for the secondary male pile bore to be cut into the concrete of the primary female pile concrete to produce a water-resistant pile interlock. The accuracy and efficiency of the cut and the pile verticality that can be achieved are influenced, among other things, by the strength of the primary pile concrete at the time the cut is made. Minimum characteristic primary pile concrete strength depends also on the long-term function of the pile and can vary widely from about 0·5 MPa for 'soft' non-structural piles to about 40 MPa for 'hard' structural piles. Thus, there are potentially conflicting concrete requirements for early and long-term strength. This paper reviews current practice for concrete used in secant piling, identifies that there are areas of uncertainty in standard specifications, that over-specification and over-provision of strength is probably commonplace and shows how a window of allowable compressive strength would be a superior method to control pile concrete strength.

Notation

B	interlock dimension between male secondary piles
d	pile diameter
f	extreme fibre stress
f_c	compressive strength of concrete
f_{cd}	design value of compressive strength of concrete
f_{ck}	characteristic compressive cylinder strength of concrete at 28 d
f_{cm}	mean value of concrete cylinder compressive strength
$f_{cmu(2)}$	mean compressive cube strength of concrete at age 2 d
$f_{cmu(28)}$	mean compressive cube strength of concrete at age 28 d
f_{cu}	characteristic value of cube strength concrete at age 28 d
$f_{cu(2)}$	compressive cube strength of concrete at age 2 d
$f_{cu(7)}$	compressive cube strength of concrete at age 7 d
$f_{cu(56)}$	compressive cube strength of concrete at age 56 d
$f_{cu(t)}$	compressive cube strength of concrete at age t days
k_0	coefficient of horizontal earth pressure at rest
l	horizontal span between adjacent secondary secant piles
M	bending moment
S	pile spacing
s	coefficient in calculation of β_{cc} linked to cement grade
t	time being considered (age of concrete (d))
u	pore water pressure
v	design shear stress
v_c	design concrete shear stress
v_u	ultimate concrete shear stress
w	distributed load on equivalent beam
z	section modulus
β_{cc}	coefficient linking strength of concrete at different ages to strength at 28 d age
γ_F	partial safety factor for load
γ_M	partial material factor for concrete in shear
σ'_h	effective horizontal ground stress
σ'_v	effective vertical ground stress

1. Introduction

This paper presents a review of current practice for the specification of concrete used to construct unreinforced primary female firm concrete piles which form part of a secant piled retaining wall. Secant pile walls are used in preference to contiguous piled walls where a substantially water-resistant barrier is required. Therefore the primary pile must interlock with the secondary male pile either side of it. This is achieved by boring the secondary pile down through part of the primary pile so that one pile interlocks or secants with its neighbour, the overlap at each interface being up to 30% of the diameter of the primary pile. It is common and preferred practice for the primary pile to be of plain unreinforced concrete. Typical spacings of primary and secondary piles are shown in Figure 1 (taken from Ciria C580 (Ciria, 2003)).

Where the primary and secondary piles are both reinforced, there is a need for the concrete of both piles to achieve a characteristic compressive strength normal for that of structural concrete. Where only the secondary pile is reinforced, the required characteristic compressive strength of the primary pile

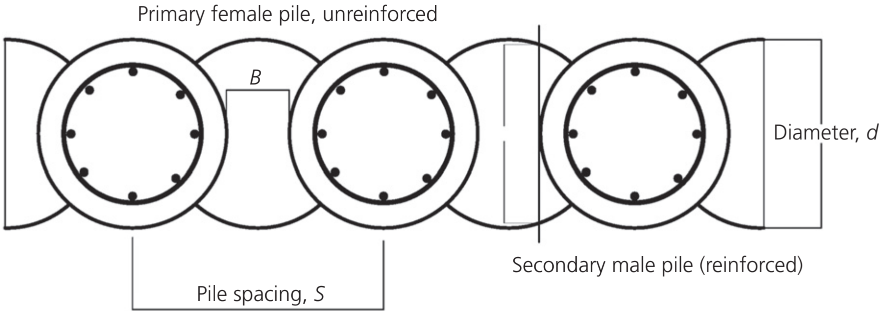

Figure 1. Typical pile spacings in a secant wall

can be lower as the unreinforced concrete is easily capable of transferring the soil and/or groundwater pressures onto the closely adjacent secondary reinforced piles. The decision on what strength of concrete is required depends on several factors, for example strength, durability, permeability and degree of water-tightness. The latter may be influenced by the amount the concrete may shrink during drying or crack during drilling.

The characteristic compressive strength of material forming secant piles (and therefore the piles themselves) is commonly referred to as either hard, firm or soft. The secondary pile is usually a hard pile, so there are three possible combinations of pile type: hard/hard, hard/firm and hard/soft.

Soft piles utilise unreinforced weakly cemented materials such as cement–bentonite–sand slurries with a characteristic compressive cube strength at 28 d of up to 3 MPa. They are typically used in temporary works applications and are not considered further here.

Firm piles utilise concrete with a characteristic compressive cube strength at 28 or 56 d of about 10 MPa to 20 MPa while the characteristic compressive cube strength of hard pile concrete at 28 d is greater than 25 MPa.

The specification of the strength and the rate of strength gain of concrete in firm primary piles is of particular concern and is the subject of this review. It is argued that, provided permeability, shrinkage and cracking is controlled and long-term durability provided, a lower than normal concrete strength should be adequate for most applications.

The benefits of carefully controlling the properties of a firm primary secant pile concrete are to enable less powerful piling rigs to be used to achieve the specified pile verticality and interlock. In practice this means that the uncased continuous flight auger (CFA) method of rotary bored piling, the fastest and most cost-effective form of replacement secant piling, can be applied with greater confidence. Where concrete strength development is poorly predicted and controlled and primary piles are cut when they have developed excessive strength, pile wall alignment and interlock suffer, see for example Figure 2.

Figure 2. Out-of-position continuous flight auger bored secant piles

This paper makes reference to compressive strength of concrete established by tests on cylinders and on cubes. Practice in the UK is generally to test cubes, not cylinders, and unless the context specifically requires, compressive strengths should be taken to mean those determined on cubes.

2. Current practice

2.1 ICE specification for piling and embedded retaining walls

The de facto standard specification in the UK for secant pile wall construction is the second edition of the *ICE Specification for Piling and Embedded Retaining Walls* (Sperw2) (FPS, 2007). For both hard/hard and hard/firm walls, the guidance provided in section 9 of this document is to utilise low-strength high-cement replacement prescribed concrete mixes with characteristic compressive strength measured at 56 d. The control of early-age strength gain is stated to be critical to the secant pile construction. In practice, either a prescribed concrete (for which the composition and constituent materials are specified) or a designed concrete (in which the properties are specified) is used.

Section 19 of Sperw2 deals with the requirements for concrete. Structural concrete is defined in table C19.1 as that which has a compressive strength class of C16/20 or higher, the 16 referring to cylinder strength and the 20 referring to cube strength. This grade of concrete is used to form a hard pile. Non-structural concrete used for 'infill piles' is of lower strength class.

Compressive strength conformity testing and acceptance criteria in Sperw2 follow the requirements of BS 5328 Part 4 (BSI, 1990). For structural concrete, this may be considered to be appropriate even though BS 8500 (BSI, 2006a, 2006b) was extant at the time Sperw2 was produced. For non-structural concrete it is not.

In order for trial concrete mixes to be acceptable, the average strength of two 28 d cubes is required to exceed the characteristic strength by not less than 11·5 MPa. It is assumed that for normal grades of structural concrete with a characteristic strength in the region of 40 MPa, a margin of 11·5 MPa might represent 2 standard deviations between the mean value and the value at which 95% of results lie. Such a large finite margin is not appropriate for lower-strength firm primary secant pile concrete.

In order for works concrete to be acceptable, Sperw2 requires the strength of 28 d cubes to exceed the characteristic strength by not less than 1 MPa to 3 MPa, the actual value depending on the number of cubes tested.

Sperw2 also requires trial cubes and works cubes to be tested at age 7 d, but no acceptability criteria are specified. The compressive strength test results at 7 d are thus taken to be early indicators of the likely 28 d strength. Concrete's early strength development is dependent primarily on its Portland cement content and Table 1, taken from The Concrete Centre guidance (Specifying Sustainable Concrete, 2011), provides an indication for concretes made with varying proportions of Ordinary Portland Cement (OPC = CEM1) with partial replacement by fly ash (PFA) or ground granulated blast-furnace slag (GGBS).

Clearly, the focus of Sperw2 is to ensure that the characteristic compressive strength of 28 d cubes comfortably exceeds the specified characteristic cube strength. It is considered that this is not appropriate for firm secant pile concrete.

2.2 Strength development

The use of GGBS and/or PFA to replace CEM1 is common practice, desirable and to be encouraged. Using the 7 d strength indicator for a 70% GGBS replacement mix on Table 1 of say 40%, Figure 3 presents a chart of required cube strength against cube age for two typical non-structural firm pile concretes.

Concrete	Strength at 7 d[a]: %	Strength gain from 28 to 90 d[a]: %
CEM1 concrete	80	5–10
30% fly ash concrete 50% GGBS concrete	50–60	10–20
50% fly ash concrete 70% GGBS concrete	40–50	15–30

[a]Strength as a proportion of 28 d strength.

Table 1. Rate of strength gain of different concretes

BS EN 1992-1-1:2004 (BSI, 2004) section 3 provides equations to estimate the compressive strength at a given age, the strength being dependent on grade of CEM1 cement, temperature and curing conditions. It should be noted that the concrete strength is measured on cylinders, not cubes, although the equation holds for cube strengths. For uniform curing conditions, the compressive strength of concrete at age t days is given by

1. $$f_{cm}(t) = \beta_{cc}(t)\, f_{cm}$$

in which $\beta_{cc}(t) = e^n$ and $n = s(1 - (28/t)^{0 \cdot 5})$

The coefficient s depends on cement grade and the values in Table 2 are given in the code.

It is noted that cements of class S contain between 66 and 80% of GGBS and as such constitute cement group CEMIII. (BS EN 197-1 (BSI, 2000a)). Cements of class N are CEM1 cements with ordinary early gain of compressive strength, whereas cements of class R are CEM1 cements with high early strength gain. For concretes made with high CEM1 substitution and requiring a low rate of strength gain, it is thus logical to expect cement of class N and grade 42·5 to be mixed with GGBS and/or PFA for firm pile concrete.

For the prediction of the rate of strength gain of high-cement replacement mixes, it might therefore be appropriate to adopt an s coefficient of not less than 0·25 and probably more, perhaps substantially more, than 0·38.

Figure 4 shows theoretical strength development curves for C8/10 and C16/20 concretes made with class N CEM1 cement cured in accordance with BS EN 12390 (BSI, 2000c) at 20°C and assuming $s = 0{\cdot}25$. At age 7 d, some 78% of the 28 d

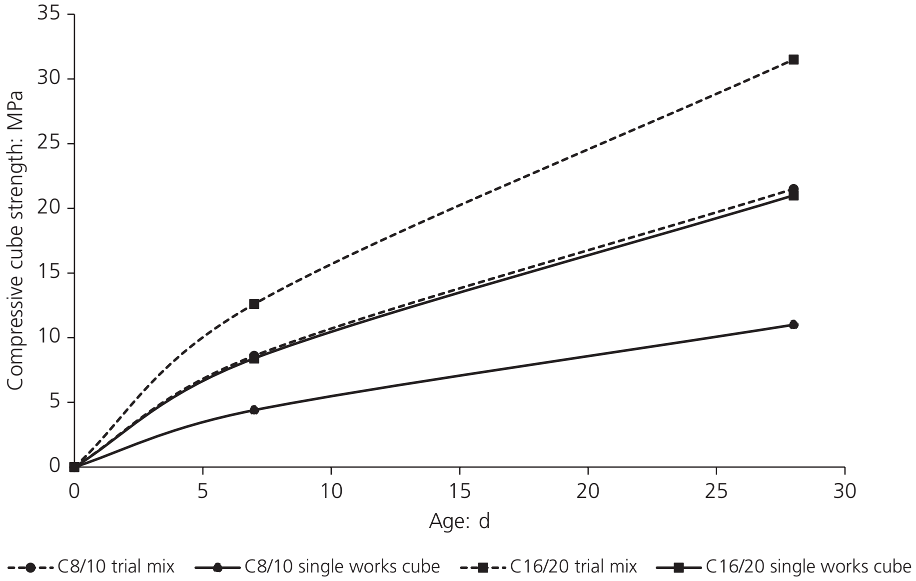

Figure 3. Typical minimum compressive cube strength required by Sperw2

Cement class	Cement grades	*s*
S	32·5 N	0·38
N	32·5 R, 42·5 N	0·25
R	42·5 R, 52·5 N, 52·5 R	0·20

Table 2. Strength gain coefficient *s* for of different cement grades

strength is predicted to have been achieved and the difference between the 28 and 56 d compressive strength is only some 8%. The Table 1 figures for a substantial amount of CEM1 replacement suggest that, on average, approximately 50% of the 28 d strength is predicted to be achieved at age 7 d and the difference between the 28 and 56 d compressive strength is predicted to be some 20%. There is thus significant variance between the Table 1 guidance (the basis of which is not known) and the Eurocode 2 (BS EN 1992-1-1:2004 (BSI, 2004)) predictive equation when used with recommended *s* values. The *s* value required to approximately produce the Table 1 gain percentages is about 0·6.

Wharmby (2010) comments that in a number of secant piling projects in New Zealand there was considerable variance in the concrete strength at any given age. The details of the concrete mix are not known but may be assumed to have involved considerable CEM1 substitution. The standard deviation of sample strength at 3 to 56 d is given as 0·65 MPa to 2·99 MPa for a specified concrete cylinder strength of 6 MPa at 28 d. Approximately 48% of the mean 28 d cylinder strength is shown to have been reached at age 7 d and the difference between the mean 28 and mean 56 d compressive cylinder strength is shown to be 27%.

2.3 Cement replacement

The replacement of OPC with GGBS or PFA has a successful track record for use in primary secant piles. The advantages are several: reduced rate of strength gain; inherent resistance to acid and sulfate attack; sustainable use of waste/industrial by-product; and slightly improved workability for a given cement content. Up to 95% of CEM1 may be replaced by GGBS and BRE Information Paper IP17/05 (Quillan *et al.*, 2005) presents the case for such concrete, the CEM1 replacement level of which exceeds the 80% value covered by the guidance on the chemical attack of concrete given in BRE Special Digest 1 (SD1 (BRE, 2005)). The maximum replacement level for CEM1 by PFA in SD1 is 55%. There appears to be no reason why this cannot be safely increased without unduly compromising long-term strength or durability and further confirmatory research in this area is desirable.

SD1 appears to limit the amount of CEM1 replacement by GGBS to 80% to ensure that the long-term strength and durability of the concrete is satisfactory for the majority of structural applications. For unreinforced firm primary female piles which are not considered to be formed of structural concrete, long-term strength is not a critical design consideration. What is crucially important is very slow early rate of strength gain, the mean early strength and its variation. The concrete must be strong enough not to be damaged during boring but not so strong that it cannot be bored through accurately and

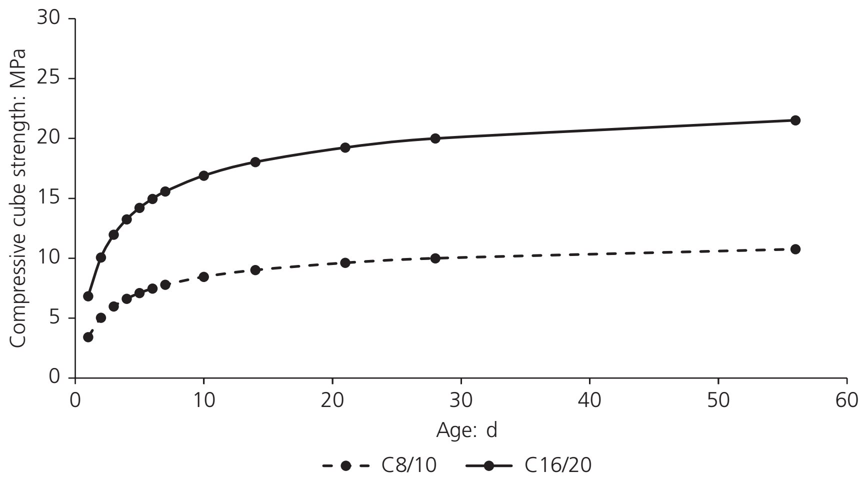

Figure 4. Concrete strength development curves for class N cement from section 3 of BS EN 1992-1-1: 2004 (BSI, 2004)

efficiently. Usually the secondary piles are cut into the primary piles when the concrete is about 2 to 7 d in age and has a compressive cube strength of about 2 to 7 MPa.

Also of importance to the designer are durability and resistance to cracking. Durability with respect to aggressive ground and groundwater is offered by the CEM1 substitution. Cracking is caused primarily by shrinkage and is best controlled by maintaining as low a water–cement ratio as possible. However, concretes made with CEM1 and with a low water–cement ratio typically achieve high characteristic strengths and possess poor workability. High-workability concretes are essential for constructing primary female piles by the CFA method, which require the concrete to pumped down the central stem of the auger in order to form the concrete pile cylinder 'bottom-up' as the auger is withdrawn. Hence, a high proportion of CEM1 substitution by GGBS and/or fly ash in conjunction with the use of water-reducing admixtures to keep the water–cement ratio low, offer a practical compromise.

2.4 BS EN 206-1 concrete

Section 7·2 of BS EN 206-1 (BSI, 2000b) requires the strength development of a designed concrete to be stated by the concrete producer in terms of table 12 (reproduced here as Table 3) or by a strength development curve at 20°C between 2 and 28 d.

Firm secant pile concrete will require a very slow rate of strength development. It is noted that the ratio of mean strength at age 2 d and mean strength at 28 d depends on actual test data so that if the mean strength at 28 d substantially exceeds the specified minimum characteristic strength, then the mean strength at a particular time may be substantially in excess of that which enables a primary secant

Strength development	Estimate of strength ratio $f_{cm(2)}/f_{cm(28)}$
Rapid	$\geq 0{\cdot}5$
Medium	$\geq 0{\cdot}3$ to $< 0{\cdot}5$
Slow	$\geq 0{\cdot}15$ to $< 0{\cdot}3$
Very slow	$< 0{\cdot}15$

Table 3. Strength development of concrete

pile to be accurately cut. For example, if the specified strength class is C15/20, the minimum works compressive strength permitted by Sperw2 for a single cube would be 23 MPa and the maximum compressive strength at 2 d would be 3·45 MPa. However, if the actual compressive strength of cubes at 28 d was, say, 40 MPa, then the maximum compressive strength at 2 d would be 6 MPa and such a concrete would probably have to be cut at 2 or 3 d age for CFA piles to be straight, vertical and well interlocked.

3. Case histories

Compressive cube strength test results have been obtained for three firm secant pile concretes provided by UK Namas accredited ready-mix concrete suppliers; a summary of the mix designs and the retaining wall construction is given in Table 4. All concretes were pumped mixes, class DC2, maximum aggregate size 20 mm and the CEM1 cement was grade 52·5N.

Figures 5–7 show the compressive strength test results for work cubes and, where available, trial cubes. The solid curve represents a logarithmic fit to the data. The dashed line represents the best available fit to the data using the Eurocode 2 prediction equation for the stated value of *s*.

Mix	Grade	Total binder content: kg/m^3	Proportion of binder content: %			Water–cement ratio	Male pile diameter and spacing: mm	Wall retained height: m	Pile type
			CEM1	GGBS	PFA				
1	C8/10	280	19	81	0	0·60	600/900	4·0	CFA
2	C12/15	280	10	90	0	0·56	600/800	7·0	CFA
3	C8/10	340	26	0	74	0·57	750/1150	9·0	RC & CFA

Table 4. Primary pile concrete and construction details (RC = rotary cased, casing outer diameter (OD) 880 mm)

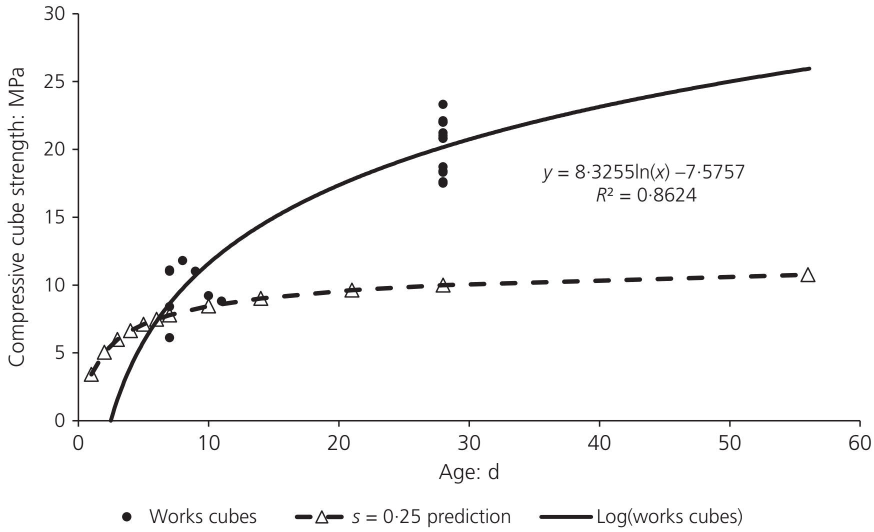

Figure 5. Compressive cube strength plotted against age – mix 1 (C8/10)

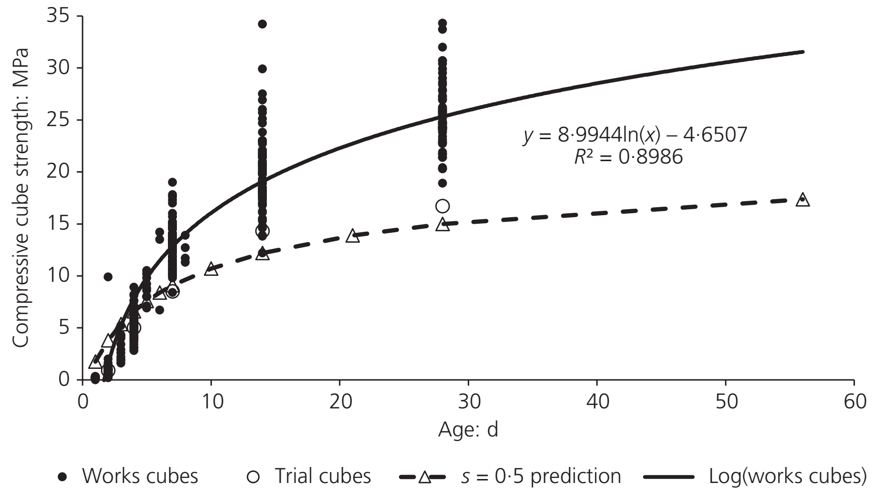

Figure 6. Compressive cube strength plotted against age – mix 2 (C12/15)

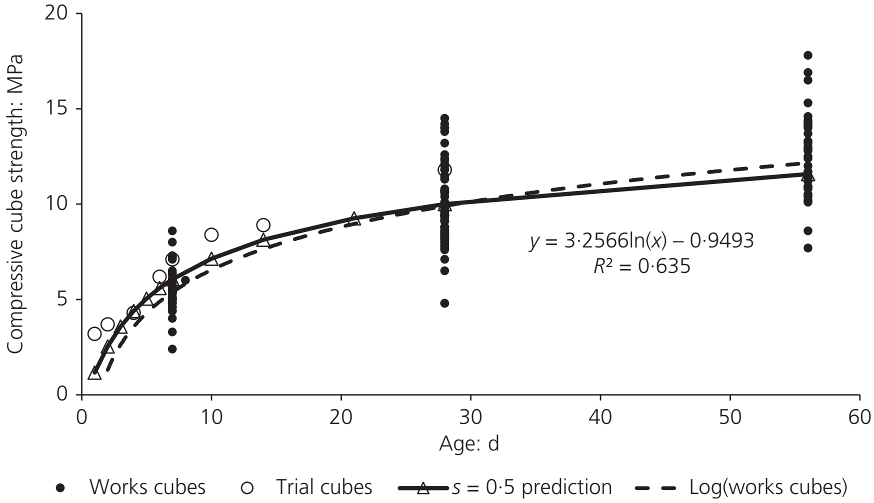

Figure 7. Compressive cube strength plotted against age – mix 3 (C8/10)

Table 5 presents the indicated strength development coefficient used to generate the dashed line in Figures 5–7 and a series of strength ratio values that may be used to characterise the test results. Where there are no test data at 2 and 56 d, the best-fit equation has been used, where possible, to estimate the value that would have been achieved:

Mix	s	$f_{cu(2)}/f_{cu}$	$f_{cu(7)}/f_{cu}$	$f_{cu(56)}/f_{cu}$
1	0·25	—	0·35	1·30
2	0·50	0·05	0·50	1·28
3	0·50	0·13	0·54	1·23

Table 5. Primary pile concrete strength ratios

3.1 Mix 1 (GGBS replacement)

Compressive strength achieved at 28 d ranged from 17 MPa to 23 MPa, up to more than double the characteristic strength of 10 MPa. There was no trial mix and compressive strength was determined on works cubes at only 7 and 28 d. There is a wide spread of test results. The mean fit to the data is reasonably well correlated but there is a complete mismatch between this and the predicted strength development curve constructed using a lower bound s value of 0·25. At 7 d, only some 35% of the 28 d strength is achieved and the extrapolated mean strength at 56 d is 30% higher than the mean 28 d strength.

3.2 Mix 2 (GGBS replacement)

Compressive strength achieved at 28 d ranged from 18 MPa to >30 MPa, up to more than double the characteristic strength of 15 MPa. A trial mix was carried out with cubes crushed at 1, 2, 3, 4, 7, 14 and 28 d. The predicted strength development curve constructed using an s value of 0·5 fits the trial mix test results tolerably well. The works cubes test results are very different from the trial mix results. At 7 d, about 50% of the mean 28 d strength is achieved and the extrapolated mean strength at 56 d is 32 MPa, some 28% higher than the mean 28 d strength of 25 MPa. The strength gain index $f_{cu(2)}/f_{cu}$ is below the Table 3 value of 0·15 for a very slow rate of gain.

3.3 Mix 3 (PFA replacement)

Compressive strength achieved at 28 d ranged from 5 MPa to 15 MPa, between half and one and a half times the characteristic strength of 10 MPa. A trial mix was carried out with cubes crushed at 2, 3, 5, 7, 14 and 28 d. The predicted strength development curve constructed using an s value of 0·5 fits the trial mix test results fairly well and is quite similar to the works cube results trend line, although due to variation in the results, the correlation coefficient is low. At 7 d, about 54% of the mean 28 d strength is achieved and the extrapolated mean strength at 56 d is 12 MPa, some 20% higher than the mean 28 d strength of 10 MPa. The strength gain index $f_{cu(2)}/f_{cu}$ is below the Table 3 value of 0·15 for a very slow rate of gain.

4. Discussion

The overriding observations from the three sets of case history results for concrete made with CEM1 substitution by 70–90% GGBS or PFA are given below.

- Strength at any age is very variable, much more so than is desirable.
- Works concrete appears to be stronger than trial mix concrete.
- A strength development curve s value of about 0·5 might be typical for these high-CEM1 replacement mixes.

- The 7 d strength may be 35 to 55% of the 28 d strength.
- 56 d strength is indicated to be 20 to 30% higher than 28 d strength, which is broadly as predicted by Table 1. There is thus some merit is establishing characteristic compressive strength f_{cu} at 56 d rather than 28 d.

The variance of strength appears to be a common problem, see for example Wharmby (2011) where 28 d cylinder strengths varied from 3 MPa to 9 MPa, 100% either side of the mean.

The variability could be related to the fact that small variations in moisture content in the aggregates have a disproportionately large effect on the water–cement ratio when relatively small quantities of binder, 280 to 340 kg/m^3, are being used. It is therefore important that the moisture content of the aggregates and the weights of all batched constituents are carefully measured and the added free water content of the mix adjusted accordingly. Wharmby (2010) makes similar observations and his remarks also may be interpreted to suggest that the batching tolerances at ready-mix plants can be too large.

It is also possible that contractual responsibilities to customarily provide concrete for general structural applications get in the way – low early strength is not a normal requirement for ready-mix concrete suppliers and there is an understandable tendency for them to supply a product with a compressive strength that comfortably exceeds the characteristic strength. This may be the reason why works cube strengths are significantly higher than trial mix cube results. Clear communication of the permissible lower and upper compressive strength limits for use in primary secant pile applications therefore would be beneficial.

4.1 Minimum compressive strength

The following considers how the minimum compressive strength of the firm primary pile concrete may be established. A structural design procedure using compressive cube strength, as set out in BS 8110 part 1 (BSI, 1997), is followed for simplicity. The secant piled retaining wall shown in Figure 1 is installed in soil with a unit weight, $\gamma = 20$ kN/m^3 and with groundwater level at surface in the retained soil. Piles are 900 mm in diameter (d) at 1200 mm centres (S) with the interlock dimension between male secondary piles of $B = 300$ mm. The dimension A is given by

2. $$A = 2\left[\left(\frac{d}{2}\right)^2 - \left(\frac{B}{2}\right)^2\right]^{0.5} = 849\,\text{mm}$$

4.2 Shear stress in pile

The shear stress (v) acting across a concrete section 1 m long and with the width A at an average depth of 15 m is given by

3. $$v = (\sigma'_h + u)\frac{B}{2A}$$

where σ'_h is the effective horizontal soil pressure and u is the pore water pressure (hydrostatic)

4. $$\sigma'_h = k_0\sigma'_v$$

Let $k_0 = 1{\cdot}0$, $\sigma'_v = \sigma'_h = 15 \times 20 - 15 \times 10 = 150$ kPa

$$u = 15 \times 10 = 150\,\text{kPa}$$

Hence $v = (150 + 150) \times 0{\cdot}3/(2 \times 0{\cdot}849) = 53$ kPa.

4.3 Flexural stress in primary pile

The maximum fibre stress, f, due to horizontal bending of the unreinforced primary pile will be negligible in most instances.

Consider the following in which d is the diameter of primary pile, l is the effective horizontal span of unreinforced primary pile, and w is the uniformly distributed load on one side of the primary pile

5. $$z = \frac{\pi d^3}{32}$$

6. $$M = \frac{wl^2}{8}$$

7. $$f = \frac{M}{z}$$

Let $w = 300$ kN/m, $l = 0{\cdot}3$ m (B of Figure 1), $d = 0{\cdot}90$ m

$$M = \frac{300 \times 0{\cdot}3^2}{8} = 3{\cdot}4\,\text{kN m}$$

$$z = \frac{22}{7} \times \frac{0{\cdot}75^3}{32} = 0{\cdot}041\,\text{m}^3$$

$$f = \frac{3{\cdot}4}{0{\cdot}041} = 83\,\text{kPa}$$

The mean tensile strength of concrete in flexure f_{ctm} is given by BS EN 1992-1-1 (BSI, 2004) as

8. $$f_{ctm} = 0{\cdot}3\, f_{ck}^{(2/3)}$$

Hence, the required mean characteristic cylinder strength in the above example is $\sim 0{\cdot}1$ MPa and the characteristic cube strength is $\sim 0{\cdot}13$ MPa, that is, negligible.

4.4 Design shear strength

Steel shear reinforcement is provided when the design concrete shear stress (v_c) exceeds 0·4 MPa. The ultimate concrete shear stress may be related to the unconfined compression strength in the usual way

9. $$v_u = \frac{f_{cu}}{2}$$

Hence there appears to be no necessity to adopt a characteristic concrete compressive cube strength of more than 0·8 MPa if the concrete is not reinforced, provided the piles are fully interlocked.

By adopting a concrete material factor for concrete in shear $\gamma_M = 1{\cdot}5$ and a partial safety factor for load $\gamma_F = 1{\cdot}35$, the minimum required characteristic compressive strength of concrete is given by

10. $$f_{cu} \geq 2v\, \gamma_F \gamma_M$$

Therefore in this example, $f_{cu} \geq 0{\cdot}21$ MPa.

Allowing for an imperfect interlock in which the bearing area is reduced, the required characteristic compressive strength of the female pile concrete is unlikely to exceed 1 MPa.

Arching in planar walls, and also the force transference in circular construction where hoop compression forces are transmitted circumferentially from pile to pile, are therefore best facilitated by consistent good pile interlock and the provision of even pile to pile bearing. In circular construction, the pile to pile bearing stress may well exceed 1 MPa but seldom will it need to be more than 10 MPa, except in very deep shafts where the soil and groundwater pressures are large and/or in shafts in which the diameter to wall thickness ratio is large and the hoop buckling stress is low.

For circular construction, hard/hard secant piles constructed using cased bored piling methods are often used. However, where it can be shown that a lower-strength concrete can be used, firm primary piles constructed using CFA piling methods should prove adequate and economical. Therefore the approach to follow generally should be to specify low concrete strength and to achieve good interlock. Increased concrete strength should not be specified in the mistaken belief that a more durable and/or stronger concrete structure necessarily will be produced.

4.5 Crack width

The specification of maximum crack width usually arises out of concerns about durability with respect to reinforcement corrosion and water-tightness. Reinforcement corrosion is not relevant to the design of unreinforced primary female piles. The location and orientation of a crack is more important than its size. Any size of crack that passes through a section may let in water. However, wall flexure will normally cause a compression zone that will maintain the crack tightly closed and prevent water passage.

5. Proposed specification

The use of the strength development curve, as opposed to the 2:28 d strength ratio value method, offers a better possibility of communicating and controlling concrete strength development, particularly in the critical first 7 d following placement when strength develops rapidly. However, for firm primary secant piles, a strength development window, rather than a curved line which represents the minimum required strength, is preferred. The consequences of over-providing strength are more severe than those of under-providing strength. It is recommended that calculations are carried out to determine the minimum required compressive strength of the primary pile.

The requirement to achieve the characteristic compressive strength should be set at 56 d age.

Equation 1 may be used with an s value of 0·5 to generate the lower curve of the strength development window. The upper curve of the window should reflect the inconsistency of strength production evidently provided in practice and values twice the minimum are suggested as being appropriate.

The proposed strength development window is shown, for a C6/7·5 concrete, in Figure 8.

As it is the concrete strength in the first 7 d that is of importance, samples for compressive strength testing should be taken at an appropriate sampling rate and cured under water (to mimic likely conditions in the ground around a secant pile wall). Pairs of samples should be tested for density and strength at $t = 2$, 4, 7, 14, 28 and 56 d. Two samples would be spare for additional tests if required. A total of $12 + 2 = 14$ samples per sampling exercise would therefore be needed.

6. Conclusions

This paper has reviewed standard specifications in the UK for production and use of concrete in unreinforced firm primary

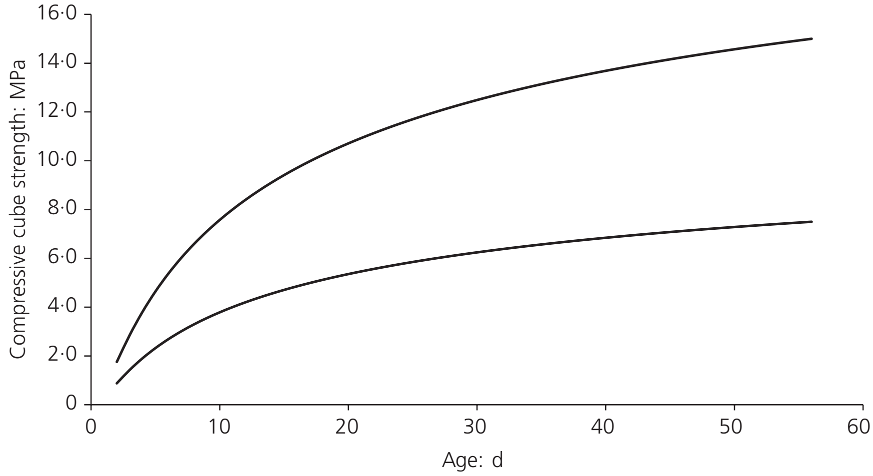

Figure 8. Proposed strength development window for C6/7·5 concrete

secant piles. It has also considered data from tests on concrete from three secant pile walling projects, as well as data published by Wharmby (2010).

The following conclusions can be drawn.

- Low-strength concrete is suitable for the majority of applications. Concrete with a characteristic cube strength of 10 MPa to 20 MPa at 28 d is commonly specified, whereas less than 10 MPa at 56 d will usually suffice.
- The secant pile designer should calculate the required minimum compressive strength from considerations of the shear, flexural and compression forces to be resisted by the primary pile. This is most important in circular construction where hoop compression stresses occur. In plane wall construction, the span between the structural secondary piles is small and low compressive strength is required to distribute the soil and water pressures to secondary hard piles.
- The standard UK specification for concrete in piles, Sperw2, is focused on requirements for structural grades of concrete and is considered unsuitable for non-structural unreinforced concrete used in primary firm secant piles.
- Concretes for secant piling generally utilise high CEM1 substitution by GGBS and/or PFA where the required rate of strength development is very slow and resistance to acid and sulfates is inherently high.
- Provided strength is commonly highly variable, typically 50% either side of the mean at age 56 d. This may be due to poor control over water–cement ratio, inaccurate and inconsistent weighing of constituents and variable curing conditions.
- A modified equation for strength development given in section 3 of BS EN 1992-1-1 (BSI, 2004) is proposed. The characteristic strength (consistently cube or cylinder) is specified at 28 d and validated at 56 d and the suggested s coefficient is 0·5

$$f_{cm}(t) = \beta_{cc}(t) f_{cm} \quad (11)$$

in which $\beta_{cc}(t) = e^n$ and $n = s[1 - (28/t)^{0\cdot5}]$.

- The message to concrete producers should be not to grossly over-provide concrete strength and to carefully control water–cement ratio and the weighing of material, as well as uniformity of test sample curing conditions.
- It is noted that producers are accustomed to ensuring individual compressive strength determinations lie comfortably above the characteristic strength which, for a normal distribution, implies 95% of test results will lie above a value that is 2 standard deviations below the mean strength. The target for producers now should be to control the strength within an upper and a lower limit.
- Current practice for low-strength concrete suggests that setting the limits only 2 standard deviations either side of the mean will be overly restrictive and difficult to achieve. Therefore it is suggested that the mean strength should be set at 1·5 times the characteristic strength and the strength limits taken as 0·5 times the characteristic strength on either side of the mean.
- For example, for a specified C8/10 concrete, 95% of cube compression test results at age 56 d would be required to be in the range 10–20 MPa with a mean strength of 15 MPa.
- Trial concrete mixes are recommended. Lower grades of CEM1 class S (32·5N) often will be adequate and generous amounts of substitution by GGBS and/or PFA are to be encouraged. Pairs of concrete samples should be crushed at 2, 4, 7, 10, 14, 28 and 56 d to establish strength development.

- To minimise cracking due to shrinkage, the water–cement ratio of the mix should be minimised. This will require use of water-reducing admixtures to enable pumped mixes to be provided. Where it is expected soil conditions apply (e.g. dry sand) that allow any free water to flow out of the concrete and induce a premature set and subsequent accelerated strength gain, the concrete mix design should be modified to promote water retention.
- Primary secant piles should be cut early, usually at age 2 to 7 d, when the concrete strength is typically 10 to 50% of the characteristic value. This requires meticulous work planning and sequencing.
- The control of early strength is one factor, albeit a very important one, which influences the quality and economy of secant pile walls. Other factors include drilling tool design, work sequencing, driver influence and over-use of pull-down forces on augers.

The careful specification, through the proposed strength window, and the use of low-strength firm primary pile concrete which gains in strength very slowly, can lead to the multiple benefits. These include improved cost effectiveness through reduction in the use of conventional cements, increased sustainability through routine use of GGBS and/or PFA cement substitutes, improved pile construction accuracy and build quality and greater ease, and therefore health and safety benefits, for pile trimming.

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