

EFFECT OF METASTAR™ ON THE MECHANICAL PROPERTIES OF CONCRETE

METASTAR ACCELERATES THE FORMATION OF CSH PHASES, LEADING TO FASTER SETTING AND IMPROVED STRENGTH DEVELOPMENT AT ALL AGES.

When specifying concrete for the construction industry, those specifications which relate to mechanical properties are usually given the highest priority. The following mechanical properties are generally considered to be the most useful:

- **compressive strength**
- **tensile strength**
- **creep strain in response to a high sustained load**
- **abrasion resistence**

In addition, certain early-curing properties are equally important because what happens during the first (say) 28 days will determine the long-term mechanical properties of the concrete. For example, freshly placed fluid concrete should set relatively quickly to prevent aggregate settlement and bleeding; tensile strength should then increase rapidly, in order to prevent internal stresses (caused by shrinkage or drying) from causing cracks in the young concrete.

The early curing properties of most importance during this period are:

- **setting time**
- **early strength development**
- **shrinkage properties**
  - **- chemical shrinkage**
  - **- autogenous shrinkage**
  - **- expansion in water**
  - **- drying shrinkage**

MetaStar has a beneficial effect on the strength properties of concrete, and this has been proven in numerous laboratory and field trials. **MetaStar** also increases the curing rate of concrete, so that compressive and tensile strengths both build up faster during the crucial first 28 days. Within experimental error, MetaStar has no effect on the shrinkage properties of concrete used in the construction industry.

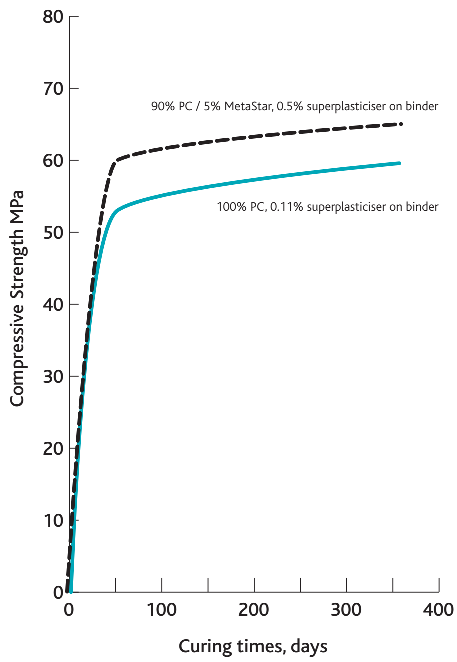
All these observations are discussed in detail below.

STRENGTH RELATED PROPERTIES

COMPRESSIVE STRENGTH - At a given binder content and water/binder ratio, **MetaStar** usually increases the strength of concrete. This is mainly due to the densification of the interfacial zone[1], and improved adhesion between the aggregate and cement paste[2]. During the first 28 days, **MetaStar** concrete gains strength faster than PC concrete so the required 28 day strength is achieved earlier, typically in 17 days for 10 mass% replacement of PC by **MetaStar.** Figure 1 shows typical results for the development of strength with curing time. Figure 2 shows the effect of binder content on 28 day strength, at various levels of **MetaStar** substitution.

FIGURE 1: Compressive strengths of cubes stored in water

Mix design: 355 kg binder/m³
0.52 water/binder ratio
superplasticiser to give 75mm slump



Real concrete is not normally cured under ideal conditions; ideal curing is in air at 100% relative humidity, or submerged in water. Figure 3 shows the effect of storing demoulded 100mm concrete cubes in the open laboratory[5]. Compressive strength is significantly lower than similar samples stored in water, but **MetaStar** concrete is still stronger compared with the PC concrete.

TABLE 1: Mix designs for 60 MPa concrete for a range of MetaStar levels. Constant 75mm slump achieved by varying water/binder ratio and superplasticiser dose.
(Data courtesy of the University of Dundee.)

Mass % MetaStar in binder	Total binder content for 60 MPa, kgm^{-3} MetaStar/PC)	Water/binder ratio	Mass % S'Plasticiser on binder for 75mm slump
0(PC control)	415 (0/415)	0.45	0.21
5	385 (19/366)	0.48	0.41
10	372 (37/335)	0.50	0.70
15	355 (53/302)	0.52	0.80

TABLE 2: Strength properties for a range of MetaStar levels
Formulation: binder content 310 kgm^{-3}
water/binder ratio 0.60
constant 75mm slump achieved by varying the superplasticiser dose.

Mix (% superplasticiser)	Cube strength MPa	Flexural strength MPa	Young's modulus GPa
100 PC (0.13)	41.0	5.0	30.0
90 PC:10 M'Star (0.43)	47.0	Not measured	33.0
80 PC:20 M'Star (1.04)	50.5	5.3	33.5

Since **MetaStar** increases compressive strength it is possible to reduce the total binder content for a given 28 day strength. For example, a 60 MPa concrete can be formulated at various different binder levels by adjusting the **MetaStar** content and water/binder ratios, as shown in Table 1.

Studies at the University of Dundee have confirmed that **MetaStar** concrete is more durable even if the total binder content is reduced in accordance with Table1. For example, "reduced binder" **MetaStar** concrete shows considerable improvement in the initial surface water absorption test (ISAT); there are similar improvements in the chloride diffusion tests (concentration difference method) and in the electrochemical chloride ingress test (potential difference method).

In general it is found that **MetaStar** can replace twice its mass of Portland cement, for a given strength specification. However, in practice **MetaStar** is normally used to replace Portland cement on a 1;1 mass basis, because of the extra beneficial effects on a wide range of durability properties (see other application data sheets in this series).

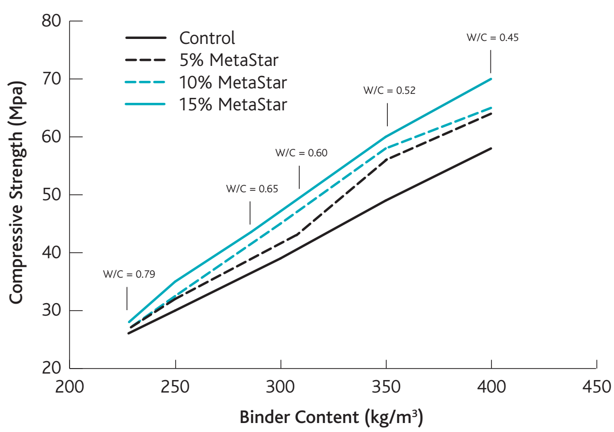
TENSILE STRENGTH

The flexural strength and Young's modulus of **MetaStar** concrete are similar to those of PC concrete of equivalent 28 day crush strength. Therefore, when **MetaStar** replaces part of the PC, the flexural strength is expected to increase. In a study at Dundee University, flexural strength and Young's modulus were determined in accordance with BS 1881:Parts 118 and 121 respectively. Specimens were cured in water at 20°C for 28 days, and the average results for two prisms are shown in Table 2.

CREEP STRAIN

Creep strain has been measured at the University of Dundee for a range of **MetaStar** levels. Table 3 shows results (average of two measurements) for cubes, cured in water for 28 days and then loaded to 40% of their 28 day strength for 90 days. **MetaStar** has little significant effect on creep strain.

FIGURE 2: Effect of binder content on 28 day strength, at various MetaStar contents *(superplasticiser dose and water/binder ratio adjusted to give constant slump of 75mm)*



ABRASION RESISTANCE

In laboratory tests, abrasion resistance correlates well with 28-day compressive strength. Therefore **MetaStar** concrete has better abrasion resistance than equivalent PC concretes, because it is stronger.

In the field, it would be expected that **MetaStar** concrete is more abrasion resistant due to improved adhesion of the cement paste to the aggregate. It is well established that metakaolin densifies and strengthens the interface zone between paste and aggregate. **MetaStar** concrete has been used to construct quarry roads, floors for bulk storing and handling hard rock, and areas for handling bulk scrap metal. In highly abraisve environments, **MetaStar** concrete has shown excellent abrasion resistance.

EARLY CURING PROPERTIES

SETTING TIME

MetaStar slightly reduces the initial and final setting times of concrete. Table 4 shows results from our own laboratories for

TABLE 3: Creep strain for a range of MetaStar levels

Formulation: binder content 310 kg m^{-3}
water/binder ratio 0.60
constant 75 mm slump achieved by varying the superplasticiser dose.

Mix (% Superplasticiser)	28-day strength MPa	Creep Strain $x10^{-6}$
100 PC (0.13)	41.0	790
95 PC: 5 M'Star (0.26)	44.5	800
90 PC: 10 M'Star (0.43)	47.0	825
85 PC: 15 M'Star (0.69)	49.0	840
80 PC: 20 M'Star (1.04)	50.5	810
75 PC: 25 M'Star (1.30)	50.5	835

three different samples of **MetaStar** pastes, at various substitution levels. The water binder ratio was adjusted to give constant consistency, according to BS-EN 196-3: 1995. Similar studies of the effect of metakaolin on setting times have been reported by Ambroise et al[3] and by Zhang and Malhotra[4]. These authors confirm the trends shown in Tables 4 and 5.

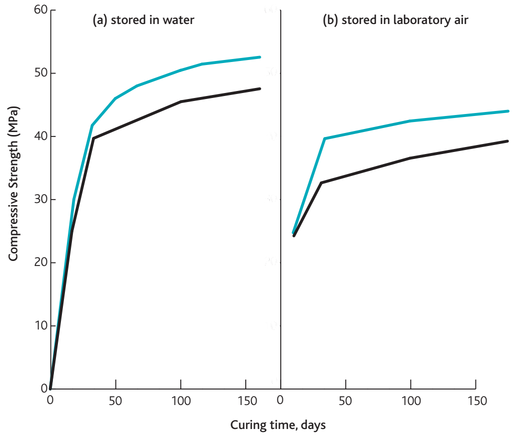
EARLY DEVELOPMENT OF COMPRESSIVE STRENGTHS

MetaStar has no significant effect on early compressive strength development in concrete (i.e. over the first seven days). Even where it is necessary to use higher superplasticiser levels in **MetaStar** concrete, there is no effect on strength development. Figure 4 shows compressive strength development over 7 days for a range of **MetaStar** levels at different water/binder ratios and superplasticiser doses[5]. It is seen that there are no significant differences compared with the control PC concrete.

EARLY DEVELOPMENT OF TENSILE STRENGTH

Trials at the University of Surrey[5] have shown that **MetaStar** significantly accelerates the development of early tensile strengths. Using concrete specimens, supported on an air cushion, it was possible to measure tensile strengths as little as one hour after casting. Results are showing in Figure 5. No superplasticiser was used in these formulations.

FIGURE 3: Compressive strengths of cubes stored
(a) in water and (b) in air
Mix design: 345 kg binder/m^{-3}
0.67 water/binder ratio



It has been observed that metakaolin accelerates the early hydration of calcium silicate, to give extra polymeric silicate gel[6], and this might account for the early development of tensile strength.

SHRINKAGE PROPERTIES

Fresh concrete can shrink or expand during the curing process, depending on its formulations and on environmental conditions. Several mechanisms are thought to be involved as discussed below. Shrinking can cause cracking, if the shrinkage forces are greater than the developing tensile strength (see previous section).

Chemical shrinkage is due to the fact that the volume of hydrates, produced by cement reacting with water is less than the volume of the reactants.

Antogenous shrinkage is the measured reduction in length of a concrete bar during curing, without any migration of water into or out of the specimen. The driving forces are due to chemical

TABLE 4: Setting times for cement pastes containing various levels of MetaStar, at constant consistency.

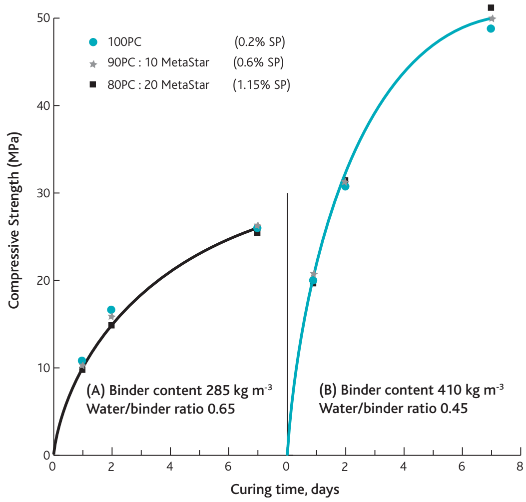
Paste Composition	Water/binder ratio	Initial set time (min)	Final set time (min)
PC	0.275	145	200
85 PC: 15 M'Star 1	0.324	110	205
85 PC: 15 M'Star 2	0.292	95	180
80 PC: 20 M'Star 3	0.346	110	180
80 PC: 10 M'Star 3	0.316	125	185

Setting times for MetaStar have been independently measured by CERIB in France. Again MetaStar accelerates the inital and final set, Table 5.

TABLE 5: Setting times for mortars, with and without MetaStar
(Data courtesy of Centre d'Etudes et de Researches de l'Industrie du Beton.)

Paste Composition	Water/binder ratio	Initial set time (min)	Final set time (min)
PC	0.50	263	415
80 PC: 20 M'Star	0.50	248	336
80 PC: 20 M'Star	0.67	385	475

FIGURE 4: Effect of MetaStar on early strength development at two binder contents, A and B.
Note that MetaStar concretes have higher levels of superplasticiser:



shrinkage as well as surface tension forces due to internal self desiccation.

Expansion can occur if concrete is cured by immersing in water. Water is sucked into the concrete to counteract self desiccation and to swell and hydrate the CSH phases. This phenomenon is mainly observed with small (i.e. 100 mm) specimens.

Finally, **drying shrinkage** is due to surface tension forces in the near-surface capillaries as water evaporates from them. If evaporated water is not replaced by water bleeding towards the surface from the bulk concrete, shallow surface cracking can occur.

Studies on chemical shrinkage, autogenous shrinkage and swelling in PC/**MetaStar** pastes have been reported by S.Wild et al, University of Glamorgan[7].

PC/**MetaStar** pastes, containing 5-15 mass % **MetaStar,** show a slightly elevated chemical shrinkage. Typically, after 10 days PC paste showed a shrinkage of 0.045 ml/g of binder. The PC/**MetaStar** pastes showed corresponding shrinkages of 0.050 - 0.053 ml/g of binder.

Values for autogenous shrinkage were much lower. After 10 days, typical values for both PC and PC/**MetaStar** mixtures were 0.0005 ml/g of paste. There was a sudden increase in autogenous shrinkage at higher **MetaStar** levels, for example 0.0012 ml/g of paste for the 85% PC: 15% **MetaStar** mixture.

The expansion observed when the paste bars are cured in water is very low (i.e. 0.0005 ml/g of binder, after 14 days) for pastes containing 0.5 and 10% **MetaStar.** Again, expansion is higher (0.0011 ml/g of binder) at the 15% **MetaStar** level.

It should be emphasised that all these shrinkage and expansion values will be considerably reduced when the binder is blended with aggregate, as in concrete.

FIGURE 5: Early Tensile strengths of concretes - effect of MetaStar
Mix Design: 345 kg binder m-3
0.67 water/binder ratio,
no superplasticiser

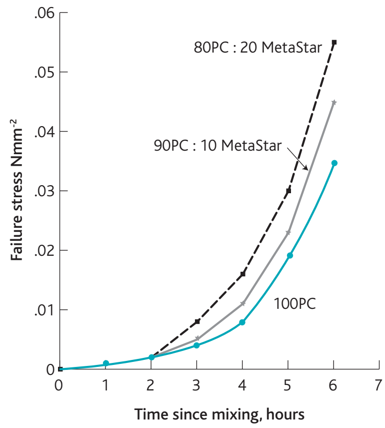


TABLE 6: Effect of MetaStar on drying shrinkage
Formulation: binder content 310 kg m^{-3}
water binder ratio 0.60
constant 75mm slump achieved by adjusting

Binder (% superplasticisier)	Drying shrinkage after 90 days x 10^{-6} (av. of 2 days measurements)
100 PC (0.13)	680
95 PC: 5 M'Star (0.26)	690
90 PC: 10 M'Star (0.43)	700
85 PC: 15 M'Star (0.69)	645
80 PC: 20 M'Star (1.04)	715
75 PC: 25 M'Star (1.30)	720

Drying shrinkage of **MetaStar** concrete was measured at the University of Dundee. Concrete specimens 75 x 75 x 300 mm size were demoulded after 24 hours and stored in a room maintained at 20° and 55% relative humidity. Length changes were recorded for 90 days. Results show that **MetaStar** at levels up to 25 mass % does not significantly increase drying shrinkage, Table 6.

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