ELSEVIER

Cement & Concrete Composites 26 (2004) 573–580

Cement & Concrete Composites

www.elsevier.com/locate/cemconcomp

Effect of PVA, glass and metallic fibers, and of an expansive admixture on the cracking tendency of ultrahigh strength mortar

A. Schwartzentruber [a,*], M. Philippe [b], G. Marchese [a]

[a] CTG—Italcementi Group, Laboratory of Material Evaluation, Rue des Technodes, 78931 Guerville Cedex, France

[b] DESS Materials, Université Paul Sabatier, Toulouse III, 118 Route de Narbonne, 31062 Toulouse Cedex 4, France

Abstract

Ultrahigh strength mortars (UHSM) are new materials with high compressive and tensile strengths. For such materials, autogenous shrinkage can sometimes induces cracks in restrained conditions without any external loading. In order to determine if a UHSM has a cracking tendency, the knowledge of the autogenous shrinkage, Young's modulus and tensile strength is not sufficient. The relaxation of the specimen must also be taking into account. Therefore, a cracking testing bench has been set up. It measures continuously the stress needed to maintain the strain in the range of ± 4 μm/m. The ratio between induced tensile stress and direct tensile strength, both aged in restrained conditions, is a good indicator of the cracking tendency. Different possibilities to reduce the cracking tendency have been investigated: PVA fibers, glass fibers, metallic fibers and an expansive admixture. Results show that two ways are interesting to reduce the cracking tendency: reducing restrained tensile stress and/or increasing tensile strength. The first can be obtained by using moderate dosage of expansive admixtures and/or glass fibers, the second by using high dosage of metallic fibers.

Keywords: Ultrahigh strength mortar; Autogenous shrinkage; Crack; Relaxation; Fibers; Expansive admixtures

1. Introduction

Ultrahigh strength mortars (UHSM) are new materials with high compressive and tensile strengths. High performances are obtained by reducing drastically the water to cement ratio, increasing the cement content and the packing density of solid components by using fine additions and high water reducing admixtures. These modifications have two important consequences: the reduction of porosity and the increase of the chemical shrinkage due to the high quantity of cement used.

Autogenous shrinkage, which is a consequence of self-desiccation of the paste, begins as soon as cement and water are in contact. After setting, the rigidity of the material increases and autogenous shrinkage is more and more restrained, internally by the aggregate skeleton and the reinforcement, and sometimes externally by the hyperstaticity of the structure. Tensile stresses are induced and if these stresses are greater than the tensile strength, cracks occur. Nevertheless, the knowledge of the evolution of autogenous shrinkage, Young's modulus and tensile strength in function of time at early age is not sufficient to determine if a UHSM has a cracking tendency in restrained conditions. Indeed, in restrained conditions, the relaxation of the specimen decreases significantly the induced stresses.

In order to take into account the relaxation, a cracking testing bench has been set up at the CTG Guerville. On this bench, the effect of PVA fibers, glass fibers, metallic fibers and of an expansive admixture on the cracking tendency of UHSM has been investigated. This article describes the characteristics of the different materials used, the testing methods and finally compares the effect of the different possibilities on the cracking tendency.

* Corresponding author. Address: SIKA S.A., Market RMC-Precast, 84 Rue Edouard Vaillant, B.P. 104, 93351 Le Bourget Cedex, France. Tel.: +33-1-49-92-80-63; fax: +33-1-49-92-81-21.

E-mail address: schwartzentruber.arnaud@fr.sika.com (A. Schwartzentruber).

0958-9465/$ - see front matter © 2004 Published by Elsevier Ltd.
doi:10.1016/S0958-9465(03)00076-3

2. UHSM mix

2.1. Materials

2.1.1. Cement

The cement used in this study is a CEM I 52.5 adapted to the design of UHSM. Its C_3S content is high: 65% and its C_3A content is very low: 2% (cf. Table 1). A low C_3A content guarantees a good durability against sulfate attack. A high C_3S content speeds up the hardening.

2.1.2. Silica fume

The silica fume (SF) used is nondensified. It is a by-product of the manufacture of silicon alloys. Its characteristics are given in Table 2.

2.1.3. Sand

Siliceous sand rounded with a grading range of 100–300 μm has been used. This sand is washed, dried and sieved.

2.1.4. Superplasticizers

The superplasticizer (SP) used is a modified polycarboxylate (cf. Table 3) adapted for the precast manufactory. Even at high dosage, this SP does not increase drastically the setting time. This property is essential to guarantee daily production rate without any thermal treatment.

Table 1
Cement characteristics

Characteristics	Value (%)
C_3S	65.09
C_2S	10.58
C_3A	2.37
C_4AF	11.95
Na_2Oeq	0.51
Free CaO	0.70

Table 2
Silica fume characteristics

Characteristics	Value
SiO_2	95.21%
Fineness BET	23.9 m^2/g
Density	2.36
Ignition loss	2.89%
Na_2Oeq	0.66%

Table 3
Superplasticizers characteristics

Characteristics	Value
Dry extract	31.6%
Density	1.08

Table 4
UHSM mix design

Constituent	Dosage (kg/m^3)
Cement	980
Sand	997
Silica fume	147
Superplasticizer	19.6
Add water	250.8

2.2. Mix design

The SF to cement ratio is 15% by mass. The water to cement ratio (w/c) is equal to 0.26. It has been chosen in order to obtain a compressive strength of 130 MPa at 28 days without fibers or thermal treatment.

The proportion of sand has been chosen in order to optimize the packing density of all solid grains: sand, cement and SF. It leads to a UHSM containing in volume 65% of paste and 35% of sand.

The dosage of SP is chosen in order to obtain a slump flow of 310 mm measured with a mini-cone (half dimensions of Abrams cone). With such slump flow, the UHSM is almost self-compacting. No vibration is needed to fill the mold. The UHSM mix design is given in Table 4. This mix is called the *reference* mix.

3. Possibilities investigated

In order to reduce the cracking tendency, different possibilities can be used alone or combined:

1. increasing the tensile strength;
2. preventing the opening and development of cracks;
3. reducing the autogenous shrinkage by adding an expansive product.

Two types of additions have been investigated, fibers and admixtures:

- PVA fibers (PVAF) (1 vol%).
- Glass fibers (GF) (1 vol%).
- Two types of metallic fibers (MF): galvanized (MFG) and brassed (MFB) (1 and 2 vol%).
- A calcium oxide based expansive admixture (EA) (1% and 3% of weight of cement).

The characteristics of the fibers are given in Table 5. The effects of these additions on the rheology of the UHSM are not similar (cf. Table 6). MF, 1% GF and 1% EA decrease the slump flow from 310 mm to almost the same value: 245 ± 15 mm. This value is enough to cast the specimen without any vibration. 1% PVAF and 3% EA decrease the slump flow more significantly, respectively to 200 mm and 100 mm. This latter value is

Table 5
Fibers characteristics

Nature	Length (mm)	Diameter (μm)	Fiber strength (MPa)	Density	Young's modulus (GPa)	Dosage (vol%)
Galvanized metallic fibers	13	200	2500	7.8	200	1 2
Brassed metallic fibers	13	200	2500	7.8	200	1 2
PVA fibers	12	95	1200	1.3	31.4	1
Glass fibers	12	Strand of 14 μm filaments	3500 1700	2.68	72	1

Table 6
Slump flow measured with a mini-cone and DTS

Constituent	Dosage	Slump flow (mm)	DTS (MPa)	Test time after casting
UHSM reference	/	310	3.20	34 h 27 min
MFB	2 vol%	233	9.74	51 h 16 min
	1 vol%	252	4.18	40 h 4 min
MFG	2 vol%	240	9.84	40 h 12 min
	1 vol%	260	4.11	40 h 4 min
PVAF	1 vol%	200	3.23	40 h 20 min
GF	1 vol%	250	3.40	40 h
EA	1% woc	245	4.30	40 h 28 min
	3% woc	100	3.80	41 h 8 min

the lowest measurable with our mini-cone. The loss of slump flow due to the introduction of 1% PVAF could be compensated by an increase of SP dosage but the use of 3% EA is not conceivable.

4. The cracking bench

4.1. Principle

The bench used in this study is a modified version of the bench developed by Serrano [1]. The cracking tendency is determined on a $500 \times 40 \times 25$ mm specimen, each end of the specimen is hold by a grip, one fixed and one mobile (cf. Fig. 1). The bench is located in a regulated room: 20 ± 2 °C and relative humidity of 65%. The displacement between the two grips is continuously measured with two displacement sensors (LVDT). The displacement measured on the fixed grip gives information about the deformation of the bench due to the load applied by the jack. This deformation is subtracted to the one measured on the mobile grip. Since the displacement of the specimen is higher than ± 2 μm, the jack pushes or pulls the specimen to maintain the displacement in the range of ± 2 μm. Continuously, the stress applied by the jack is measured with a load cell. The elements of the mold are made in plastic excepted the grips, which are metallic. The lateral faces of the mold can be removed since the setting of the material in order to prevent any friction with the mold.

After 40 h of restrained conditions, if the specimen did not crack, the jack breaks it in order to determine its direct tensile strength (DTS).

The restrained shrinkage can also be deduced from this test by summing the "natural" deformations, i.e. not induced by the jack, which occurs in the range ± 2 μm. This method has been proposed by Kovler [2] (cf. Fig. 2).

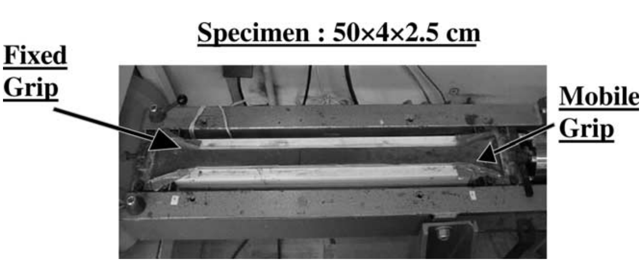

Fig. 1. Description of the cracking bench.

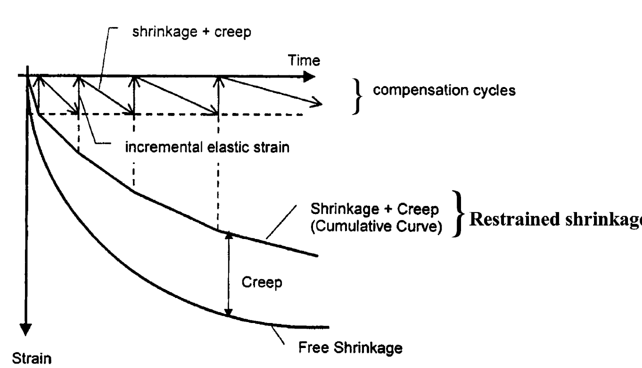

Fig. 2. Schematic description of the determination of the restrained shrinkage, after Kovler [2].

4.2. Casting method

A double layer of a fine plastic sheet is placed against the walls of the mold in order to reduce the friction. Glue, able to set in moisture condition, is applied on the grips before casting in order to guarantee a good adherence between the specimen and the grips. Indeed, during the test, load can change of sign, at first swelling and afterwards shrinkage. No gap between the specimen and the grips must appear during the test.

UHSM used are almost self-compacting materials. Therefore, castings could be done without any vibration.

After casting, a wet towel covered by a plastic sheet is laid on the surface of the mortar to maintain the material in saturated condition during the test period. These arrangements have to be taken, it is the only way to prevent the cracking of the reference UHSM specimen before the first 40 h. Indeed, without any protection, i.e. in contact with air at 20 °C and 65% relative humidity, or covered by only a plastic sheet, the specimen cracked just after setting.

After casting, a thermocouple is embedded in the grip zone in order to measure the evolution of material temperature during the test.

4.3. Repeatability and accuracy

In order to determine the accuracy of measurements, the reference UHSM has been tested three times on the cracking bench.

4.3.1. Temperature

The temperature evolutions are presented in Fig. 3. After casting, the temperature decreases from 20.7 to 20.0 due to the temperature regulation of the room. Ten hours after casting, it is the end of the dormant stage and the temperature increases due to hydration reactions, which are exothermic. These repeatability tests show that, despite the high cement dosage used, the range of temperature variation is ±0.5 °C. Thus, with a thermal dilatation coefficient of 20 μm/m/°C at early age [3,4], which is very pessimistic, the thermal strain variation will be atmost ±10 μm/m. Therefore, the thermal dilatations have a slight effect compared to the one due to autogenous shrinkage.

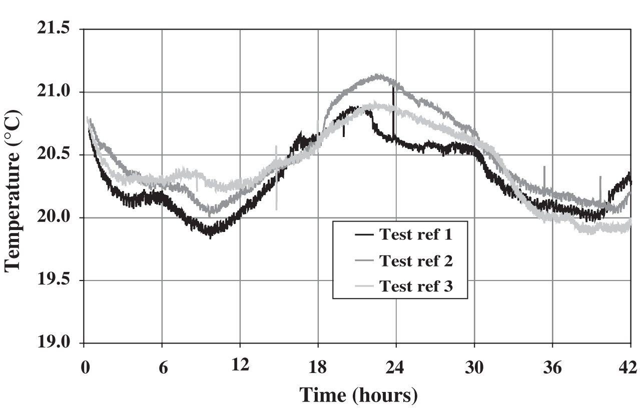

Fig. 3. Temperature evolution during repeatability tests.

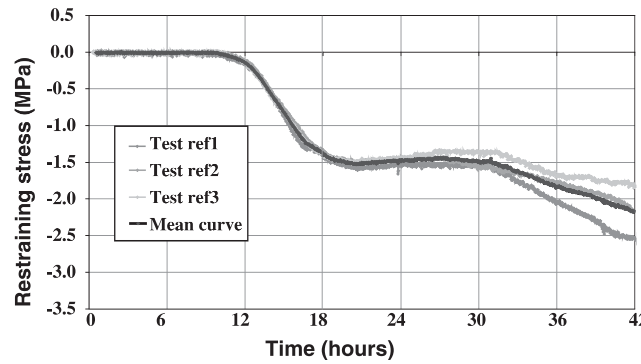

Fig. 4. Restraining stress evolution during repeatability tests.

4.3.2. Restraining stress

The restraining stress can be deduced from the stress needed to maintain the strain of the specimen between the range ±4 μm/m. The three repeatability tests are presented in Fig. 4. Before the end of the dormant stage, i.e. first 10 h, no stress is recorded. Indeed, during this period, the specimen has no rigidity and the stress necessary to compensate the plastic swelling is negligible. After the dormant stage, a tensile stress must be applied to maintain the specimen in the strain range of ±4 μm/m. The tensile stress increases during 17 h after casting, then, slows down and, after 20 h, stops. A slight decrease of the tensile stress followed by stabilization is observed. This phase lasts 5–7 h. After that, the tensile stress increases again until the end of the test. The increase of the tensile stress continues during several days but we are interested only in the early age cracking risks, i.e. during the first 42 h.

Results show that, during the first 30 h, the accuracy on restraining stress can be taken equal to ±0.15 MPa. Therefore, if fibers or admixtures induce a modification of the restraining stresses greater than the accuracy, the effect becomes significant. After 30 h, the accuracy decreases drastically (±0.35 MPa after 42 h).

4.3.3. Displacement

Displacements of the specimen during the three repeatability tests are presented in Fig. 5. Before the setting, a slight swelling is detected. This swelling can be imputed to the cure used. Indeed, the application of a wet towel on the mortar surface induced a slight absorption of water by the specimen.

At the end of the dormant stage, shrinkage begins and lasts 20 h after casting. Then, a slight swelling is detected. Its maximum amplitude is equal to 10 μm/m

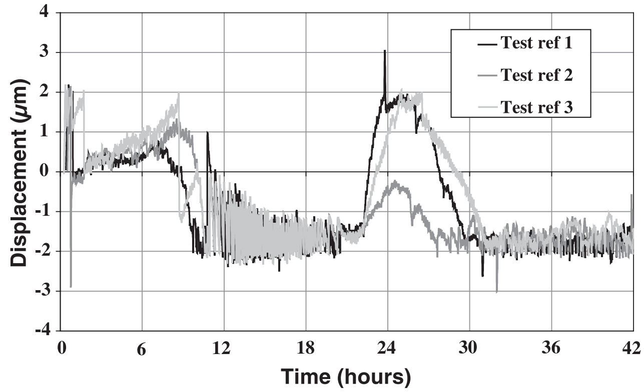

Fig. 5. Displacement evolution during repeatability tests.

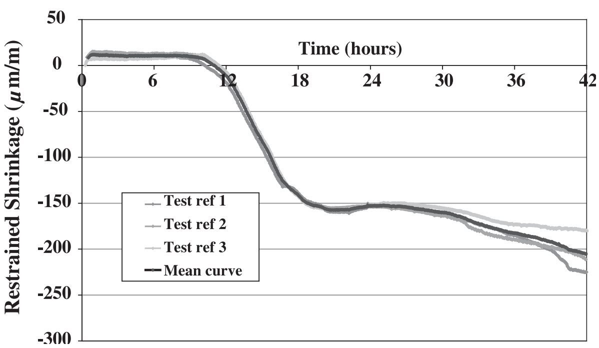

Fig. 6. Restrained shrinkage evolution during repeatability tests.

but it is not repeatable. After swelling, a second shrinkage appears until the end of the test.

4.3.4. Restrained shrinkage

The restrained shrinkage is deduced from the displacement by summing the natural deformations of the specimen, i.e. not induced by the jack. The three repeatability tests are presented in Fig. 6. The temperature effects are corrected by assuming that the thermal dilatation coefficient is constant and equal to 10 μm/m/°C. After temperature correction, the swelling is still detected. The three repeatability tests show that the accuracy of restrained shrinkage can be taken equal to ±5 μm/m during the first 30 h. After this delay, the accuracy decreased progressively (±25 μm/m at 42 h).

5. Experimental results

After the repeatability tests, another delivery of the same cement have been used. However, the assumption is taken that the accuracy values determined in the first part of the study do not depend on the cement delivery. This new delivery has been used in the following tests.

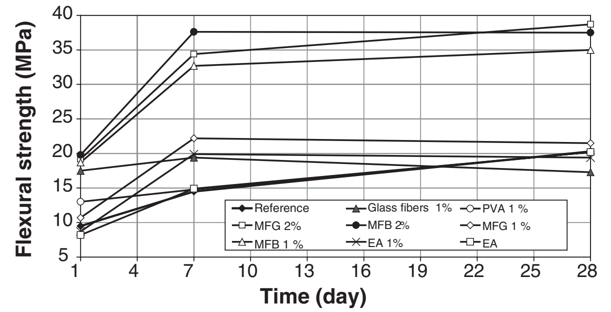

Fig. 7. Flexural strength of the reference UHSC and with the different solutions investigated.

5.1. Mechanical characteristics

Compressive and flexural strength of UHSMs: reference mix and those with the different possibilities investigated are measured on $4 \times 4 \times 16$ cm prisms. The prisms are demolded 24 h after casting and put in 20 °C water until tests. Each result is the average of three measurements.

5.1.1. Flexural strength

The three point flexural strengths at 1, 7 and 28 days are presented in Fig. 7. The reference UHSM has a 1, 7 and 28 day's flexural strengths of respectively 9.5, 14.5 and 20.3 MPa.

1% PVAF and 1% or 3% EA, do not modify significantly the 28 day's flexural strength, for both additions: 20.2 MPa.

1% GF increases significantly the 1 day flexural strength (17.5 MPa) but at 28 days, it is lower than the reference (17.3 MPa).

For a dosage of 1% of MF, surface treatment influences the flexural strength: MFB increases drastically the flexural strength, 35 MPa at 28 days, whereas the increase due to the use of MFG is low: 21.3 MPa. With 2% MF, the flexural strengths are the best but the type of surface treatment is less sensible, with 38.7 and 37.5 MPa for respectively galvanized and brassed fibers.

5.1.2. Compressive strength

Compressive strengths at 1, 7 and 28 days are presented in Fig. 8. The reference UHSM has a 1, 7 and 28 day's compressive strengths of respectively 53.9, 99.3 and 134 MPa.

1% PVAF or GF do not modify significantly the 28 day's compressive strength with respectively 133.9 and 138.5 MPa.

1% or 3% EA induces a decrease of the 28 days compressive strength with respectively 114.2 and 114.3 MPa. Nevertheless, for 1% EA, at 7 days, the compressive strength is higher than the reference mix with 127 MPa.

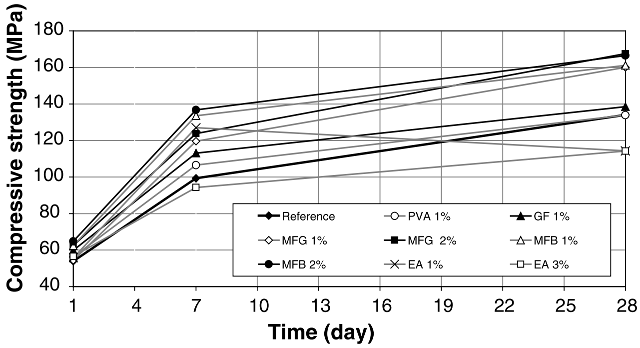

Fig. 8. Compressive strength of the reference UHSC and with the different solutions investigated.

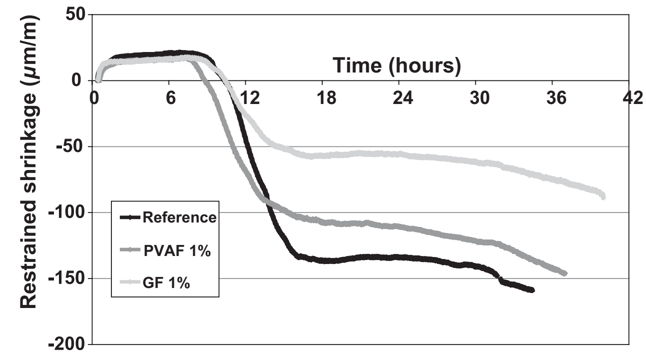

Fig. 10. Influence of 1% glass fibers and 1% PVA fibers on the restrained shrinkage.

The use of at least 1% MF is the best way to improve significantly the compressive strength. The MF content (1% or 2%) has a little effect on results. Nevertheless, at 28 days, the best compressive strengths are obtained with 2% content of MF, 167.5 and 166.5 respectively for brassed and galvanized fibers. Conversely, at 7 days, the surface treatment is more important than the fiber content. Indeed, 1% MFB are more efficient than 2% MFG with respectively 133.5 and 123.8 MPa.

5.2. Cracking bench

5.2.1. PVAF and GF

Restraining stress and restrained shrinkage of UHSM containing 1% PVAF or 1% GF are presented in Figs. 9 and 10.

Results show that the effect of 1% PVAF on the restraining stress is not significant because the effect is lower than the accuracy, ±0.175 MPa. Conversely, for 1% GF, the decrease is slightly greater than the accuracy. During the test, the specimen with 1% PVAF micro-cracked or slipped suddenly 37 h 3 min after casting inducing a decrease of restrained stress. Nevertheless, the remaining stress is still high, −1.23 MPa, which indicates that the specimen did not completely break.

The restrained shrinkage is only slightly decreased by the use of 1% PVAF. Conversely, with 1% GF, restrained shrinkage is drastically decreased by a coefficient of 2.3.

Globally, the effect of PVAF is not significant. Moreover, these fibers induce an important loss of rheology. GF are more efficient and reduce significantly the restrained shrinkage and induce a decrease of the restraining stress. The Young's modulus seems to be increased by the use of 1% GF.

5.2.2. MF

The effect of using 1% or 2% brassed or galvanized MF is presented in Figs. 11 and 12, respectively for the restraining stress and the restrained shrinkage.

Results show that the effect of 1% or 2% brassed or galvanized MF is not significant on the restraining stress.

Conversely, the restrained shrinkage is decreased by the use of MF. There is no significant difference between the two types of fibers, brassed or galvanized. However, the decrease is a little greater for 2% volume content than for 1%.

The use of MF seems to increase the Young's modulus of the UHSM. The shrinkage is lowered but the

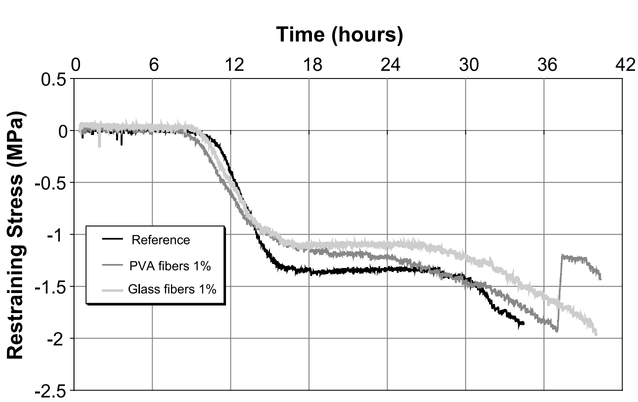

Fig. 9. Influence of 1% glass fibers and 1% PVA fibers on the restraining stresses.

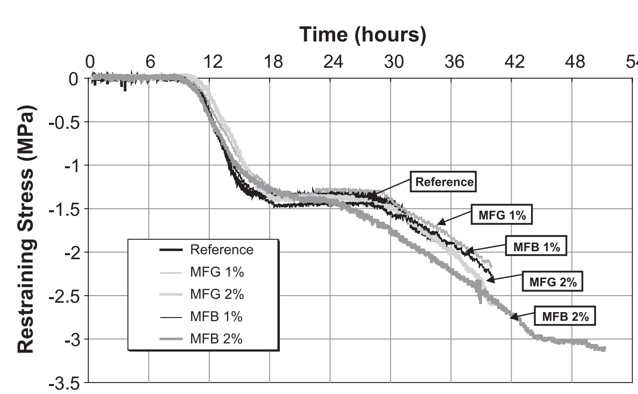

Fig. 11. Influence of 1% or 2% brassed or galvanized metallic fibers on the restraining stresses.

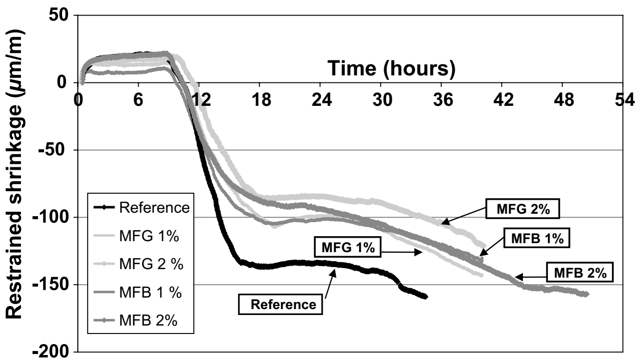

Fig. 12. Influence of 1% or 2% brassed or galvanized metallic fibers on the restrained shrinkage.

increase of the rigidity implies that the restrained stress is not reduced.

5.2.3. EA

The effect of using 1% or 3% of EA is presented in Figs. 13 and 14.

Results show that this EA has an important effect on the evolution of the restraining stresses and restrained shrinkage. For 1% EA, the set is faster and the

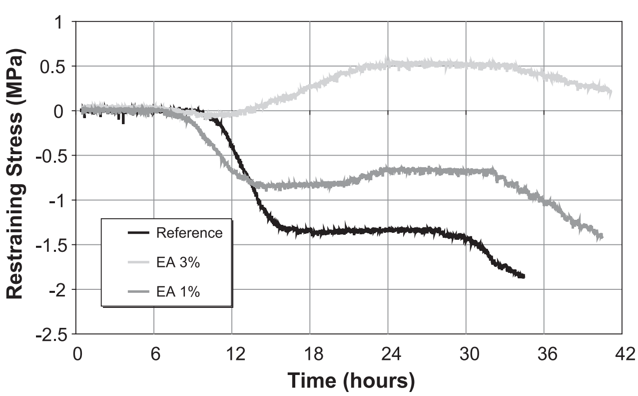

Fig. 13. Influence of 1% or 3% of an expansive admixture on restraining stresses.

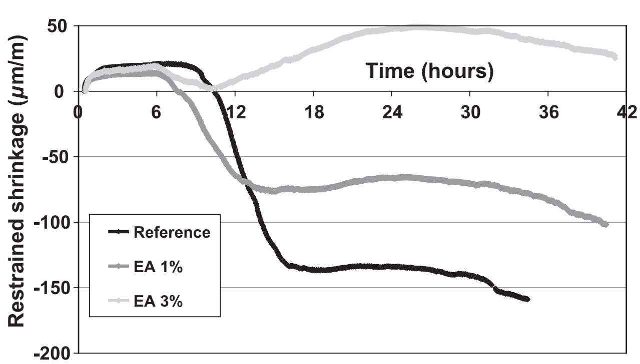

Fig. 14. Influence of 1% or 3% of an expansive admixture on restrained shrinkage.

restraining stress is significantly decreased. Moreover, a decrease of the restraining stress is detected 21 h after casting. It is due to the swelling of the material. Indeed, during a short period, the hydration of EA induces an expansion greater than the autogenous shrinkage.

For 3% EA, no restrained shrinkage is detected, only restrained swelling appeared. In fact, during the first 40 h, the expansion is greater than the autogenous shrinkage. Therefore, the restraining stress is all the testing time positive, i.e. the jack pushes continuously the specimen.

5.3. Direct tensile strength

At the end of the test on the cracking bench, the jack pulls the specimen until it breaks in order to determine its DTS. This value cannot be directly compared to classical direct tensile tests because the specimen is loaded since the set. But, this value is closer to the real tensile strength of the in place restrained material. Table 6 presents the DTS measured and the test time. All the tests have done around 42 h after casting, except for the UHSM and the MFB 2%, respectively 34 h 27 min and 51 h 16 min.

The UHSM reference mix has a DTS of 3.2 MPa. PVAF and GF do not increase significantly the DTS, respectively 0.9% and 6.2%. EA, for 1% and 3% dosage, increase the DTS more significantly, i.e. 34.4% and 18.8%. The type of MF does not influence the DTS increase, only the dosage does. With 1% MF, the increase of the DTS is smaller than with 1% EA. But, with 2% MF, the increase is greater than 200%.

6. Discussion

In order to compare the cracking tendency of the different possibilities investigated, a cracking indicator has been defined. There is a cracking risk since the tensile stress becomes greater than the DTS, both in restrained conditions.

The ratio between these two characteristics has been calculated for each possibility at the end of the test (cf. Table 7).

Results show that, compared to the reference UHSM, 1% PVAF increases the cracking risk whereas 1% GF does not improve it. 1% MF decreases slightly the cracking risk. Nevertheless, 1% EA seems to have a better effect on the cracking risk than 1% MF. In fact, 1% EA decreases the restraining stress and increases the DTS whereas 1% MF only increases the DTS without modifying the restraining stress.

The best reduction of the cracking risk is obtained with 2% MF. In fact, DTS drastically increases and the restraining stress is not modified.

Table 7
Cracking risk indicator (in decreasing order)

Constituent	Dosage	Cracking risk indicator (%)
PVAF	1 vol%	66
UHSM reference	/	58
GF	1 vol%	57
MFB	1 vol%	54
MFG	1 vol%	53
EA	1% woc	33
MFB	2 vol%	32
MFG	2 vol%	26
EA	3% woc	−6

Three percent EA has a negative cracking risk because the specimen swells and there is no risk of cracking due to tensile stress. Moreover, the compressive stress induces is clearly smaller than the compressive strength.

7. Conclusions

Results show that the effectiveness of each investigated possibility is quite different and the more appropriate depends on the use aimed for the UHSM:

1. About 1 or 2 vol% metallic fibers do not modify the stress induced by restrained conditions but increase the tensile strength, particularly with a dosage of 2%. Therefore, metallic fibers reduce significantly the cracking tendency. Nevertheless, metallic fibers are costly. Moreover, the shrinkage is not drastically reduce, therefore it will be difficult to demold specimen with hard core and the use of flexible mold is essential.
2. About 1 vol% PVA fibers does not modify significantly the stress induced by restrained conditions. Moreover, the tensile strength is not improved. Among the investigated possibilities, it is the less effective for reducing the cracking tendency.
3. About 1 vol% glass fibers reduces the restrained stress (24% reduction at 24 h). This reduction is greater than with PVA or metallic fibers. Nevertheless, glass fibers do not improve the DTS and finally, the reduction of the cracking tendency is not so significant.
4. Calcium oxide based EA reduces significantly the stress in restrained conditions. For 3% EA dosage, no tensile stress appears in restrained conditions. But, the 28 days mechanical characteristics are reduced. Moreover, with 3% EA dosage, the workability is also drastically reduced. One percent EA is a good compromise. The reduction of the restraining stress is significant and the DTS is increased. The use of EA is interesting if the remaining strength is sufficient for the applications aimed. Moreover, if the mold contains hard core, the demolding will be easier.

Finally, two ways are interesting to reduce cracking tendency: reducing of restrained tensile stress and/or increasing the DTS. The first can be obtained by the use of a moderate dosage of EA and the second by using a high dosage, 2 vol%, of metallic fibers.

Acknowledgements

The authors acknowledge Mr. J. Serrano for providing the cracking bench and for given us expert advice for its updating.

References

[1] Paillère A-M, Serrano. Appareil d'étude de la fissuration du béton. Bulletin de Liaison du Laboratoire des Ponts et Chaussées 1976;May–June.
[2] Kovler K. Testing system for determining the mechanical behavior of early age concrete under restrained and uniaxial shrinkage. Mater Struct 1994;27:324–30.
[3] Laplante P. Propriétés mécaniques des bétons durcissants: analyse comparée des bétons classiques et à très hautes performances. PhD thesis. Paris: Ecole Nationale des Ponts et Chaussées; 1993.
[4] Bjontegaard Ø. Thermal dilatation and autogenous deformation forces to self-induced stresses in high performance concrete. PhD thesis. Trondheim: The Norwegian University of Science and Technology; December 1999.