THE USE OF HIGH PERFORMANCE ADMIXTURES IN PRECAST CONCRETE

Dr Ray Hudd[1]
Mr Mike Edwards[2]

Summary

In recent years the development of synthetic concrete admixtures based on acrylic and carboxylic acids has resulted in products with excellent performance as high range water reducers or superplasticisers, used in the production of high slump and flowing concretes. More recent developments have resulted in materials designed to give, not only high workability, but also rapid setting and strength gain characteristics, for pre-casting applications.
A series of tests were carried out to establish the performance of one product under New Zealand conditions. Test results will be used to show the potential increases in strength, the potential to reduce cement contents, improvements in performance at different temperatures, the potential to reduce or eliminate the need for heating in winter, and the potential to produce self compacting concrete. Other benefits which will be discussed include the potential for time and cost savings resulting from faster placing and finishing.

INTRODUCTION

The concrete industry in New Zealand produces between 2.5 and 3 million cubic metres of concrete annually, of which approximately 5% is used for precast manufacture(1). This is a significant proportion of the total concrete manufactured, and is especially important within the concrete industry because much of this concrete is used in high performance applications.

PRECASTING REQUIREMENTS

Although concrete may be regarded as a relatively simple material, each individual application has specific requirements. Concrete for precast manufacture is no exception and the requirements can be considered to be particularly demanding.

For precasting to be cost competitive with site cast concrete or other construction materials the finished unit cost must be lower or quality must be superior. To keep overhead costs to a minimum it is necessary to maximise the benefit of the labour and equipment used; accordingly, moulds need to be prepared, concrete poured, and the mould stripped and prepared for reuse within a 24 hour period.

To achieve this turn-around concrete will normally be poured in the afternoon. It must then be strong enough for the moulds to be stripped and the casting lifted the following morning, prior to the mould being reassembled and ready for reuse that day. As a result, the hardening times for the concrete are less than 18 hours, which is a demanding requirement during cooler overnight periods.

In addition to strength requirements, precast units are often complex shapes or have thin section thicknesses, and may contain congested reinforcement. Therefore, the concrete must be easy to place and compact. Furthermore, the surface finish requirements can also be demanding with exposed concrete surfaces to be given an F4 finish or better. This can mean that concrete poured in the afternoon must be finished to this high standard late in the day, requiring extended working hours.

Three clear requirements for concrete in precasting are: placability; finish-ability; and early strength gain. There is a need for some compromise between these requirements to achieve an acceptable performance.

To achieve good placability the concrete needs a consistency which will allow it to be easily poured and compacted into the mould and around the reinforcement.

Placability can be improved by increasing water content; increasing cement contents; or using workability admixtures. Increasing the water content will detrimentally affect the early strength gain and may also extend the time before the concrete can be finished. Adding cement will improve early strengths without affecting the finishing time. Admixtures can combine several of these benefits to give controlled placability and finishing.

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1. Sika (NZ) Ltd- Company Chemist
2. Sika (NZ) Ltd- Technical Manager

For optimum finishing the concrete needs to achieve a consistency conducive to trowelling or floating as soon as possible after placing. As with the placability this is largely affected by mix design and water content.

There are numerous factors affecting early strength gain, including water content, cement content, cement type, and the curing temperature. It is important to remember that specifications often consider only the ultimate strength requirements (usually expressed in terms of 28 day compressive strength). To achieve a good early strength, precast concrete must often be designed for higher 28 day strengths than those specified, or must be manufactured in a way that increases early strengths.

Changes to the concrete mix design can be used to increase early strength including the use of higher cement contents; the use of HE cement in place of GP cement; or the use of admixtures. Increasing early strength through the manufacturing process can be achieved using heat (typically using heated forms or steam curing) to accelerate setting times and early hydration, thereby increasing early strengths without affecting the ultimate strength.

Whichever compromise is reached between the requirements of placability; finish-ability; and, early strength gain, there is an additional manufacturing cost, of extra cement; more expensive cement; admixtures; additional labour; longer working hours; or heat.

Although admixtures may represent a significant additional material cost of the concrete, their use can be highly beneficial to improve concrete properties in any given application.

ADMIXTURES IN PRECASTING

To determine how admixtures can be used in precasting applications, it is first necessary to understand the controlling parameters of concrete performance, and then assess how an admixture will affect these properties.

As discussed above, concrete strength and placability are two of the main criteria to be achieved, and there is a well established relationship between workability and strength (see Figure 1).

Increasing the water content of the concrete will increase the workability (often defined by concrete slump), but will also reduce the concrete strength.

A water reducing or plasticising admixture can be used to increase the workability of the concrete

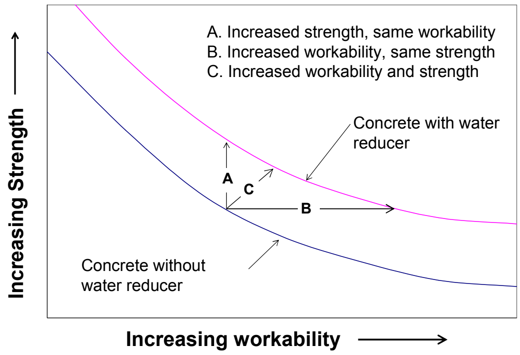

Figure 1: Relationship between concrete workability and strength, and the benefits of using a water reducer

without affecting the strength. Alternatively the water reducer can be used to reduce the water content of the concrete to give a higher strength at the same slump, or can be used to combine these two effects, giving concrete with improved workability and strength.

An additional advantage of reducing water in this manner is that the permeability of the concrete will be reduced and the long term durability will be improved.

It should be noted that the relationship shown in Figure 1 is independent of the age of the concrete, and applies equally to early and ultimate strengths.

Water Reducers

Water reducers, therefore, are materials which reduce the amount of water in a given concrete mix to achieve the same slump while giving an increase in concrete strength. The Australian Standard AS1478(2) gives six different categories of water reducers for concrete. The most appropriate to give high early strength is the High Range Water Reducer which is required to give a 24 hour strength at least 30% higher than a control.

However, while high range water reducing admixtures can be used to increase early strengths to a significant degree, the effect on other properties can be detrimental.

It is important to note that workability is not synonymous with slump. At a given slump, the use of a high dose of high range water reducer will give significant water reduction. This will make the concrete stiffer and more cohesive making it necessary to plasticise the concrete to a higher slump to achieve the same ‘workability’.

The reduction in water content will also affect the concrete consistency and the stiffening characteristics can change, affecting both the placability and finishing properties of the mix.

Furthermore, although the use of high range water reducers will give improved early strengths, high doses may result in some set retardation.

Accelerators

If the high range water reducer does result in some set retardation, a set accelerator can be used to give more acceptable finishing times and improve early strengths.

In addition to set accelerators, there are also hardening accelerators available which have a more pronounced effect on the early strength development than the setting time[3].

By using high range water reducers, setting accelerators and/or hardening accelerators it is possible to achieve a range of improvements in concrete performance which can be of benefit in precast manufacturing.

However, such combinations of admixtures need to be used at relatively high dose rates (1.5 to 2.0% bwc (by weight of cement)), to gain significant benefit. This gives a high material cost, and also requires precise control of the dosing and mixing on site. These additional costs need to be weighed against any cost savings from using the admixtures.

Polymer Admixtures

The term polymer admixture is used to describe recently developed synthetic high range water reducer technology (as opposed to latex emulsion polymers). These admixtures are synthetic compounds of polycarboxylic or polyacrylic acid esters consisting of a molecular backbone with attached side chains. The shape of these polymers has led to the term 'comb' polymer (see Figure 2).

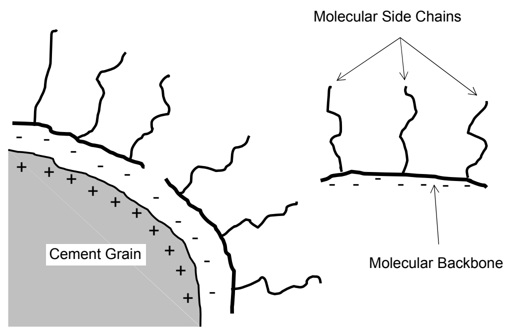

Figure 2: Schematic diagram of comb polymer molecule.

Conventional water reducers work solely by giving the cement particles a common electrostatic charge. With the 'comb' polymers, the polymer backbone attaches to the cement grains electrostatically, leaving the side chains extending out from the surface. This gives enhanced performance by extending the electrostatic charges beyond the normal limits of the interaction and produces an effect called steric hindrance.

This makes these types of polymers very efficient as water reducers, but can also result in extended working and setting times and slow early strength gain. These characteristics do not normally pose problems in ordinary concrete, but have limited benefit in precasting.

However, by modifying the chemical backbones and side chains of the polymers it is possible to synthesise products with controlled working and set times, and good early strength performance – making them suitable for precasting. The control of the chemistry at a molecular level means that these materials are very efficient even at dose rates less than 1.0% bwc, making them more cost effective than traditional materials.

Precasting Polymers- New Zealand Experience

These products have been developed in recent years in Europe[4] and have recently become available in New Zealand. A series of tests were carried out to evaluate a number of commercially available materials targeted at the precasting industry.

Initial tests showed that, under New Zealand conditions, with the raw materials and work practices currently in use, the working times were too short, typically less than 30 minutes, although the finishing times were good. However, despite the rapid stiffening and setting, the early strength performance was not adequate across a range of temperatures.

Various blends of materials were assessed to determine whether improvements in performance could be realised. These included the use of alternative polymers to improve the working life and other components to improve the early strength performance.

Following this assessment process, Sika ViscoCrete®-20 HE (NZ) was introduced to the New Zealand market. The following is an overview of the results of laboratory and field tests on Sika ViscoCrete®-20 HE (NZ), carried out under a range of conditions.

LABORATORY ASSESSMENT OF A PRECASTING POLYMER ADMIXTURE

Tests were carried out to assess the effect of the product on the following:

- Water reduction;
- Early age strength development including such factors as curing temperature; heating; and cement type;
- Overall strength development and the relationship with cement content;
- Self compacting concrete.

Mixes were varied according to the test requirements, but in the majority of cases a standardised concrete mix using Auckland basalt coarse aggregates and PAP, East Coast Sand and a cement content equivalent to 370kg/m^3 were used.

Water Reduction and Strength Development

Initial tests were carried out using a New Zealand manufactured GP cement to determine the water reduction at different admixture dose rates for a given slump. The results in Figure 3 show that, at increasing dose rates, water reduction is almost linear, with a reduction of approximately 15 litres of water per cubic metre of concrete for every 300ml of admixture per 100kg of cement.

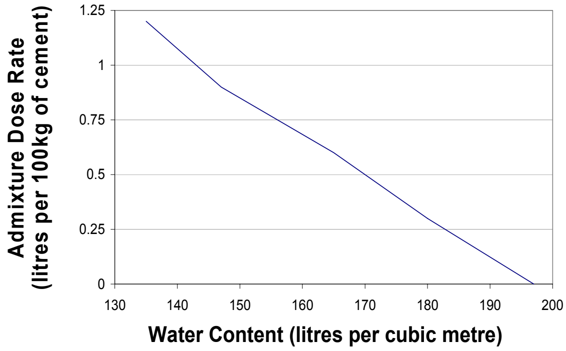

Figure 3: Relationship between polymer dose rate and water content

In these initial tests, 18 hour compressive strengths were measured. Figure 4 shows the relationship between 18 hour strength and water content obtained from these tests. This graph shows the expected behaviour discussed earlier – that a reduction in the water content of the concrete gives a higher strength at the same slump. Based on these tests, it can be seen that for every 10 litres water reduction, there is a strength increase of approximately 3MPa.

It should be noted that although the target slump for these mixes was 100mm, the slump also increased by approximately 20mm for each 0.3%bwc of admixture. So, in addition to the significant water reducing effect of the product, it also has a substantial super-plasticising effect, giving the added benefit of increased workability.

Of particular interest for precasting is the strength

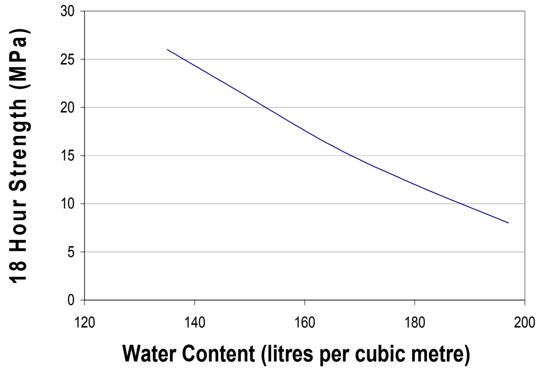

Figure 4: Relationship between strength and water content from trial mixes

development over the first 24 hours. To determine how mixes with the polymer admixture behaved, a series of tests were carried out at an admixture dose rate of 0.7%bwc, which from the previous test results equated to approximately 20% water reduction. Mixes were also made with a non-chloride set accelerator (dosed at 2% bwc) in conjunction with the polymer to determine the effect this would have on the very early strengths.

Results of these tests (Figure 5) show that when using the polymer on its own the early strengths are at least 6 hours ahead of the control, and the 24 hour strength of the control is achieved in just 14 hours. With the addition of 2% accelerator, the 24 hour control strength is achieved in just 8 hours, meaning that it would be possible to make two concrete pours in one day.

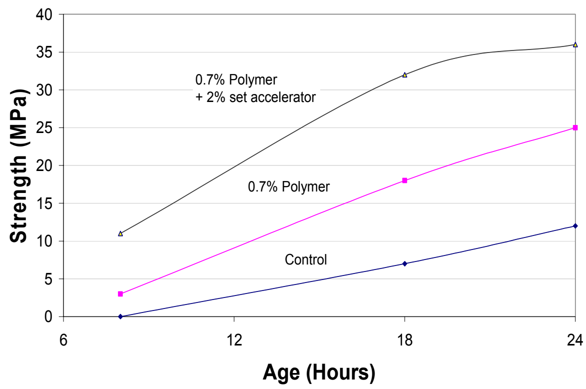

Figure 5: Early strength development using polymer admixture with and without set accelerator

Low Temperature Performance

Of great importance, when considering early strength, is the effect that low mixing temperatures can have on the performance. To evaluate this effect, tests were carried out using the same concrete mix design as the initial tests, with the mixes conditioned to 10°C. A set accelerator dose rate of 1.3% bwc was used to compensate for the reduced temperature and the polymer dose rates were varied.

Similar tests were also carried out on mixes conditioned at 5°C with the accelerator dosed at 2%bwc.

It was recognised with these tests, that the strength gain in cylinders cured at low temperatures, does not represent the strength gain which may be achieved by a large mass of the same concrete. To try and simulate this condition, cylinders were stored in insulated containers.

Strengths were measured after 18 hours. The results are illustrated in Figure 6 and as expected show increasing strengths with increasing dose rates of the admixture. The results also show clearly the importance of measuring strengths from insulated cylinders, to provide better assessments of actual on-site concrete strengths. In practice the use of temperature matched curing could be advocated for optimum results.

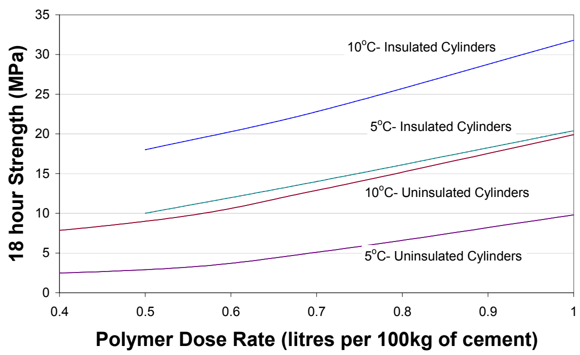

Figure 6: Relationship between polymer dose rate and 18 hour strength at low temperatures

By comparing these results with those shown in Figure 5, it can be seen that, at low temperatures and with insulated concrete, the addition of 1 to 2% bwc of accelerator will result in similar strengths to that achieved by un-accelerated mixes at 20°C. (At all temperatures the concrete mix contained 0.5 to 1% bwc of polymer.)

Effect of Heat on Early Strength Gain

Although these tests at low temperatures show the benefits of using the polymer in conjunction with setting accelerators, it is normal in precasting operations to use some form of heat to ensure adequate strength gain, especially when low overnight temperatures are expected.

Accordingly, a further series of tests were carried out, with admixture dose rates of 0.5% and 1.0%bwc to determine the effect of curing temperature on mixes made at normal temperatures. Mixing was carried out at 20°C and cylinders from the mixes were then placed in different curing environments ranging from 5°C to 80°C, to determine the effect on the strength gain after 18 hours.

The results illustrated in Figure 7 show that by using the polymer it is possible to reduce the amount of heat required to achieve a given strength. For example, the unmodified mix needs to be heated to 40°C to achieve 20MPa in 18 hours. With 0.5% polymer bwc the concrete only needs to be heated to 25°C to achieve the same strength, and at 1.0% polymer bwc it requires no heating.

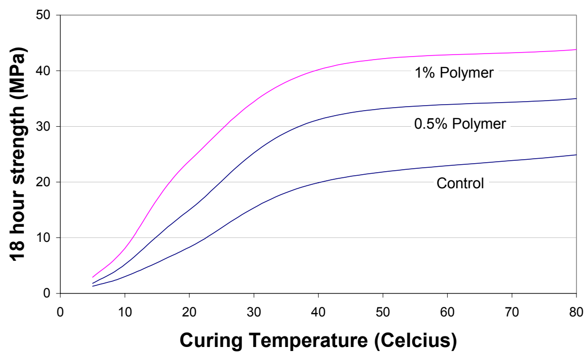

Figure 7: Relationship between 18 hour strength and curing temperature with different polymer dose rates.

Based on these results, it is clearly possible to reduce the amount of heat required in a given precasting process. Alternatively it may be possible to reduce the time over which the heat is applied. In either case, there is the potential to make savings in the cost of heating. Additionally, removing the heating requirement altogether may simplify the precasting operation to some degree.

Effect of Cement Type

Tests were carried out to determine how much polymer was required in a concrete with GP cement, to achieve the same early strength as a mix using HE cement. Results of these tests showed that a polymer dose rate of 0.5% by weight of GP cement was required to match the strength performance of HE cement with no polymer.

To confirm this performance for precasting, a test was also carried out using different curing temperatures. The results (Figure 8) show consistent strength gain across the temperature range. This shows that replacing HE cement with GP cement is a practical option.

A limited number of tests were carried out using slag cement and fly ash as partial replacements of GP cement.

The replacement of GP cement with slag cement

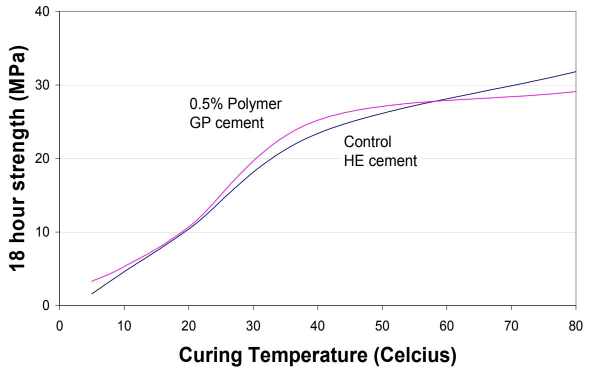

Figure 8: Relationship between 18 hour strength and curing temperature for mixes using HE cement and GP cement with polymer admixture

, as expected, resulted in significant reduction in early age strength. However, there was a still a significant benefit from using the polymer admixture. Using slag cement to replace two thirds of the GP cement in the polymer mix, resulted in a reduction in 24 hour strength by about a half. However, the strength of the slag cement/GP cement mix with the polymer admixture, was double that of the mix without the polymer.

Tests with fly ash showed that the addition of the polymer admixture gave significant improvements in the early age strength of concrete that had up to 30% fly ash replacement of GP cement. The results (Figure 9) show that 18 hour strengths with polymer dose rates of 1.0%bwc are increased from 3MPa to 18.5MPa at 20^{o}C and from 15MPa to 38.5MPa at 40^{o}C.

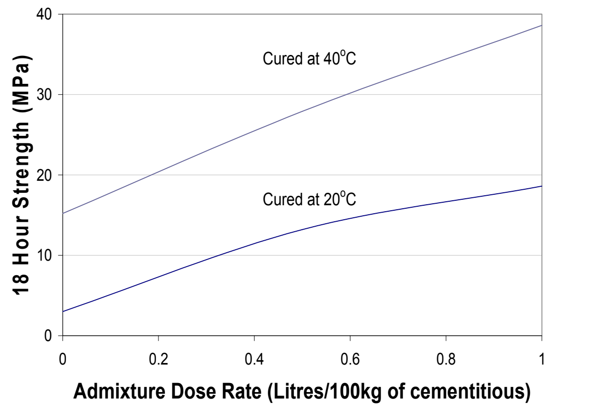

Figure 9: Relationship between polymer dose rate and 18 hour strength using 30% Fly Ash at different curing temperatures

Cement Savings

When using the polymer admixture, strengths are improved at all ages. For this reason, another potential benefit is the reduction of the cement contents of typical mixes.

To evaluate this, tests were carried out to determine the strength gain up to 28 days of a 40MPa concrete, a 30MPa concrete without polymer admixture and the same 30MPa mix dosed with 0.7% bwc (which gave a water reduction of 30 litres per cubic metre). The 30 MPa design mix had 70kg less cement than the 40 MPa mix.

Results of these tests in Figure 10 show the strengths of the three mixes up to 28 days. It can be seen that by using the polymer higher strengths were achieved at all ages when compared with the 40MPa design mix.

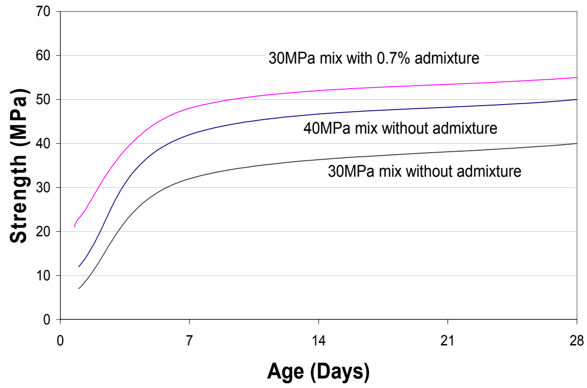

Figure 10: Relationship between strength and age for mixes with and without polymer admixture

Self Compacting Concrete

Much interest has been expressed in the use of self compacting concrete (scc) for both on-site and precasting operations. The benefits of scc can be realised to a much greater degree in precasting applications because of the potential for more complex designs, easier placement around heavy reinforcement and the need for good off-form finishes. Vibration noise is also eliminated.

The use of polymers is normal in scc so a series of tests were carried out to determine the behaviour of the new polymer in a scc mix.

The mix design used in these tests contained 350kg/m^3 of GP cement and 150kg/m^3 of limestone flour as the filler. The polymer admixture was dosed at rates of 0.8, 1.1 and1.4% bwc with the water content of the mixes adjusted for flow and stability. As expected, with increasing dose rates of the polymer greater water reduction (up to 35 litres per cubic metre) was achieved.

Figure 11 shows the strength development with different polymer dose rates. By increasing the admixture polymer content from 0.8 to 1.4% bwc, the 18 hour compressive strengths increased from 10MPa to 17MPa, the 24 hour strengths increased from 14.5 to 23MPa, and the 7 day strengths increased from 31.5 to 46MPa.

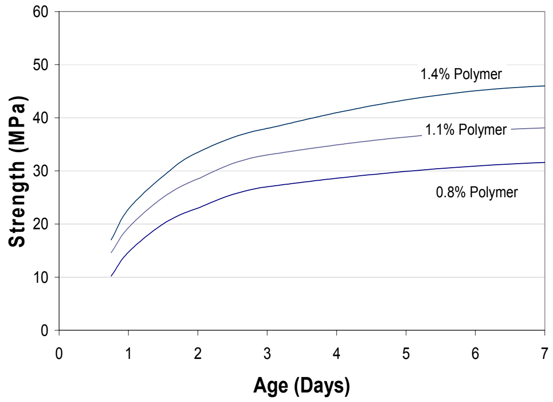

Figure 11: Relationship between strength and age of scc using polymer admixture

By using the polymer admixture it was possible to have mixes which only maintained the desired flow properties for a short period of time (approximately thirty minutes in these tests) and then rapidly lost flow to allow for finishing after two hours. Conventional scc mixes generally have extended working and finishing times.

SITE EXPERIENCE

Numerous site trials were carried out with the polymer admixture, to evaluate both the handling properties of the concrete and to confirm the strength performance that had been achieved in the laboratory tests.

The site trials showed the expected improvement in strengths when the product was used in conventional mixes with reduced water contents. They also highlighted several important factors relating to the properties of the concretes:

Concrete Yield Variations

The use of the polymer admixture gives significant water reduction and reductions in air contents. As a result concrete densities increase and the resultant drop in yield requires adjustments to be made to mix designs.

The wet density of the concrete increases by 2 to 3%, so in addition to replacing the volume of water (up to 50litres/m^3) in the mix design, additional volume is required to make up the deficit caused by the higher material density. Typically this means that an additional volume of 70 to 80 litres per cubic metre will need to be made up with aggregates.

Concrete Placing Time

Site trials highlighted the importance of timing when using this type of polymer. As mentioned earlier, one feature of this material is a rapid loss of workability. This can have both positive and negative effects.

One of the positive effects is that the concrete can be batched with a high slump or even a flow spread, which makes it easy to place and compact. The rapid loss of workability means it is ready to finish more rapidly than a conventional low slump concrete.

A negative effect occurs if the placing rate for the concrete is slow. Under these conditions, while initial placing of the concrete may be satisfactory, as the slump properties wear off placing becomes increasingly difficult; to the extent that it may be hard to finish units satisfactorily, or concrete may get stuck in the delivery skip. In such cases it becomes necessary to re-dose the concrete with the polymer once it starts to lose slump.

Experience to date has shown that, as long as this reduced placing time is understood, adjustments to the way the concrete is placed and finished can overcome these issues.

In some instances this may involve small changes to the way the concrete is discharged. For example in long beam moulds it may be normal practice to discharge the concrete at a speed controlled to allow compaction and finishing of the concrete as the truck proceeds along the mould. With the limited time to place concrete containing the polymer admixtures it may be easier to discharge and spread the concrete along the length of the mould as fast as possible, with finishing proceeding at a different rate afterwards. Because of the effectiveness of the admixture, higher slump mixes can be used to facilitate easier discharge and spreading of the concrete in such situations.

As mentioned earlier, dosing the admixture on site can be used to overcome problems of insufficient slump life and it can also be used to give more flexibility with concrete delivery. If concrete is batched without the admixture and then dosed on site this will result in the maximum amount of working time and will ensure that slump life is not lost due to any delays in preparation. However this approach requires accurate batching because the low water content concrete will be batched with a zero slump or as ‘kerb mix’. This is not always practical with certain types of concrete plant and requires very accurate control of the water content especially when aggregate moisture contents are high.

For practical purposes it may be preferable to batch the concrete with the admixture, in which case good communication is required between the concrete supplier and site, and the travel time from batching plant to the site should ideally be less than twenty minutes. Experience using this method has shown that, with good organisation, the concrete is only ordered once the moulds are ready for filling and when sufficient labour is available to place the concrete. In this way there are no delays on site once the concrete arrives.

An alternative solution is a compromise between the two, with concrete being batched with a minimum amount of polymer to give a slump, and then the remaining polymer is added on site when ready.

Concrete Finishing

Finishing of concrete with the polymer admixture requires more skill than normal concrete due to its different handling properties.

One property of mixes with high levels of water reduction is the tendency for a skin to form on the concrete surface. This is caused by the lack of bleed and concrete surfaces will dry out quickly if they are not protected. This gives a rubbery texture which does not respond to normal trowelling methods. To compound the situation attempting to trowel concrete in this condition can easily tear the surface leaving cracks which are virtually impossible to close.

Due to the lack of bleed in these mixes, there is also an increased risk of plastic cracking. To reduce this risk, temporary covers and water or evaporation retardant sprays need to be used on the concrete surface. If this issue can be overcome, then it has been found that the rapid stiffening of the concrete allows for much faster final finishing.

Once these finishing and placing characteristics are understood work practices can be modified and the benefit of reduced finishing times realised.

CONCLUSIONS

Laboratory and field tests were carried out on a range of concrete mixes using Sika ViscoCrete®-20 HE (NZ), a high performance proprietary polymer admixture. These tests showed a number of improvements in concrete properties which can be of benefit in precast concrete manufacturing. These benefits include:

1. Concrete strengths are higher at all ages.
    - Higher early strengths allow for earlier stripping or de-stressing of prestressed components.
    - Gives the potential for reductions in cement contents.
    - Strength gains are controlled by polymer dose rate and the amount of water reduction achieved.

2. Early strength gain is improved at all temperatures.
    - This allows a reduction in curing temperatures and/or the amount of time that the heat is required.
    - Early strength gain is improved dramatically when the product is used in combination with set accelerators allowing for the concrete to be poured and stripped the same day without the use of heated forms.

3. Can be used in combination with GP cement, as an alternative to HE cement. The strength gain of concrete containing GP cement and the admixture can be matched to the strength gain of concretes with HE cement alone.

4. The polymer admixture is effective with supplementary cementitious materials:
    - The polymer admixture increases the early strength gains of concretes containing slag as a partial cement replacement (though the strengths were still lower than those of pure cement mixes).
    - Early strength gain of concretes containing fly ash is significantly improved at normal and elevated curing temperatures.

5. The admixture can be used to make self compacting concrete with good early strength.

6. The reduction in permeability resulting from lower water/cement ratios will result in improved concrete durability.

7. Mixes can be made at higher slumps for easier placing and compaction.

8. Mixes have rapid slump loss allowing more rapid finishing.

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