STRENGTH DEVELOPMENT OF SHOTCRETE WITH HIGH QUANTITY OF ACCELERATING ADDITIVES

FESTIGKEITSENTWICKLUNG VON SPRITZBETONEN MIT HOHEM ZUSATZ VON ERSTARRUNGSBESCHLEUNIGERN

DÉVELOPPEMENT DE LA RÉSISTANCE À LA COMPRESSION DU BÉTON PROJÉTÉ AVEC UNE HAUTE CONTENANCE DES ACCÉLÉRATEURS

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SUMMARY

The development of compressive strength has been investigated for dry-mix shotcretes and wet-mix shotcretes with a high amount of accelerating additives over a period of more than 5 years. The result was that wet-mix shotcretes with water glass as accelerator at normal climate conditions differs significantly from normal behaviour. Due to relatively big shrinkage deformations internal stresses and microcracking occur. These may reduce the compressive strength of specimens as soon as they reach zones relevant to the ultimate strength. The stabilization of the compressive strength coincides with the reaching of the final shrinkage. If those shotcrete variants were used for temporary tasks an appropriate rise of the 28 days compressive strength is recommended. A permanent load bearing requires further investigations of the long-term behaviour.

ZUSAMMENFASSUNG

Bei Trockenspritzbetonen und Naßspritzbetonen mit hohen Gehalten an Erstarrungsbeschleunigern auf Alkalibasis wurde die Entwicklung der Druckfestigkeit über einen Zeitraum von mehr als 5 Jahren verfolgt. Dabei ergab sich, daß Naßspritzbetone mit Wasserglas als Erstarrungsbeschleuniger unter normalen klimatischen Bedingungen bei der Festigkeitsentwicklung vom üblichen abweichen. Infolge relativ hoher Schwindverformungen entstehen Eigenspannungen und Mikrorisse, die sich mindernd auf die Druckfestigkeit von Prüfkörpern auswirkern, sobald davon Zonen betroffen sind, die für die Bruchentstehung im Versuch maßgebend sind. Die Abminderung endet zeitlich mit Erreichen des Endschwindmaßes. Von diesem Zeitpunkt an bleibt die Druckfestigkeit stabil. Soll diese Spritzbetonvariante temporär eingesetzt werden, so ist die Druckfestigkeit durch ein entsprechendes Vorhaltemaß anzuheben. Für dauernde Lastabtragungen wäre das Langzeitverhalten weiter zu überprüfen.

RÉSUMÉ

On a examiné des bétons projétés secs et mouillés avec addition d'une haute quantité d'accélérateurs à la base des alcalis dans une période de plus de 5 ans. Il en ressort que pour des bétons projétés mouillés accélérés par du verre soluble et sous des conditions climatiques normales, le developpement de la résistance à la compression dévie significament de l'attitude normale. A cause d'un retrait relativement grand résultent des tensions propres et des microfissures. Celles-ci peuvent diminuer la résistance à la compression des épreuves dès qu'elles atteignent des zones importantes pour la formation de la rupture. La diminution se stabilise quand les épreuves atteignent le retrait final. Quand on veut utiliser cette variante du béton projété pour une mission temporaire une augmentation convenable de la résistance à la compression est recommandée. Au cas où l'on veut charger ce béton projété permanemment, l' examination de l'attitude de longue durée serait necessaire.

Key words

Dry-mix shotcrete, wet-mix shotcrete, accelerating additives, alcalies, water glass, compressive strength, shrinkage, internal stresses, microcracking, final shrinkage, stabilization of strength reduction

FOREWORD

In the last years studies about mechanical-technological properties of shotcretes with a high amount of accelerating additives have been carried out at the Otto-Graf-Institute in Stuttgart, sponsored by the German Industrial Research Organisation (AIF) under advice by the German Concrete Association (DBV). However there were a time limit and financial restrictions as well.

As the Research Institute of the German Cement Industry has supplied new funds it was possible to continue the investigations in view of the very interesting question of the development of strength of these types of shotcrete over a period of slightly more than 5 years. For this support we express our thanks.

In the following the facts which help to understand the aims of the research work were summarized and the previous and new test results were discussed.

1. INTRODUCTION

Due to dense population and the resulting need for protection against noises and environmental pollution the improving of the traffic networks requires more and more tunnels as construction elements. In contrary to classic tunneling in the mountains frequently less stable formations with thin covers will be crossed. In this instance shotcreting, well known as New Austrian Tunnel Construction Method NÖT, has become very economic. It is characterized by the fact that immediately after heading the face is lined with a very early setting and hardening shotcrete.

Actually fluid and powdery accelerators on the basis of alcali aluminate and alcali carbonate are on the market. For wet-mix shotcrete water glass (sodium silicate, potassium silicate) as accelerator has been and is still in use for economic reasons. However at the construction site it was and is necessary to increase the quantity of water glass above the established upper limits for the amount of additives.

Among others the aim of the above mentioned studies [1] [2] was to find out if a high amount of accelerators is of negative influence on the setting and hardening process of the shotcretes and on the mechanical-technological characteristics as well. Especially interesting were tendencies known from short time laboratory tests [1] and from construction sites that wet-mix shotcretes with a high water glass amount may show a certain reduction of compressive strength with increasing age or a reduced strength development in comparison to normal concrete without accelerators. That is why the investigation of the development of compressive strength of shotcretes of the test programme [1] has been extended up to a period of 5 ½ years.

The results shall not be described without mentioning the compatibility of accelerated shotcretes with the environment. The use of such concretes within the area of ground water may cause a water pollution by leaching of soluble alcalies. This may be especially the case if shotcretes show a low density, that means a water-permeable structure. Therefore shotcreting in ground water area makes it necessary to keep the amount of accelerators containing alcalies to water according to DIN 1045. Different investigations in the Otto-Graf-Institute have shown that this is possible.

In relation with alcalies the question of compatibility with aggregates has to be discussed. If necessary special investigations should be carried out. The aggregates used in this study may be regarded as insensitive to alcali.

2. DETAILS OF THE SHOTCRETES

The study comprehends a wet-mix- (N) and a dry-mix shotcrete (T) both stored under defined wet (n) and dry (t) conditions. As samples cores were used taken from a shotcrete surface at a tunnel construction site at the age of 2 days. The cores had a diameter of 10 cm and a length of about 30 cm. They were finally prepared in the laboratory according to the testing aim.

Besides water the shotcretes were composed of Portland cement PZ 45 F and Rhine material with a maximum grain size of 8 cm. The aggregates consisted of the two fractions 0/2 mm and 2/8 mm in a proportion of 1:1.

The wet-mix shotcretes have been accelerated by water glass with a temperature of ≈ 50 °C at two different amounts (N 10, N 15). A powdery accelerator on the basis of sodium aluminate was used for the dry-mix shotcrete only in one quantity (T 10). The numbers behind the symbols represent the planned percentage of accelerator in relation to the cement weight. Due to technical reasons the actual amounts of accelerators were somewhat different from the planned.

Further informations and details are given in table 1.

3. STORING OF THE SHOTCRETES

Immediatly after drilling from the properly cured shotcrete surface the cores were stored at humid conditions (20 °C, 99 % r.h.) up to the age of 7 days. Afterwards and according to the test programme the storing was divided into the variants dry (t) with 20 °C and 65 % r.h. and wet (n) in water with 20 °C.

Table 1. Admixtures of shotcretes; flow

Shotcrete 1)	Components Cement PZ 45 F kg/m³	Aggreg. 2) (Rhine mat.) kg/m³	Water L/m³	Additives Accelerator planned ml/kg resp. g/kg Cement	Accelerator actual	Plasticiser actual	Flow cm
N 10 t N 10 n	370 370	1740 1740	200 200	100 100	~ 130 ~ 130	~ 10 ~ 10	~ 55 ~ 55
N 15 t N 15 n	370 370	1740 1740	200 200	150 150	~ 260 ~ 260	~ 22 ~ 22	~ 60 ~ 60
T 10 t T 10 n	370 370	1740 1740	—3) —3)	100 100	~ 70 ~ 70	— —	not measured

1) N Wet-mix shotcrete, T Dry-mix shotcrete, t dry storing, n wet storing
2) Sand 0/2 mm : gravel sand 2/8mm = 1 : 1
3) no values can be stated

Afterwards and according to the test programme the storing was divided into the variants dry (t) with 20 °C and 65 % r.h. and wet (n) in water with 20 °C.

4. BULK DENSITY AND COMPRESSIVE STRENGTH

The bulk density and the compressive strength of the shotcretes have been tested according to DIN 1048 part 1, edition 1978, at the age between 7 days and 5 ½ years. Per testing date 3 cores with a relation height : diameter h : d = 1:1 were tested. The mean values of the results are compiled in table 2 whereas the upper numbers indicate the bulk density and the lower numbers the compressive strength. Moreover the development of compressive strength is represented in fig. 1. Concerning the test results is has to be mentioned that samples of concretes sprayed on a construction site may show a bigger spreading of the test results than samples of concretes sprayed under laboratory conditions. The identification of an influence by an accelerator on the compressive strength may therefore be more difficult.

At the age of 7 days, according to the test programme only for wet stored samples, a compressive strength of 19 N/mm² for the dry-mix shotcretes and of 22 N/mm² for the wet-mix variants has been established independent of the amount of accelerator.

Table 2. Bulk density and Compressive strength of the shotcretes (mean values of 3 tests, h : d = 1 : 1)

Shotcrete [1]	Bulk density in kg/ dm^3 (upper number), Compressive strength in N/mm^2 (lower number) at the age of					
	7	28	90	360 days	2	5 1/2 years
N 10 t	- -	2,16 25	2,15 26	2,09 21	2,14 20	2,14 25
N 10 n	2,19 22	2,20 23	2,20 26	2,26 31	2,23 28	2,19 30
N 15 t	- -	2,17 26	2,18 28	2,15 24	2,11 20	2,14 25
N 15 n	2,22 22	2,23 26	2,16 30	2,22 32	2,25 34	2,22 31
T 10 t	- -	2,21 25	2,21 30	2,21 33	2,21 35	2,18 38
T 10 n	2,25 19	2,25 24	2,28 27	2,30 29	2,33 37	2,25 32

1) N Wet-mix shotcrete, T Dry-mix shotcrete, n wet storing, t dry storing

Up to the age of 28 days an increase of compressive strength to values between 23 to 26 N/mm^2 could be stated, whereas the lower strengths relate to wet storing. An influence of the amount of accelerator is not obvious. Not unexpected, the bulk densities were lower than those of normal concrete.

Due to the compressive strength at 28 days the shotcretes may be ranged into strength class B 25 according to DIN 1045. If one compares the strength with that which may be expected for normal concrete composed like the wet-mix shotcrete but without accelerating additives [3] the strengthening capacity of the cement is only exploited up to $\approx$ 60 %.

With an increasing age the dry-mix shotcretes showed an increase of strength and, as expected, the results of the dry stored samples were higher than those

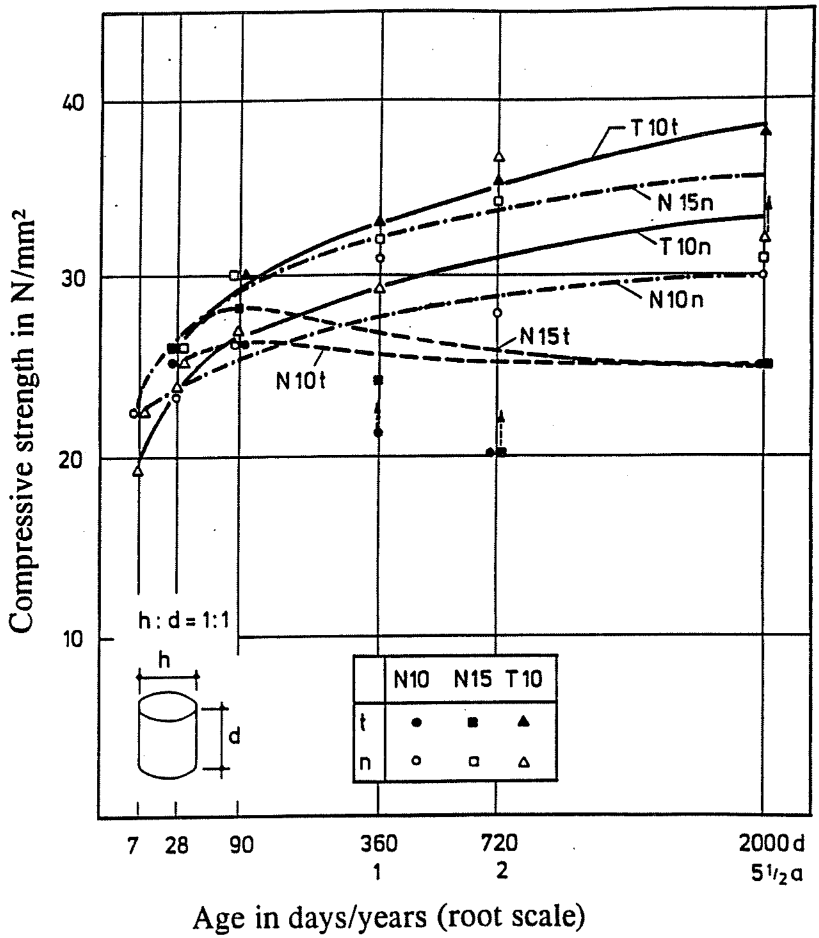

Fig.1 Development of compressive strength of wet-mix- (N) and dry-mix shotcretes (T) at storage in dry (t) and wet (n) environment

of the wet stored specimens. At the age of 5 ½ years values of 38 N/mm² (T 10 t) and 32 N/mm² (T 10 n) were stated.

The wet-mix shotcretes stored in water behave similar as dry-mix shotcretes. Moreover the wet-mix variants stored at dry conditions showed a different behaviour than expected. The flattening of the increase in strength between 28 and nearly 90 days has been followed by a decrease down lower than the values at the age of 28 days. This is also valid in view of the fact that the test results of N 10 t at the age of 1 year and N 15 t at the age of 2 years have too low bulk densities and, thus, too low compressive strengths. The strength development of these shotcretes is marked in fig. 1 as broken line. According to this the compressive strength after 5 ½ years is about 10 % lower than the strength at 28 days. It seems that the higher addition of water glass had a strength increasing effect at wet storing and, at young age, even in dry environment. As far as it can be established by these tests at long-term no influence by the amount of accelerator is obvious at dry storage.

5. DISCUSSION OF THE DEVELOPMENT OF COMPRESSIVE STRENGTH

The established long-term development of the compressive strength for wet-mix shotcretes with water glass as accelerator differs essentially from usual behaviour. This may be explained by the shrinkage of these materials.

Fig. 2 represents the shrinkage deformations versus age of the tested shotcretes at dry storing [1]. The measurements were taken in axial direction at specimens of 10 cm in diameter and 25 cm in length over a period of 1 ½ years. The deformations of the wet-mix shotcretes are significantly bigger than those of the dry-mix variant. The final shrinkage values measured for the wet-mix concrete normally can only be found for cement paste specimens. According to Pickett [4] a measured shrinkage value of nearly 3 mm/m established for N 15 t requires nearly a 5-fold higher shrinkage value for cement paste. This certainly leads to a higher level of internal stresses and to the danger of microcracking in the cement paste.

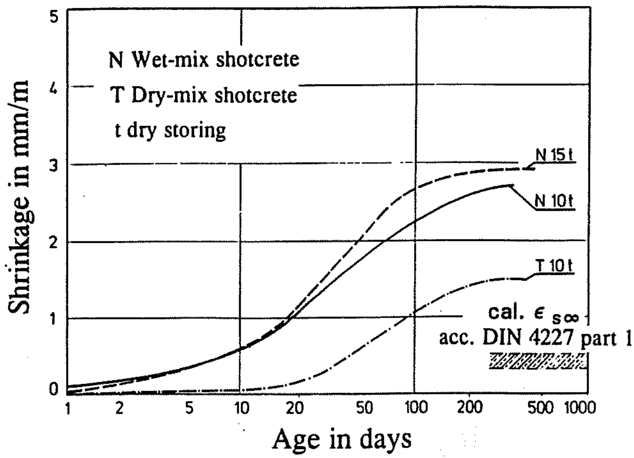

Fig.2 Shrinkage of shotcrete cylinders stored under normal climate conditions (20 °C, 65 % r.h.)

As well as in the axial direction the shrinkage must act in radial direction and at the faces of the specimens. As the samples may deform in axial direction without restraint, this is for instance not the case in radial direction. It has to be started from the fact that shrinkage of the outer border area happens before shrinkage of the samples core. The not yet shrinked core resists the deformations of the border area. The consequences - in a variable equilibrium status - are radial tensile stresses in the border area and compressive stresses in the core of the sample.

The investigation of the surface of five years old untested samples N 10 t and N 15 t magnified 35 times by a stereo microscope showed that the walls of bigger air voids or compaction voids are cracked or that microcracks connect adjoined pores. These cracks are not discernible with the naked eye. Fig. 3 shows for instance a crack pattern between two adjoined voids, fig. 4 the formation of microcracks in the wall of a void. Voids on the surface of dry-mix shotcrete cores showed only singular microcracks with an extension and a crack width not comparable with those of the wet-mix version.

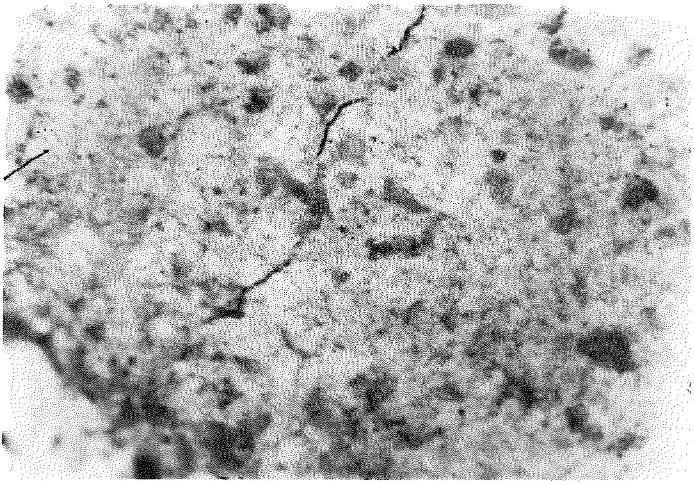

Fig. 3 Specimen N 10 t, microcrack between two adjoined compaction pores on the surface of the core (magnified 35 times)

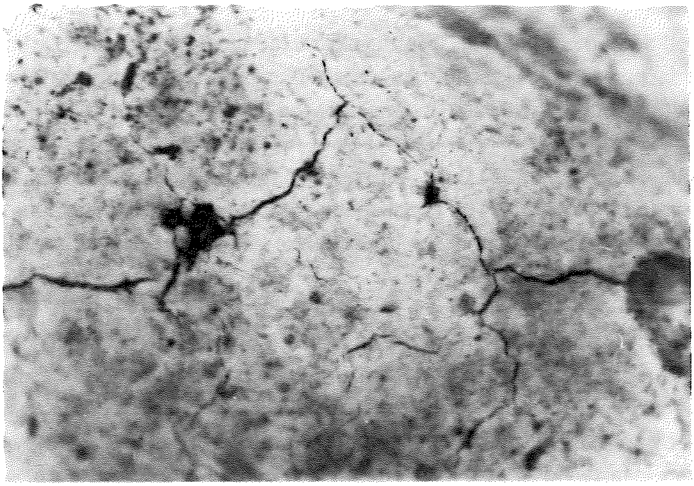

Fig.4 Specimen N 15 t, microcracks on the bottom of a compaction void on the surface of the core (magnified 35 times)

The internal stresses due to shrinkage may be calculated on the basis of very simplified assumptions and, thus, may be comparably discussed. A finite element programme (FE) was used and the calculation based on the assumptions of a concrete disk with the thickness 1 and a plane distortion status. Besides the faces of the cylinders this may be a sufficient good approximation. For the idealization isoparametric triangle elements with 6 nodal points were chosen. Due to geometric and loading rotational symmetry only one disk segment was determined by calculation (disk center as fixed point, the other nodes were displacable).

On the basis of the test results and under assumption of a constant shrinkage for the whole specimen the characteristics given in table 3 were determined. The linear-elastic analysis leads to the calculated radial stresses indicated in table 4.

Table 3. Material characteristics for the finite element calculation

	Modulus of elasticity N/mm²	Shrinkage 1) mm/m	Poisson's ratio
Normal concrete	30 000	0,5	0,2
Dry-mix shotcrete	18 000	1,4	0,2
Wet-mix shotcrete	15 000	2,5	0,2

1) radial shrinkage at the external border of the concrete disk

Table 4. Radial stresses at the disk element on behalf of a finite element calculation under idealized assumptions

	Radial stresses in N/mm² 1)	
	disk center (r = 0 mm)	disk border (r = 50 mm)
Normal concrete	- 6,6	+ 5,8
Dry-mix shotcrete T 10 t	- 11,0	+ 9,7
Wet-mix shotcrete N 10t / N 15t	- 16,4	+ 14,5

1) - Compressive stress, + Tensile stress

The calculated radial stresses may not appear in the indicated order. After reaching the ultimate tensile stresses in the concrete a crack formation will occur and reduces the level of internal stresses. However, the calculated results may be used comparably for the following conclusions:

- The radial tensile stresses for the wet-mix shotcretes are much bigger than for the dry-mix shotcrete or for normal concrete.

- The formation of microcracks due to shrinkage cannot be excluded at least for wet-mix shotcrete with water glass as accelerator. This is confirmed by observation of cracks.

For the differences in strength development between the specimens T 10 t and N 10 t or N 15 t represented in fig. 1 the following hypothesis may be established:

- At young age all shotcretes show an increasing strength with an increasing age as expected.

- With the beginning of shrinkage radial stresses develop in the specimens.

- For the wet-mix shotcretes stored in dry environment a formation of microcracks begins at the outer border of the cylinder due to shrinkage. At first this might not have any effect upon the compressive strength of the specimens. With an increasing drying of the interior of the core a progressing formation of microcracks to the inner of the core is probable. If the formation of microcracks reaches zones wich are important for the fracture of the specimens under compression an influence upon the result of the compressive strength is not surprising. The fact that the time of influencing the strength development coincides with the reaching of the ultimate shrinkage supports this hypothesis. From that time the development of strength may be regarded as stable.

6. SUMMARY

The development of compressive strength was observed for dry-mix shotcretes and wet-mix shotcretes with high amounts of accelerators on the basis of alcalies over a period of more than five years. This study was released by a stated reduced strengthening behaviour of wet-mix shotcretes with water glass as accelerator in comparison to normal concrete with the same composition but without accelerators.

It has to be stated that the development of compressive strength of wet-mix shotcretes with water glass stored at normal climate conditions (dry storage in normal climate 20/65) differs from usual behaviour:

- After an initial increase of strength, parallel with the beginning of shrinkage, the increase flattens out and at least there is a decrease of the strength down to nearly 90 % of the strength at 28 days.

- The decrease of strength coincides with the reaching of the final shrinkage.

This may be caused by relatively high shrinkage deformations. These produce microcracking, as the observations of the specimens as well as an idealized calculation have shown. The microcracking begins at the surface of the specimens and continues to the core with an increasing drying. Whereas microcracking on the surface of the specimens is of no influence on the compressive strength, an influence is stated as soon as the microcracks reach zones relevant to the ultimate compressive strength. This coincides with reaching of the final shrinkage. If the shrinkage deformations come to the end no further change of strength will happen.

Whereas dry-mix shotcretes at wet and dry storing and the wet-mix variant at wet storing with the chosen accelerators behave as expected and similar to normal concrete, the different behaviour of wet-mix shotcrete with water glass as accelerator at normal climate conditions has to be taken into account. For temporary tasks the load bearing capacity of such concretes may be sufficient if a possible decrease of strength may be compensated by an appropriate rise in 28 days strength. The question if such concretes have a sufficient long-term behaviour has not been answered. This should be investigated if wet-mix shotcrete with water glass should be used for permanent load bearing.

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