MECHANICAL-TECHNOLOGICAL PROPERTIES OF SHOTCRETE WITH ACCELERATING ADMIXTURES

MECHANISCH-TECHNOLOGISCHE EIGENSCHAFTEN VON SPRITZBETON MIT ERSTARRUNGSBESCHLEUNIGERN

QUALITÉS MÉCANIQUES-TECHNOLOGIQUES DE BÉTON PROJETÉ AVEC ADDITION D'ACCÉLÉRATEURS

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SUMMARY

Dry-mix and wet-mix shotcretes with a normal and a high quantity of accelerating additives on the basis of alcali aluminates and alcali carbonates at different storing conditions have been investigated. As a result it can be stated that according to their compressive strengths the shotcretes can be ranged into concrete classes following DIN 1045. The established stress-strain curves, splitting tensile strengths and the long-term strengths behave as it may be expected in accordance to the strength class. On the other hand it must be taken into account that the characteristic values for deformation like modulus of elasticity, shrinkage and creep, especially if high amounts of acceleraters are used, may differ significantly in comparison to normal concrete of the same strength class.

ZUSAMMENFASSUNG

Es wurden Trocken- und Naßspritzbetone mit einer normalen und einer demgegenüber erhöhten Zugabemenge an alkalialuminat- und alkalicarbonathaltigen Erstarrungsbeschleunigern bei verschiedenen Lagerungsbedingungen untersucht. Dabei hat sich gezeigt, daß die Spritzbetone gemäß ihren Druckfestigkeiten Festigkeitsklassen in Anlehnung an DIN 1045 zugeordnet werden können. Während die ermittelten Spannungsdehnungslinien, die Spaltzugfestigkeiten und die Dauerstandsfestigkeit auf ein der Festigkeitsklasse entsprechendes Verhalten hinweisen, muß bei den die Formänderungen bestimmenden Kenngrößen (E-Modul, Schwinden, Krie-

chen), insbesondere bei hohen Beschleunigerzugaben, mit nennenswerten Abweichungen gegenüber einem vergleichbaren Normalbeton gerechnet werden.

RÉSUMÉ

On a examiné des bétons projetés secs et mouillés avec addition d'une quantité normale et d'une quantité augmentée d'accelerateurs à la base des alcali-aluminates et alcali-carbonates. Les bétons etaient exposés à des conditions différentes de stockage. Il en ressortait que les bétons projetés peuvent être rangés selon leur résistance à la compression dans les classes de résistances conforme à DIN 1045. Les courbes contrainte-déformation, les résistances à la rupture par fendage et les résistances à la fatigue déterminées indiquent un comportement en relation à la classe de béton. Par ailleurs, les characteristiques influençant la déformation comme module d'élasticité, retrait, fluage, surtout après l'addition de grandes quantités d'accélerateurs, laissent attendre des différences importantes par rapport au béton normal.

Key words

Dry-mix shotcrete, wet-mix shotcrete, accelerating admixtures, storing conditions, compressive strength, splitting tensile strength, modulus of elasticity, stress-strain curves, long-term behaviour, shrinkage, creep, pore structure,

1. INTRODUCTION

The necessity to adapt the existing road and railway network to present day requirements is the reason why in the last years tunneling as an element of route selection has become more and more important. During construction frequently less stable formations, partly with only thin covers, will be crossed so that special security measures for the face of the tunnel are necessary. In this instance shotcreting has become very successful. It is characterized by the fact that immediately after heading the face is lined with a very early setting and hardening shotcrete due to the addition of accelerators.

Normally such shotcrete liners fulfil only temporary security tasks until the instalation of a final load bearing tunnel shell. However, the tunnel construction may still become more economic if later on the shotcrete liner participates in load bearing or is able to replace the usual concrete lining completely. The condition is a precise knowledge of the technological properties of the accelerated shotcrete under short-term and long-term influences.

In the following the results of investigations gathered on shotcretes with customary liquid and powdery accelerators on the active substance basis of alcali aluminate and alcali carbonate will be reported. This study represents a continuation of an earlier investigation on the behaviour of shotcretes, which among others contained water glass as accelerator. Those tests have shown [1] that the addition of water glass causes significant deviations of the behaviour compared with that of a concrete without additives. With the meanwhile developed accelerating admixtures on the basis of alcali aluminates and alcali carbonates the above mentioned disadvantages should be reduced. It became therefore necessary to investigate within a study the mechanical-technological qualities as well as the structure of shotcretes with these additives [2].

In this study nothing is mentioned about the important question of the compatibility of certain aggregates with alcali, because the aggregates of the investigated shotcretes may be regarded as resistant even against a high alcali content of concretes. This should be done in a further investigation.

Using shotcrete with accelerating admixtures within the area of ground water, apart from structural qualities the compatibility with the environment is very important. Unfavourable influences in form of pollution of ground water by leaching of water-soluble alcalis became especially known of such shotcretes which contained high quantities of water glass as an accelerator and, for that reason, had a less tight, that means a water-permeable structure. The question of compatibility with the environment, for instance by examination of the leaching behaviour, could not be investigated either. This also ought to be done in a separate study. With the accelerators tested in this investigation a favourable result in view of leaching could be expected from the very beginning because lower quantities of accelerators were used and no significantly negative influences upon concrete structure in comparison to normal concrete were known. Moreover, several investigations carried out in the OGI have shown that shotcrete may be manufactured as an impermeable concrete according to DIN 1045. That is why, for environmental reasons, only impermeable shotcrete should be fabricated within the area of ground water.

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2. TEST PROGRAM

The study comprehends a wet-mix shotcrete (N) with a liquid accelerator on the basis of potassium carbonate and potassium aluminate as well as a dry-mix shotcrete (T) with a powdery accelerator on the basis of sodium carbonate and sodium aluminate. Beside water, further components were Portland cement PZ 45 F with a Na_2O-equivalent of about 1.0 M.-%, Rhine-material with the biggest grain size of 8 mm. It has to be pointed out that both types of shotcrete have been manufactured with the support of two companies so that the components for the two shotcretes could not be identical. However, the mixings have been as usual in practice.

Two amounts of accelerators have been examined. In the first case 50 g per kg cement respectively about 20 g of active substance per kg cement (shotcretes Td and Nd) and in the second case twice of this amount was added (shotcretes TD and ND), hereafter called "normal" and "high" respectivly. More information about the composition of the shotcretes is given in tables 1 and 2.

The concretes were shot into prepared rectangular forms. Shortly after manufacturing of the concrete blocks cores for the provided tests were drilled out in the shooting direction. After cutting and grinding of the cores faces the samples were stored for 7 days under humid conditions.

Afterwards the storing was divided into the following variants:

- wet storing (n) in containers with water at 20 °C,
- dry storing (t) at 20 °C and 65 % relative humidity,
- dry/wet alternating storing (w) of 13 days in normal climate (20 °C, 65 % r.h.) and one day in water at 20 °C.

For the different tests normally 3 specimens per shotcrete variant were planned. It is true that for shotcrete more than for normal concrete inhomogeneities due to manufacturing may influence the test results but owing to the relatively big testing program the number of the specimens per test was not increased.

3. DEVELOPMENT OF COMPRESSIVE STRENGTH

The development of compressive strength was tested at cores with a diameter of 10 cm and a height of 10 cm over a period of between 1 day and 2 years. The tests were carried out according to DIN 1048 and the result was the known fact of an increase of strength with an increasing age of concrete.

With a high content of accelerators the strength values for the dry shotcrete (see fig. 1) were lower than the strength values for normal addition; thus, the 28-days strength of the shotcrete TDt with 35 N/mm^2 attained only about 85 % of the strength of 40 N/mm^2 of Tdt concrete. The wet storage in comparison to the dry storage leads to nearly 10 % lower strength values. After 2 years an increase of strength to the 1.3- to 1.4-fold of the 28-days values could be stated. The chosen alternative storage led to the highest strength values.

For wet-mix shotcrete (see fig. 2) the influence of the quantity of accelerator addition was still more obvious. There could be measured a compressive strength of about 20 N/mm² after 1 day and 62 N/mm² after 28 days for concrete Ndt. In contrast concrete NDt reached with 33 N/mm² at the age of 28 days only about 55 % of this value. While after two years highly accelerated wet-mix shotcretes reached an increase of strength up to the 1.7-fold of the 28-days values, concretes with a normal addition showed, on the basis of the balanced curves in fig. 2, no significant increases of strength in comparison to the already high 28-days values. The influence of the type of storage was not important for these concretes.

According to experience for normal concrete and the well-known correlation between water-cement-ratio and compressive strength [3], with the chosen components and the composition of wet-mix a compressive strength of about 55 N/mm² may be expected. The stated higher compressive strength may be due to the influence of plasticiser. Otherwise a concrete composition like that of dry-mix shotcrete with usually a lower w/c-value in comparison to the wet-mix shotcrete could compensate the lacking influence of plasticiser and would lead to nearly the same strength. If one compares the measured 28-days strength values it can be stated for the dry-mix shotcretes and the highly accelerated wet-mix shotcretes that the strengthening capability of the cement is only exploited up to 60 to 70 %. Wet-mix shotcrete with normal addition of accelerator reached the expected strength known of concretes without accelerators.

In view of DIN 1045 the dry-mix shotcretes and the wet-mix shotcretes with a high amount of accelerators may be ranged into the concrete strength class B 25 and the wet-mix shotcrete with a normal addition certainly into B 35, under certain circumstances even into B 45.

4. SPLITTING TENSILE STRENGTH

The splitting tensile strength was determined using the same type of specimens as for compressive tests. The values $ß_{sz}$ as well as the factors c according to the relation between the splitting tensile strength and the compressive strength [4]

$$ß_{sz} = c \cdot ß_D^{2/3}$$

are compiled in table 3.

According to shotcrete and compressive strength the splitting tensile strength values were between 2.3 and 4.8 N/mm^2. Shotcretes with a normal content of accelerator lead to higher values than those with an increased quantity. An increase of the strength with an increasing testing age could only be stated for dry-mix shotcretes. In comparison with the well-known relation between splitting tensile strength and compressive strength for normal concrete [4] the test results of the shotcretes range within the scattering of these values (see fig. 3).

5. MODULUS OF ELASTICITY

The determination of the modulus of elasticity has been carried out according to DIN 1048 with cores of 10 cm in diameter and 25 cm in height at the age of 28 days and 2 years. All tests were carried out with an ultimate stress corresponding to about one third of the cylinder compressive strength at the age of 28 days.

As is shown in fig. 4 the modulus of elasticity at this age ranged between 20,700 and 28,500 N/mm² for the wet-mix shotcretes and between 22,500 and 25,500 N/mm² for the dry-mix shotcretes. The higher values were measured for shotcretes stored in wet environment with normal addition of accelerator and the lower ones for the highly accelerated shotcretes stored in dry environment.

At the age of two years the modulus of elasticity were by 10 to 30 % higher.

The comparison of the determined values with the theoretical ones according to DIN 1045 shows that the tested shotcretes, referring to their established strength classes, reach about 75 % of the theoretical values.

In total the well-known fact for normal concrete, that under wet conditions the modulus of elasticity is inverse proportional to the compressive strength, could be confirmed, that means the wet-mix shotcretes have a higher modulus of elasticity and a lower compressive strength than the dry-mix shotcretes.

6. STRESS-STRAIN CURVE, LONG-TERM STRENGTH

With specimens equal to those for the testing of the modulus of elasticity, at the age of 28 days and 2 ½ years, the lateral and transversal strains ε_l and ε_q were determined by strain gauges in a loading test at constant strain velocity of 0.4 mm/min. The results were used for the calculation of the volume strain ε_{vol} [5]. From the volume strain conclusions may be drawn about the long-term strength [6].

As an example fig. 5 shows the stress-strain curves and the volume strain of shotcrete Tdt (normally accelerated, dry storage) at an age of 28 days. The development of deformation in relation to loading is similar in all tests. The derived total volume decreased constantly with an increasing loading up to a turning point W. The further loading reduced the decrease of the volume, due to the beginning of microcracking, up to an inversing point U. Loads higher than U led to a strong increase of volume and an early destruction of the specimens due to the loss of internal friction of the concrete structure.

Within the stress range between the turning point W and the inversing point U one has to define the critical stress σ_u, which can be regarded as the long-term strength of the material. A higher stress than σ_U does not guarantee a durable crack stabilization.

Without stating significant influences of composition, storing and age of specimens the critical compressive stresses σ_U of the dry-mix shotcretes were about 80 to 85 % of the cylinder compressive strength $ß_c$. The belonging deformations ε_{U1} reached 70 to 80 % of the deformatins ε_{c1} at ultimate load. For the wet-mix shotcretes the corresponding values σ_U with 70 to 80 % of $ß_c$ and ε_{U1} with 60 to 75 % of ε_{c1} were somewhat lower.

In conclusion it has to be stated that the stress-strain curves of accelerated shotcretes and normal concretes without additives do not show a fundamental difference. The height of critical stresses in relation to cylinder compressive strength and the belonging deformations are in accordance with literature [7]. The long-term behaviour of both types of shotcrete with normal and high addition of accelerator may be regarded as comparable to that of normal concrete without additives.

7. SHRINKAGE

The shrinkage behaviour of shotcretes was investigated by using cylinders with a diameter of 10 cm and a height of 25 cm stored in normal climate 20/65. The measured deformations in relation to time are indicated in fig. 6. It can be seen that the two dry-mix shotcretes with different addition of accelerators behave almost equally and reached, after two years, about 1mm/m. The values of the wet-mix shotcretes and a normal addition of accelerator with about 1.2 mm/m and about 1.75 mm/m for increased addition were higher. After two years the shrinkage deformations of the shotcretes with a normal addition have come to an end while the deformations of the shotcretes with a high addition were not yet terminated.

The theoretical value of final shrinkage strain $\varepsilon_{s\infty}$ for normal reinforced concrete under the present conditions but without accelerator may be determined according to DIN 4227, part 1, to about 0.4 mm/m. Taking into account that for non-reinforced concrete specimens in laboratory tests almost twice the shrinkage deformation may be expected, the deformations of dry-mix shotcretes were about 1.2-fold and of wet-mix shotcretes 1.5-fold (Nd) respectivly 2-fold (ND) higher than for normal concrete.

8. CREEP

Parallel to the shrinkage tests, equal 28 day old specimens were exposed in a normal climate 20/65 to a creep stress of 8 N/mm^2 corresponding to about one third of concrete strength class B 25. Fig. 7 represents the resulting creep curves as specific creep values (creep deformation divided by creep stress) in relation to loading time.

From the curves with the chosen scale it may be derived that after an initial rise the specific creep starts to flatten at a loading age of about 150 days and approaches asymptotically to final values. The specific final creep values, quoted in the figure at the right side, are calculated on the basis of [8]. According to that the lower values for shotcretes with normal addition of accelerator (about 0.15 mm/mm per N/mm^2 for Ndt and about 0.20 mm/m for Tdt) and the higher values for shotcretes with high addition of accelerator (about 0.20 mm/m per N/mm^2 for NDt and 0.24 mm/m for TDt) were determined. The wet-mix shotcretes had a lower creep than the dry-mix shotcretes.

The calculated specific final creep may be compared with final creep data of normal concrete. Following DIN 4227, part 1, and on the basis of a concrete consistency KP and the other parameters used in the tests, final creep data of about 0.9 mm/m per N/mm^2 may be expected for a dry stored concrete B 25 or of 0.7 mm/m for a concrete B 45. Thus, wet-mix shotcretes and the dry-mix one with normal addition of accelerator have a 2-fold, the dry-mix shotcrete with high addition a 2.5-fold higher creep deformation than a corresponding normal concrete without additives.

9. STRUCTURE OF SHOTCRETES

To characterize the structure of shotcretes, the porosity was determined by appropriate testing procedures concerning the absolute density and the dry bulk density. Additionally, the so called "open porosity" was measured by water absorption at 15 Mpa, as was the pore volume and the pore size distribution by means of intrusion mercury porosimetry.

For all testing procedures no significant differences could be stated between the various types of shotcrete and of concretes without accelerators. Thus, for normal amount of accelerators the open porosity ranges between 17.9 Vol.-% (wet-mix shotcrete) and 19.9 Vol.-% (dry-mix shotcrete). The values rise to about 19 Vol.-% for both types of shotcrete with high amount of accelerator. The variation of storage had no decisive influence.

As expected according to the different testing methods [9] the pore volumes measured by intrusion mercury porosimetry range between 60 to 80 % of the above mentioned values. In this case the wet-mix shotcretes at wet storage deliver lower values than at dry storage. Fig 8 and 9 show the pore distribution of shotcretes calculated on the basis of this test method. It may be deduced from this that shotcretes with normal amount of accelerator are tending to a higher quantity of pores with a smaller radius and thus more dense structures than for an increased amount of accelerator.

10. SUMMARY

Investigations were carried out on dry-mix and wet-mix shotcretes with a normal and a high quantity of accelerating admixtures on the basis of alkali aluminates and alkali carbonates, "normal" meaning the upper limit of the allowed quantity according to the licence for the admixture, "high" meaning twice of the normal amount. The shotcretes were stored under wet, dry and under wet/dry alternating conditions. The following conclusion about the mechanical-technological behaviour and the structure of the shotcretes may be drawn:

- The shotcretes with high quantity of accelerators tend to lower compressive strength than those with a normal accelerator amount. The difference is about 15 % and more, depending on the type of shotcrete and its age.

- The dry-mix shotcretes and the wet-mix one with high accelerator amount correspond to a concrete strength class B 25. The strengthening capability of cement was exploited up to 70 %. The strength development of the normal accelerated wet-mix shotcrete corresponded approximately to the well known water/cement relationship. This type of shotcrete may be ranged into the strength class B 35 or even B 45.

- In comparison to normal acceleration amount a high acceleration reduces the splitting tensile strength at a rate of about 25 %. However, the test results still range within the frame of results known for normal concrete without accelerator.

- The modulus of elasticity reaches between 70 and 75 % of the theoretical values according to DIN 1045 for the determined strength classes.

- The stress-strain curves of the shotcretes do not show significant differences to those of normal concretes without accelerators. The long-term behaviour of shotcretes may therefore be estimated according to the principles for normal concrete.

- The shrinkage of the dry-mix shotcretes and the normally accelerated wet-mix one is about 20 to 50 % higher than of non-accelerated normal concrete, while wet-mix shotcrete with high amount of accelerator shows a doubled value.

- At dry storing the wet-mix shotcretes and the dry-mix shotcrete with normal addition of accelerator show 2-fold, the highly accelerated dry-mix shotcrete nearly 3-fold higher creep deformations than a comparable non-acceleratd normal concrete.

- The pore structure of the shotcretes does not show any anomalies. An increase in the amount of accelerator tends to a somewhat bigger pore volume and to a greater amount of bigger pores. Thus the structure will be less dense than that of a normal accelerated shotcrete.

Summarized the results show that on the basis of the compressive strength at the age of 28 days dry-mix and wet-mix shotcretes with the investigated accelerators may be ranged into strength classes according DIN 1045. The development of strength with an increasing age corresponds to that of normal concrete without accelerator.

Whereas the determined stress-strain curves, the volume change under compression and the splitting tensile strength indicate a behaviour in accordance with the strength class, the characteristics essential for deformations may differ extremely. Thus, it is recommended to determine in a qualification test the modulus of elasticity, creep and shrinkage, if the accelerated shotcrete should be used for permanent loadbearing and if deformations may be important for the construction. An increased addition of accelertors beyond the upper limits indicated in their licenses normally causes an unfavourable behaviour of the material.

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Table 1 Admixtures of dry-mix shotcretes

Symbol of Shotcrete	Cement[1] kg/m³	Aggregate[2] [kg/m³] 0/2 mm	2/4 mm	4/8 mm	Accelerator[3] kg/m³	g/kg Cement
Td	375	872	527	351	18,5	49
TD	379	880	511	370	37,0	98

1) PZ 45 F according to DIN 1164
2) Rhine-material, grading curve AB 8 (0/2) tos BC 8 (4/8) according to DIN 4226
3) Powdery accelerator with testing label; Active substance sodium aliminate, sodium carbonate

Table 2 Admixtures of wet-mix shotcretes

Symbol of Shotcrete	Cement[1] kg/m³	Aggregate[2] [kg/m³] 0/2 mm	4/8 mm	Water l/m³	w/z	Super Plasticiser ml/kg C	a cm	Accelerator[3] ml/kg C	g/kg C
Nd	370	847	851	205	0,55	~ 8	46	29	46
ND	370	847	851	200	0,54	~ 7	46	53	83

1) PZ 45 F according to DIN 1164
2) Rhine-material, grading curve AB 8 (0/2) resp. U/A 8 (4/8) according to DIN 4226
3) Liquid accelerator with testing label; Active substance potassium carbonate, potassium aluminate

Table 3 Splitting tensile strength, factor c for the correlation between splitting tensile strength and compressive strength 4

Symbol of Shotcrete	Testing Age 28 Days[1] $\beta_{SZ\ 28}$ N/mm²	c[2]	Testing Age 2 Years $\beta_{SZ\ 2a}$ N/mm²	c[2]
Tdt	-	-	4,1	0,30
Tdn	3,2	0,28	3,8	0,28
TDt	-	-	4,8	0,36
TDn	2,8	0,28	3,2	0,26
Ndt	-	-	3,1	0,21
Ndn	3,4	0,26	3,6	0,23
NDt	-	-	2,7	0,24
NDn	2,7	0,31	2,3	0,18

1) Moist curing according to DIN 1048
2) $\beta_{SZ} = c \cdot \beta_D^{2/3}$ [4]

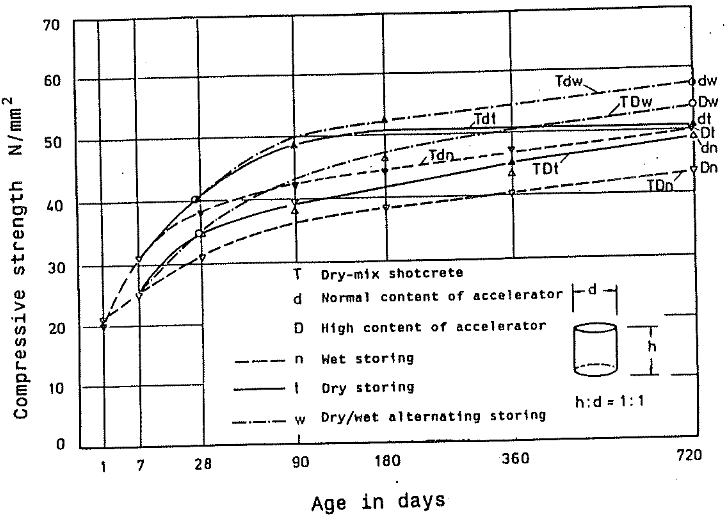

Fig. 1 Development of compressive strength of dry-mix-shotcretes

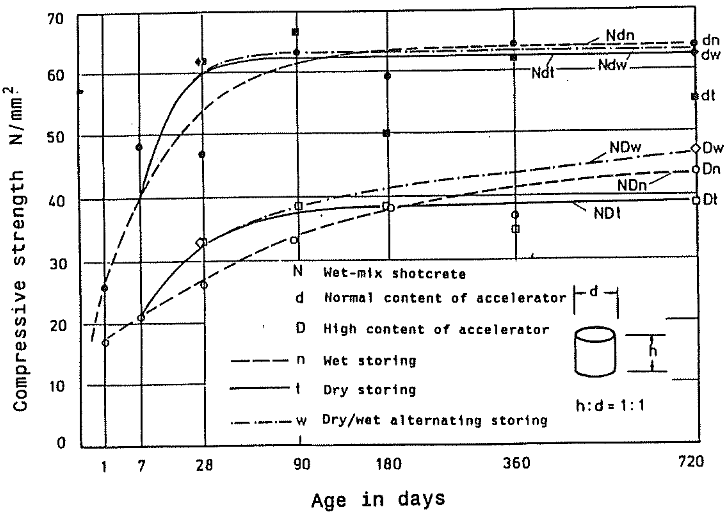

Fig. 2 Development of compressive strength of wet-mix-shotcretes

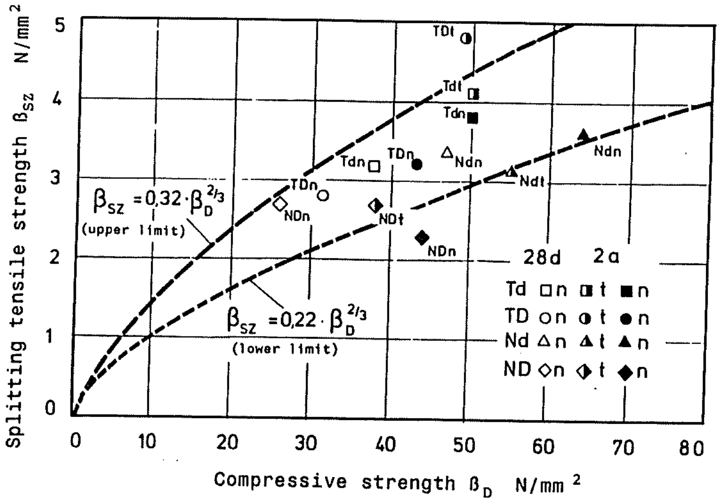

Fig. 3 Correlation between splitting tensile strength and compressive strength of the shotcretes; comparison with the mean variation for normal concrete without additives [4]

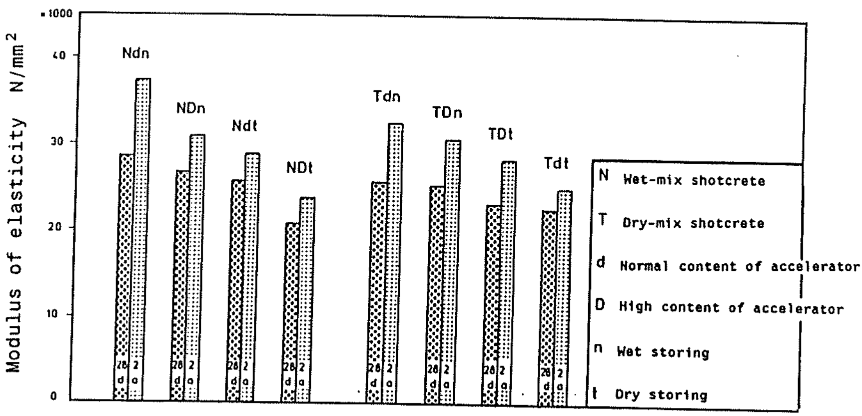

Fig. 4 Modulus of elasticity of dry-mix (T) and wet-mix shotcretes (N) at the age of 28 days and 2 years

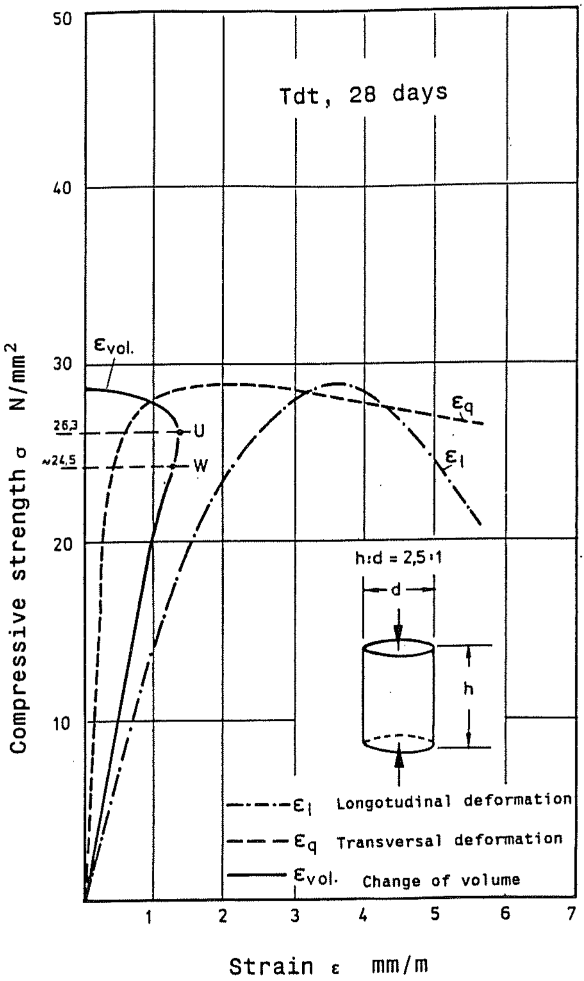

Fig 5 Stress-srain relation, change of volume, dry-mix shotcrete with normal addition of accelerating admixture (Tdt), age 28 days

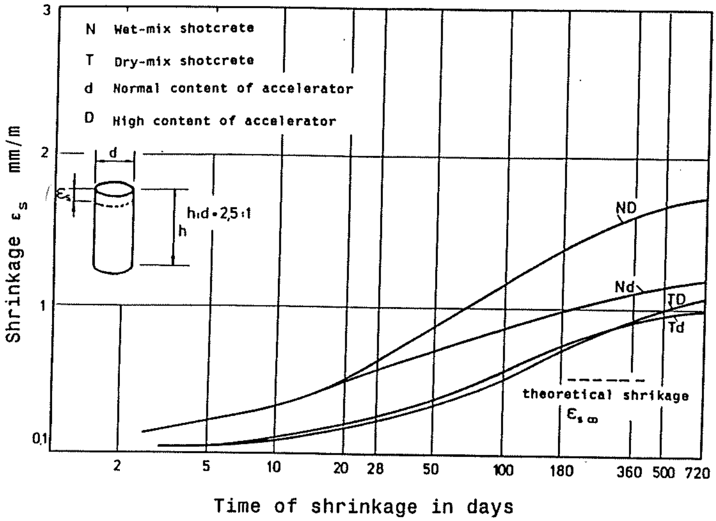

Fig 6 Shrinkage of shotcretes at normal storing conditions (20 C, 65 % r.h.)

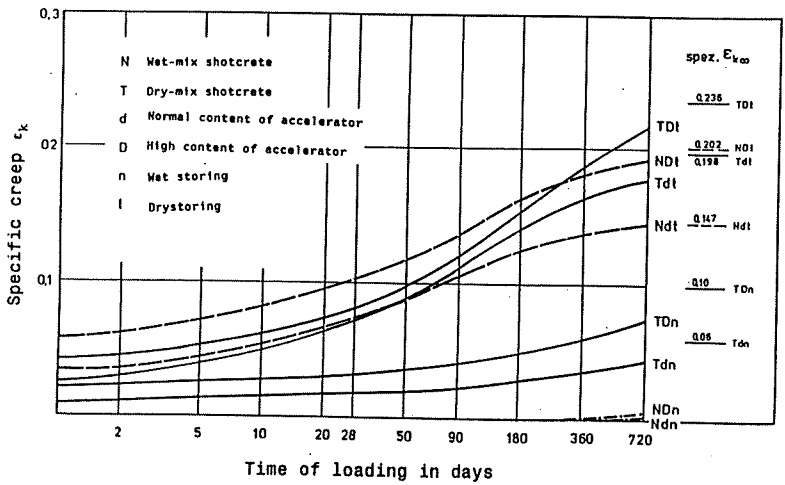

Fig. 7 Specific creep and ultimate specific creep of dry-stored shotcretes

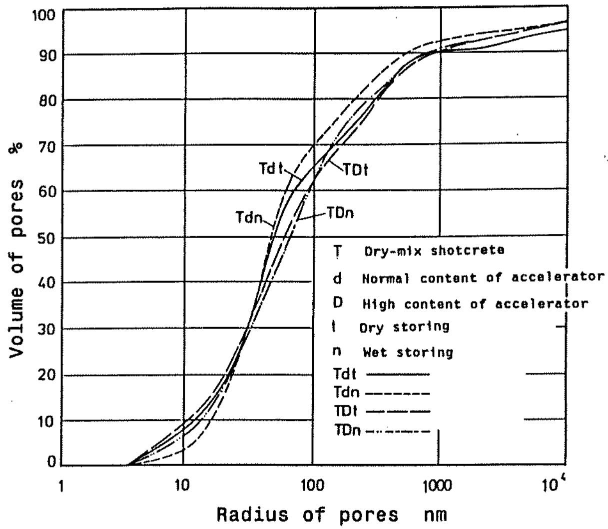

Fig. 8 Pore distribution of dry-mix shotcretes by means of intrusion mercury porosimetrie

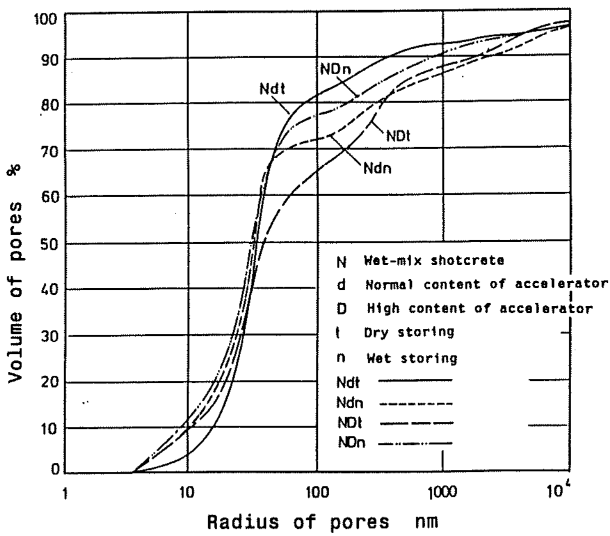

Fig. 9 Pore distribution of wet-mix shotcretes by means of intrusion mercury porosimetrie