Shotcrete for Rock Support

Guidelines and Recommendations — A Compilation



International Tunnelling Association

Towards an improved use of underground space

BeFo

Swedish Rock Engineering Research Foundation

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Shotcrete for Rock Support
Guidelines and Recommendations — A Compilation

International Tunnelling Association
Working Group: Shotcrete Use

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FOREWORD

The ITA working group on Shotcrete Use was formed at the ITA meeting in Toronto in 1989 and its first task was to implement a status report on the shotcreting technology in different countries. Two years later, the report "Shotcrete in Tunnelling. Status Report 1991" was published. The primary aim with this report was to demonstrate in brief the general status of the technology in some fifteen countries, including references to current development, existing guidelines or recommendations, actively working national groups etc. Short bibliographies and abstracts of major papers were also included.

As a result of this work, it became evident that guidelines of varying status were used in some of the participating countries. During concurrent discussions within the working group a strong interest was expressed to go a step further and make a special compilation of such guidelines and recommendations.

The Swedish national group of ITA, the Swedish Rock Engineering Research Foundation-BeFo, took on the responsibility for this work and the task was entrusted to Bo Malmberg, M.Sc., of J&W who has many years of experience in the field of shotcreting technology, in particular, as regards the composition of shotcrete mixtures including additives and fibres.

This report is not to be regarded as a scientific evaluation of what has been stated in different countries but merely as a summary of the most important parts of some selected references. It does not give any detailed background to cited recommendations and just a few personal comments. It should be noted also, that some of the references used are in a draft stage, e.g. the Norwegian guidelines and EFNARC´s specifications, whereas some are officially established regulations.

The idea is that this compilation should be of benefit as a reference material for those who are to make specifications for shotcrete support and also to inspire national committees who are preparing or updating any recommendations of their own. Furthermore, today's ongoing European integration includes normative work e g in the construction sector, involving also concrete technology. So far, no technical committee on shotcrete has been established within the CEN organization. It is, therefore, of vital importance that the tunnelling community look after and participate in any planned work in this respect.

It is the hope of the ITA working group that this report will serve as a basis for further enhancement of the shotcreting technology and the exchange of information in this field within the international tunnelling community.

Stockholm, December 1992

Tomas Franzén
Animateur, WG Shotcrete Use

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SUMMARY

This compilation includes different guidelines on materials and mix design, production and performance of shotcrete, as well as guidelines concerning quality control and test methods.

Guidelines on basic materials often refer to national standards for normal use of these materials in concrete, but there are also specific recommendations concerning the use for shotcrete, for instance, the aggregate grading, use of additives and fibres.

When calculating the composition of shotcrete it is important to consider the rebound effect, as well as the total water content, including the water content in additives and admixtures.

Guidelines on fresh concrete are few and focused on the consistency and setting time of wet mix shotcrete.

For the hardening (young) shotcrete there are recommendations on the strength in order to withstand early active rock pressure as well as the effect of blasting shortly after shotcreting.

Guidelines on hardened shotcrete focus on compressive strength, which in many guidelines, is the basic for grading shotcrete in different classes of utilisation. However, an increasing interest can be observed concerning requirements on thougness on shotcrete, naturally linked to the increasing use of fibre reinforcement. The most applied method to quantify thougness is according to ASTM C 1018, and different values are suggested for the thougness indicies I_5, I_{10} etc. Also presented are different suggestions regarding the connection between performance level and thougness.

Guidelines on batching, mixing, transport, equipment, performance etc, are not very much quantified. Thus, information concerning these areas are to be found in different recommended practice (eg ACI 506), handbooks, manufacturers recommendations etc. Though, quantitative data are presented concerning the tolerances when batching material for shotcrete as well as different requirements on the equipment used (hose dimensions, air pressure, pump capacity).

Some guidelines concerning health and safety aspects are also presented.

As regards the performance, aspects are presented on spraying procedure, layer thickness, surface treatment and precausions when spraying in warm or cold weather.

Recommendations for curing comprise conditions as well as methods for curing.

The extent of quality control at site is very much dependant on the actual shotcrete process, that is
- dry mix shotcrete: mixed on site or using prebagged materials.
- wet mix shotcrete: site mixed or using ready mixed concrete.

The compilation gives recomendations concerning extent and requirements on both preconstruction tests and routine tests, as well as applicable test methods.

Different approaches for design models where the load situation is connected to the design of the shotcrete lining are presented in an Appendix.

1.INTRODUCTION

This report is a compilation of existing guidelines and recommendations concerning shotcrete and particularly, fibre reinforced shotcrete, for rock support. The work has been done on request of the ITA Working Group on Shotcrete Use and has aimed at putting together a consensus of what is more or less officially recommended practice in different countries today.

The compilation is mainly based on documents received from different members of the above mentioned working group on request of BeFo in July-91 and complemantary documents recieved at and after the ITA Conference in Acapulco May-92.

The aim of the author has, primarily, been to put together different quantified and preferably measurable recommendations or standards for a variety of properties of shotcrete, without making any deeper analysis concerning the reasons for the reported values. Thus, obvious selfevidencies and very subjective statements have been neglected as well as different kind of information in research reports.

The list of references has been as extensive as possible, in order to give the reader the possibility to find further information in the current publication. The references have been marked in the margin of each page adjacent to the statements.

The compilation may serve as a basis for further discussions concerning reasonable recommendations and standards on shotcrete.

2. NATIONAL WORK IN PROGRESS ON SHOTCRETE

Before examining different recommendations it may be interesting to overview work on shotcrete that is going on or recently has been carried out, as well as existing guidelines, in different countries. The overview is mainly based on information provided in the status report of ITA, 1991. 21

Finland:
No permanent working group. Working groups are set up for special purposes when needed. A "Guideline for Shotcreting" exists. The guideline is meant for shotcreting in rock engineering applications. It represents the measures by which a good technical and economical result can be obtained. It also deals with working safety aspects. The guideline

can be included in contract documents, but does not replace specifications for an actual job. The guideline consists of recommendations, which are not official standards.

France:
A working group, Group nr 6- Shotcrete, has drafted the AFTE:s Recommendations on Technology and Application of Shotcrete (1974). The working group was in 1989 requested to update existing texts and to draft a recommendation on the use of fibre reinforced shotcrete.

Germany:
Existing working groups are:
- The Working group Shotcrete-DIN 18551, of the German Committee of Concrete (DAfStb)
- Committee for national railway standards-DS 853 Shotcrete of the Central Department of National Railway (BZA)
- Working group steel-fibre-reinforced shotcrete of the German Concrete Institute (DBV)

The most recently presented guideline is the handbook "Stahlfaserbeton" 1991. This reference has not been available for the present compilation.

Italy:
Societa Italiana Gallerie (SIG) has set up an Italian working group on shotcrete. The group has been divided into five subgroups:
- Characteristics of shotcrete for structural use
- Mix design (criteria): aggregate, cement, tests and research on the behaviour of green concrete
- Additives, admixtures and fibres
- Equipment and safety in the work
- Items for contract and tender specifications

Japan:
The Japan Tunneling Association has a working group on shotcrete. Existing standards and guidelines are:
- Tunneling Standard Specification by the Society of Civil Engineers (JSCE) in 1986 (in Japanese)
- Standard Specification for Design and Construction of Concrete Structures by JSCE in 1986 (in English)
- Recommendations for Design and Construction of Steel Fibre Reinforced Concrete by JSCE in 1983 (in Japanese)
- NATM Guideline for Design and Construction by Japan Railway Construction Public Corporation (JRCC) in 1983 (in Japanese)

- Construction Manual for Civil Engineering works by Japan Highway Public Corporation(JHPC) in 1989 (in Japanese)
- Guideline for Construction by JHPC in 1987 (in Japanese)
- Guidelines of SFRC by Japan Tunneling Association (JTA) in 1980 (in Japanese)

Norway:
A new working group on shotcrete was established in 1990 supported by the Norwegian Rock Blasting Association. The working group has presented a draft on the use of wet mix shotcrete for rock support, supposed to become a official recommendation in 1993.

Sweden:
No national working group exists with particular interest in shotcrete. Nor does any formally adopted guideline exist, though some major clients have established their own routines and guidelines.
In addition some recommendations exist in the Swedish "Concrete Handbook".
An applicable ongoing work is a new "Handbook on Shotcrete" for the Swedish State Power Board, supposed to be presented in 1992.

Switzerland:
The SIA-standard 198 is at present under revision.

USA:
The most active organisation is the "Shotcrete Committee" of the ACI committee 506. ASTM has established a subcommittee in order to:
- assemble and study shotcrete properties
- develop test methods
- formulate standards for shotcrete

Besides existing documents there will be a "Standard practice for Preparing and Testing specimens from Shotcrete test Panels".

Australia:
The Australian Underground Construction and Tunneling Association (AUCTA) has a subcommittee on shotcrete.

Austria:
The Austrian Concrete Society has installed a working committee which has published the Austrian Guideline on Shotcrete- Part 1- Application.
Part 2- Testing of Shotcrete- is in preparation.

Canada:
No formal shotcrete organisation exists. For general shotcrete applications, references are made to documents presented by ASTM, ACI and CSA (Canadian Standards Association)

South Africa:
The South African National Council on Tunnelling, SANCOT, have established a Working Group on Shotcrete, representing tunnel owners, the mining industry, consulting engineers, contractors and material suppliers.
National standards exist concerning both safety and general specifications. The former include particular specifications concerning protection of workmen from rebound material, insufficient lighting and dust levels. The latter specifications are mainly based on specifications of ACI, ASTM and certain Canadian sources, though existing specifications of the S.A Bureau of Standards (SABS) have been substituted where possible.

UK:
No standards exist in the UK with regard to shotcrete technology. Each contract has its own specification based on those developed on the Channel Tunnel Project.

A publication concerning shotcrete is also under preparation by EFNARC-TC-Sprayed Concrete Committee, to be published in 1992. (EFNARK: European Federation of National Association of Special Repair Contractors and Material Suppliers). 29

The Sprayed Concrete Association has presented separate general recommendations for wet process sprayed concrete and dry process sprayed concrete. 30

The following compilation of shotcrete recommendations are, thus based on information from some of the countries above. A general view of the types of documents recieved from the different countries are:

- Guidelines from Japan, Austria, Finland, Germany USA and Norway.
- Standards from Germany, South Africa and USA.
- Tender documents from Sweden and South Africa
- Articles and litterature from Canada, Belgium and Sweden.

3. MATERIALS

3.1 Cement

Cements for shotcreting should normally fulfill demands for normal standard or rapid hardening Portland cement according to national standards, for instance:
-DIN 1164
-ÖNORM B 3310 (Austria)
-ASTM C 150
-SABS 471 (South Africa)
-CEN standard EN 197 or national standard, according to EFNARC. 29

Other types of cements are also allowed to be used, for instance according to ASTM C595 (Blended Hydraulic Cements).

Some presented quantified data concerning cement for shotcrete are as follows:

- start of setting time: 1,5-4 hours. 10
  ≥ 1 " 1
- fineness of grinding: 3500-4500 cm2/g 10
  ≥ 2500 " 1
- bleeding: ≤ 20 cm3 10
- Standard compressive strength, MPa; of cement:

days	Austria*	Japan	1,10
1	≥ 7	-	
	≥ 9 **	-	
3	-	≥ 7	
7	-	≥ 15	
28	≥ 39	≥ 30	
90	≥ 50		

* 5 % fractile
** (normal shotcrete)

- C_3A content 10
  - ≤ 3 % if SO_4^{2-} content of water exposed to concrete>400mg/l
  - as low as possible (highly sulfate resistant cement) if $SO4^{2-}$ content > 1000 mg/l
- Alcali content ($Na_2O+0.65K_2O$): ≤ 0.6 % 1
- if required· Test influence of the temperature and of the chemical composition of the cement on the reaction time. 10
- cement temperature ≤ +70 °C when filled into silo on site 10

ACI recommends: 15
- low-alkali cement where the aggregates are reactive with the alkalies in cement.
- Type V cement (ASTM) where the shotcrete will be exposed to soluble sulfates.
- Type III cement where high early strength is required.

Norwegian draft for shotcrete guidelines prescribe the use of sulfate resistant cement when there is a risk for sulfate attacs but only if there is no simultaneous risk for cloride attacs. 28

Swedish tender documents prescribe the use of sulfate resistant cement only, and other documents prescribe the use of sulfate resistant cement or rapid hardening cement, alternatively, though the latter is not sulfate resistant 7,14 16

French recommendations prescribe that the validity of chosen cement shall be demonstrated in the presens of: 23
- acid water
- not highly mineralized water
- polluted water

3.2 AGGREGATES

Most recommendations concerning aggregate refer to ordinary national standards for concrete aggregates such as DIN 4226, ASTM C33, C330, C637, SABS 1083(South Africa), BS 882.

In Austria the choice of aggregate is linked to the type of shotcrete used. 10
- For types SC II (supporting shotcrete) and SC III (structural concrete) only segregated aggregates are allowed. The segregation should take place every 4 mm.
  Maximum size is recommended to 16 mm, though for structural concrete the recommendation is 11-12 mm.
- If no "class I" aggregate is used the actual aggregate must be tested according to certain specifications.

There are also specific recommendations regarding aggregates suitable for shotcreting. TAB 1.

TAB 1 . Recommended aggregate gradation according to different sources.

Sieve mm	Percent by weight passing sieve size, mm: wet mix 8	wet mix 16	dry mix 16	not specif[1] 8	not specif[1] 16
32	100[2]	100[3]	100[3]	100[5]	100[5]
			100[4]	100[6]	100[6]
16	100	85-100	80-100	100	100
			85-97	100	100
8	90-100	70-100	56-100	100	60-88
			66-81	100	71-88
4	73-100	58-99	40-100	61-85	36-74
			46-66	68-80	51-69
2	55-90	42-78	28-58	36-71	21-62
			30-50	48-63	38-52
1	37-72	30-56	18-32	21-57	12-49
			18-30	32-48	28-40
0.5	22-50	19-38	10-20	14-39	8-34
			8-20	20-30	18-30
0.25	11-26	10-25	4-11	5-21	3-18
			7-18	10-16	10-19
0.125	4-12	8-15	3-10	3-9	1-9
	4-6[7]		3-10	5-10	7-10

1) probably for dry mix shotcrete
2) acc to Norwegian draft /28/
3) " Swedish Concrete Handbook
4) " ref ACI /15/
5) " DIN 1045
6) " AFTES
7) " Japanese guidelines /1/

Other specifications are:

Coarse aggregate:

- Max aggregate size:		
Dry mix shotcrete:	16 mm	1
	normally 10 mm (possible 20 mm)	30
Wet mix shotcrete:	8 mm	1
	16 mm	30
- no single fraction > 30 % of total aggregate		28
- Specific gravity:	$\geq$ 2.5 kg/dm^3	1
- Water absorbtion:	$\leq$ 3.0 %	1
- Loss by washing:	$\leq$ 1.0 %	1
- Clay:	$\leq$ 0.25 %	1

Sand:

- fineness modulus:	2.8-3.2	1
- surface water:	4-6 %	1
	recommended 2-4 %	23
	max 7 %	
- specific gravity:	$\geq$ 2.5 Kg/dm^3	1
- water absorbtion:	$\leq$ 3.0 %	1
- loss by washing:	$\leq$ 5.0 %	1

The chloride content is, according to EFNARC, regulated by CEN standard ENV 206 and the alcali content by national standards. 29

3.3 Additives

3.3.1 Fly Ash

General:

Pulverized Fly Ash (PFA) may be added to reduce the cement content and improve the workability of the mix, according to South African specifications. 17

Recommendations:

Maximum allowable addition:

- for Portland cement:	$\leq$ 15 %	10
	$\leq$ 30 %	21,29
- for PFA cement:	$\leq$ 15 %	29
- for Blast-Furnace Slag cement:	$\leq$ 20 %	10,29

Specific surface:	$\geq$ 450 m^2/kg	10
	acc to BS 3892	3
Carbon content:	$\leq$ 5 %	3
SO_3 content:	$\leq$2.5 % (Total SO_3 content in cement + PFA: $\leq$ 4 %)	3

3.3.2 Silica Fume

General:

Condensed Silica Fume may be added to provide the mix with good adhesion/cohesion characteristics for overhead application thus, providing possibilities to build up full thickness in one layer and to significantly reduce rebound according to South African tender document. Possible to use together with fly ash according to ITA Status Report. 17 21

Recommendations:

Recommended addition: (wet mix shotcrete)		
- 3-5 % drift support on front		28
- 4-8 % combination with PFA cement and for permanent support		28
- 6-10 % combination with Portland or SR cement for permanent support		28
- 8-13 %		9
Alowable limits of addition (wet mix):		
- 3% ≤ addition ≤ 15 %		28
Surface area:		
- ≥ 1800 m^2/kg (densified)		3
- ≥ 1200 " (BET)		29
Particle size:	average 0.2 micron	3
SiO_2 content:	≥ 85-90 %	3,18.29
Carbon content:	≤ 5 %	3,18
Tot alkali:	≤ 1 %	3
Soluble SO_3:	≤ 1 %	10
Loss on ignition:	≤ 4 %	29
Cloride content:	≤ 0.1 %	29
Free CaO:	≤ 1.0 %	29
Hydraulic effectiveness:	100% (ÖNORM B 3320)	10
Activity index:	≥ 95 % (28 d)	29

3.3.3 Blast Funace Slag

South African specifications, refered to in ITA's status report on shotcrete, do not recommend the use of Blast Furnace Slag Cement, due to slow early strength gain. 21

Japanese guidelines, though, recommend the use of 30-60 % addition of Blast Furnace slag in the cement and EFNARC recommend at least 30 %. 1 29

3.4 Admixtures

Requirements for admixtures for shotcrete mainly concern the use of accelerating admixtures. The use should be approved by the Engineer but the method of introduction and concentration should be left to the Specialist Contractor's discretion. 30

Specifications concerning other admixtures often refer to specifications or standards for normal concrete additives, for instance DIN 1045 or, as in Finland, certified by national concrete associations. The use should, according to The Sprayed Concrete Association, be approved by the Engineer. 2 11 30

The admixtures used (normally water glass) must be adapted to the cement with regard to the effect on: 10,29
- setting time
- early strength
- decrease in strength at advanced ages

The use of accelerators shall also guarantee 1
- good adhesion
- no corrossion effect to steel
- effective operation even at water inflow
- harmlessness to human body

A typical dosage shall be specified with detrimental effects of overdosing, especially regarding long term durability. 30

The use of high amounts of accelerators may, according to Norwegian draft, be compensated by high strength in concrete mix design. 28

Recommendations for accelerators:

Recommended ammount:

- powdery type:	6-8 %	10
	average 6 %	29
- liquid type:	4-6 %	10
	6-8 %	29
- water glass:	10-15 %	10
- not specified:	2-5 %	9
- dry mix:	4-7 %	1
- wet mix:	5-10 %	1

Allowable ammount:

- powdery type:	$\leq$ 10 %	10
- liquid " :	$\leq$ 8 %	10
- not specified:	$\leq$ 3 % (documented experience $\geq$ 5 years)	3

Alowable decrase of strength: 10
$\leq$ 45 %, powdery accelerators
$\leq$ 30 %, liquid "

Approval test:
- Proctor test 10 min : $\geq$ 130 N 29

Water soluble aluminate:
- $\leq$ 0.6 % if shotcrete exposed to water with SO_4^{2-} content > 600 mg/l. 10

Calcium cloride or admixtures containing clorides must not be used or the chloride content must be limited in reinforced structures, for instance, according to Austrian guidelines 17 10

When cement containing fly ash is used, special consideration must be given before use of accelerators. 3

Other admixtures are used for shotcrete and the normal dosage rates are, according to Morgan: 9

- water reducing agents: 0.5 % by weight of cement
- superplacticizers: 1-1,5 % "

When using air entraining agents, the air pore volume should be expected to be:
- 10-12 % by the pump
- 4-6 % after shotcreting

Air entraining agents shall not be used without approval of the contractor while high air content might reduce the pumpability. 28

When several admixtures is contemplated, a compatibility study shall be carried out before the suitability trial. 23

3.5 Fibres

General:

The use of steel fibres as reinforcement in shotcrete(SFRS) is well established in many countries, for instance USA, Canada, South Africa, Germany, Sweden, and Norway.
Other countries regard the fibre reinforcement technique as special methods (Austria) or technique used only after sufficient structural tests (Finland).

Regarding different kinds of fibre reinforcement, ASTM 820 classifies fibre reinforcement in three types

- Type I : Steel-fibre-reinforced concrete or shotcrete
- Type II : Glass-fibre-reinforced concrete or shotcrete
- Type III: Concrete or shotcrete reinforced with synthetic fibres.

Recommendations:

The type of fibre used often refers to ASTM 820, for instance for Type I fibers:

Equivalent diameter:
- 0.5 mm (Type I, ASTM 820)

Fiber length:
- $\leq$ 30 mm for dry mix 10
- $\leq$ 20 mm " wet mix 10
- $\leq$ 0.7x internal diameter of pipes and hoses used 29

Aspect ratio l/d:
- 40-60 (Type I,ASTM 820)
- 65-100 17

Ultimate elongation:
- 12-22 % 17

Fiber amount:
- Normally 50-80 kg/m^3
- $\leq$ 5-6 % (weigth) or 120-140 kg/m^3,adapted to pumpability 29
- Related to fiber length (l): 28
  - $\geq$ 65 kg/m^3 for $l \leq 20$mm
  - $\geq$ 50 kg/m^3 " $21 \leq l \leq 39$ mm
  - $\geq$ 40 kg/m^3 " $l \geq 40$ mm

Other, not quantified, recommendations are:
- fibres must be dry, free from corrosion, oil, grease or other contaminants or surface coating. 17
- fibers shall be high strength, deformed, drawn or slit sheet steel fibres 9
- a certain product shall be used (eg Fibrex HC 25 or DRAMIX ZC 30/.50).

Due to rebound, the effective amount of fibres, is reduced to about only 50-70 % of the amount in the mix in dry mix shotcrete.
For wet mix shotcrete the amount of fiber rebound is approximately 5-10 %. 29

Galvanized fibers, sometimes used in agressive environment, give very good bond to the concrete but there is a risk for gas generation in reaction with de-chromatized cement. (The use of de-chromatized cement is prescribed in countries as Sweden and Norway). 28

Other types of fibres such as glass, polymer and carbon fibres may be used if the requirements according to applied guidelines are fulfilled. 10

Synthetic fibers contribute to the stability of shotcrete material having exessively low mechanical properties by modifying for rheological behaviour of the fresh concrete and of the concrete during hardening (improved cohesion and shearing resistance) Contribution to improve the hardened properties are negligable.
Normal dosage is 1-2 kg/m^3.

4. MIX DESIGN AND PERFORMANCE

4.1 Composition

The contractor should, according to The Sprayed Concrete Association, be free to design the mix to achieve the specified characteristic strength.

Shotcrete without special requirements up to a certain strength levels (SC 16) can, according to the Austrian guidelines, be produced without any trial mix tests using mix proportions for dry or wet mix.

The composition of the shotcrete mix is normally determined by long time experience or by trial mix tests. One example of recommended trial mix proportions is presented in TABLE 2.

TABLE 2 Trial mix batch proportions for 1 m3 dry mix shotcrete, kg/m^3.

Shotcrete Class	A	B
Description	Plain	Steel Fibre
Normal Portland Cement	380	380
Silica Fume	50	50
Coarse Aggregate (SSD) 10 X 2.5 mm	500	500
Concrete Sand (SSD)	1230	1230
Steel Fibre	N/A	65
Water (Estimate)	140	140

Recommendations concerning composition normally refer to "designed" composition. It should be noticed that the real composition, that is, in the lining deviates from the designed, due to rebound. This is specially important for dry mix shotcrete. 2

The result is, according to AFTES, an average increase of the order of 10 to 20 % in cement proportioning for spraying of the order of 70 mm in thickness and a transfer towards fine aggregates of 10 to 20 % (relative value of the undersize) on the grading curve of the concrete in place. The thinner the applied layer the greater will this increase in proportioning be, for ceiling application. 23

Japanese guidelinees states that the rebound, when tested, should be less than 25 %. 1

Rebound may be reduced by: 6

- for wet mix shotcrete:
  - higher cement content
  - more fines
  - smaller maximum size of aggregate
  - proper moisture content of aggregate
  - finer gradation
  - inclusion of fly ash or silica
- for dry mix shotcrete:
  - more fines
  - process controlled predampening
  - reduced air pressure

The cement content should be higher than for normal concrete in order to improve pumpability and shotcrete production. 28
The ready mix concrete supplier must not reduce the cement content due to high strength margins without agreement with the shotcrete contractor.

Other quantified recommendations:

- Cement content:
  - fine shotcrete 0-4 mm : 450-600 kg/m^3 6
  - shotcrete 0-8 mm : 350-450 kg/m^3 6
  - coarse shotcrete 0-15 mm : 300-350 kg/m^3 6

- Water/cement ratio
  - for dry mix shotcrete: 0.3-0.4 — 9
    0.45-0.55 — 1
    ≤ 0.5* — 2
  - for wet mix shotcrete: 0.4-0.5 — 9
    0.50-0.65 — 1
  - for fibre reinforced shotcrete:
    ≤ 0.5 — 10

    * not meassurable. If there are demands on maximum w/c, it may be assumed that w/c ≤ 0.5

- Sand/aggregate ratio:
  0.55-0.60 — 1

- Aggregate/cement ratio:
  3.5:1-4.0:1 — 30

According to Norwegian draft, the shotcrete shall be classified according to the aggressivity of the current environment which regulates the maximum mass ratio* and the minimum cement content. TABLE 3.

TABLE 3. Environmental classes and corresponding specifications of concrete composition according to Norwegian draft./28/

Environment class	Environment	Max mass ratio	Min binder-content,kg
NA	Some aggressivness	0.60	360
NMA	Some more aggressivness	0.50	420
MA	Very aggressive	0.45	470
MMA	Very much aggressive	0.40	530

* Mass ratio: $m = \frac{v}{c + Kxp}$

where: v = water content.
c = cement content
p = silica fume content
K = coefficient of efficiency
= 2.0 for silica fume content < 8 % of portland clinker content
= 1.0 for silica fume content 8-15 %.

A similar classification is proposed by EFNARC, TABLE 4, where requirements on air content also is concidered, in order to guarantee the freeze-thaw durability on shotcrete, primarely used for repair work. 29

TABLE 4. Environmental classes according to EFNARC /29/.

Class Environment	Max. W/(C+)	Min. cem. kg/m^3)	Air Cont. fresh con. (%)
2a Humid, no frost	0.60	360	
3 Humid, frost, de-icing salt	0.50	380	6
5c Highly aggressive chemicals	0.45	400	
EA Extremely aggressive,			
no frost	0.40	350	
frost	0.40	450	6

When calculating water content for wet mix shotcrete, concideration shall be taken to the water content in admixtures and additives. If no special agreement exists between contractor and concrete supplier, it should be assumed that 25-30 l/m^3 accelerator will be used, which means the concrete recipe must have a margin for addition of 25 l water at the site. 28

4.2 Performance - Fresh shotcrete

Properties of fresh concrete considered are:
- consistency or workability
- air pore volume
- setting time or workability time

Recommendations:

Consistency:(wet mix)
- class KP-KF, according to DIN 18551,for dense-flow conveying 2
- class KS-KP for thin-flow conveying 2
- slump 60-100 mm 1,9
  100-150 mm 23

Air pore volume:
The use of air entraining agents for shotcrete is not very common, thus, recommendations concerning air pore volume are very few and concentrated on wet-mix shotcrete where freeze/thaw durability is important.
Some recommendations are: 9
- 10-12 % air pore volume at the discharge pump
- 4-6 % air pore volume as shot

Settingtime:
The setting time is often referred to tests according to ASTM C 403.
Recommended time ranges for plain or steel fibre reinforced shotcrete with an accelerator: 3,6,9
- Initial Set, min: 3-10 27
- Final Set, min: 9-30

4.3 Performance - Young shotcrete

General:

Young concrete means the state of hardening of concrete to a strength level of, approximately 10 MPa.

Requirements on young concrete are prescribed when there is a need for security against
- influence from blasting near the shotcreting site
- influence of early freezing

Recommendations:

- The concrete shall, according to Finnish guidelines, have a strength level of approximately 60 % of the final strength in order to withstand blasting near the shotcreting site.(design strength normally 30 MPa).Permissible peak particle velocities for shotcrete structures of different ages are: 11

shotcrete age days	max peak particle velocity mm/s
0-3	10
3-7	35
>7	110

  In temporary shotcreting when using accelerators, blasting can be carried out 12 hours after shotcreting.

- Austrian guidelines classify young shotcrete in three strength development ranges, J1,J2,J3, with strength development characteristics according to FIG 1 10

- Other recommendations:
  - required strength ≥ 5 MPa at 8 hours 3,6
  - " ≥ 5 MPa before influence of frost 7,29
  - the concrete temperature must be kept > +5°C until it reaches the freezing strength, normally 3-4 days. 11

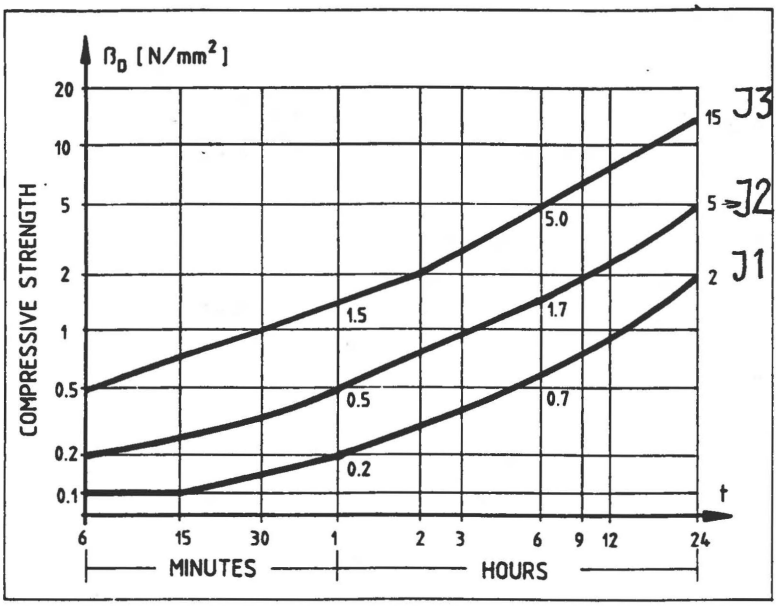


FIG 1 Young shotcrete-strength requirements according to /10/

J1- is applicable when shotcrete has to be placed as quickly as possible in thick layers, inflow of water is observed, stresses occur as result of operations following immediately after concrete placement.
J2- is applicable when early active rock pressure is present
J3- only for exceptional cases (high early strength generally leads to reduced later age strength increases)

4.4 Perfomance - hardened shotcrete

4.4.1 Compressive strength

The requirements for compressive strength are often related to different strength classes or grades.

The Sprayed Concrete Association recommend specification of shotcrete in three grades:

Grade	Characteristic strength at 28 days
30	30 MPa
40	40 MPa
50	50 MPa

More detailed grades are presented in the Austrian guidelines, TABLE 5, and the Finnish guidelines refer the strength class to different applications, TABLE 6.

TABLE 5 . Strength grades of shotcrete according to Austrian guidelines/10/. The strength grades may refer to an age of 28,56 or 91 days.

Grade	Average value of compressive strength N/mm², at least	Notes
SC 12	12	
SC 16	16	
SC 19	19	with requirements J_1 or J_2, **generally** obtainable strength at 28 days
SC 22.5	23	with requirements J_1 or J_2, **maximum** obtainable strength at 28 days
SC 25	25	
SC 28	28	with requirements J_1 or J_2, **maximum** obtainable strength at 90 days
SC 30	30	without special requirements for the "young" shotcrete (e.g. reinforced concrete repair work)
SC 40	40	

TABLE 6 .Shotcrete classes according to Finnish guidelines/11/

Class	Min. compr. strength	Application
I	K30	Sites with strict structural requirements, bridges etc.
II	K30	Rock reinforcement, normal concrete structures etc.
III	K20	Fill shotcreting, no structural significance
IV	K20	Temporary support during the excavation to ensure the safe continuation of the excavation process.

Examples of requirements for compressive strength in other documents are:

Age	Compressive strength MPa	
8 h	5	27
1 d	5	1
	8*	23
	10	9,3,27,29
3 d	20	27
7 d	17*	23
	25	29
	30	9,27
28 d	18	1
	25**	23
	30	17,29
	35	16
	35***	26
	40*	26
	40	9,3,14,18,27
	45	7
90 d	35	29

* : Aritmetic mean
** : Characteristic strength
***: Single value

The compressive strength shall, according to EFNARC, be classified in classes according to TABLE 7.

TABLE 7. Strength classes for Sprayed Concrete tested on sawn or drilled samples from sprayed panels.

Strength class	C20/25	C25/30	C30/37	C35/45	C40/50	C45/55	C50/60
Characteristic strength/MPa							
Cylinder	20	25	30	35	40	45	50
Cube	25	30	37	45	50	55	60

The Norwegian draft does not either specify any particular compressive strength but states that the evaluation of compressive strength shall be based on cores from the lining and specify the minimum strength of the cores for different strength classes. TABLE 8. 28

TABLE 8. Minimum strength of concrete cores in different concrete strength classes, according to Norwegian draft. /28/

Strength class	C30	C35	C40	C45	C50	C55
Min characteristic cube stength, cast concrete MPa	30	35	40	45	50	55
Min strength cores, h/d=2.0 MPa	19.2	22.4	25.6	28.8	32.0	35.2

If no other agreement exists, the relation between the compressive strength of the concrete tested before spraying and the strength of the shotcrete in the lining should fullfill strength classes according to TABLE 9.

TABLE 9. Relations between strength classes for sprayed concrete and concrete before spraying, according to Norwegian draft/28/.

Strength class sprayed concrete	C30	C35	C40	C45	C50	C55
Min strength class before spraying	C38	C43	C48	C54	C60	C65

Special recommendations for fiber reinforced concrete:
- Strength grade ≥ SC 22,5. 10
- Strength class ≥ C 25,(preferably ≥ C35) to ensure sufficient bond between fibers and the matrix 29

4.4.2 First crack and/or ultimate flexural strength

Examples of requirements for first crack strength and/or ultimate flexural strength are as follows. All tests refer to ASTM C 1018 and are only applicable for fibre reinforced shotcrete.

Age days	First crack strength and/or ultimate flexural strength, MPa	
7	4	3,9,27
28	6	3,9,27

Norwegian draft specifies the flexural strength related to the actual compressive strength class, according to TABLE 10. 28

TABLE 10. Minimum flexural strength in different compressive strength classes, according to Norwegian /28/ and EFNARC /29/ draft.

	Min flexural strength, MPa, in class						
Strength class	C25	C30	C35	C40	C45	C50	C55
Norwegian		3.8	4.2	4.4	4.6	4.8	5.0
EFNARC	3.5		4.5		5.2		

4.4.3 Toughness

The use of toughness values to characterize the strength and deformation capacity of the fiber reinforced shotcrete has become of increasing interest in many countries. Requirements expressed in these terms can be found in documents from Sweden, USA, Canada, South Africa, and Norway.

All requirements presented concerning toughness refer to tests according to ASTM C 1018-89 or modifications there of. However, other test methods have been proposed, for instance, the test according to Japanese standard(JCI). These two methods are presented in section 13.4.2.

Examples of values presented for the toughness quantities are as follows:

Quantity	Age,days	Value	
I_5	7	3.5	3,18,27
	- 2)	3.5	9
	28	5.0	17
I_{10}	7	5.0	3,18,27
	- 2)	5.0	9
	- 2)	7.0 (for C25)	29
	28	7.0	31
	28	8.0	17
I20	- 2)	10.0 (for C25,35,45)	29
I_{30}	- 2)	14.0	9
	28	19.0	17
	28	21.0	31
$\frac{R_{5,10}}{100} xf_s$	- 2)	4.0Mpa 1)	7
$\frac{R_{10,30}}{100} xf_s$	- 2)	2.5MPa 1)	7

Note:1)Requirements for routine tests.
Corresponding requirements for preconstruction tests: 5 MPa and 3 MPa.
2)Not specified

In addition to the requirements presented in the table above (reference 29), EFNARC does also present requirements on thoughness indicies for various concrete grades, according to TABLE 11.

TABLE 11. Requirements, tensile strength and thoughness in bending according to EFNARC /29/.

Concrete Grade according to Section 10.1	Average flexural strength (MPa)	Toughness indices ASTM C1018 (Fibrous concrete) I_{30}	I_{20}	I_{10}	I_5	Max design strength (MPa)
C25	3.5	10	8	5	3.5	0.8
C25	3.5	20	15	7	4	1.7
C25	3.5	30	20	10	5	2.1
C35	4.2	10	8	5	3,5	1.0
C35	4.2	20	15	7	4	2.1
C35	4.2	30	20	10	5	2.5
C45	4.6	10	8	5	3,5	1.1
C45	4.6	20	15	7	4	2.3
C45	4.6	30	20	10	5	2.7
C55	5.0	10	8	5	3,5	1.2
C55	5.0	~~30~~	15	7	4	2.5
C55	5.0	30	20	10	5	2.9

The requirements for toughness may, according to ASTM C1116-89 be linked to various performance levels, TABLE 12 5

TABLE 12. Toughness values for various performance levels according to /5/.

Performance Level	Toughness Index, I_5		Toughness Index, I_{10}	
	Specified Value	Test Result	Specified Value	Test Result
I	2.7	3.0	5.4	6.0
II	3.6	4.0	7.2	8.0
III	4.5	5.0	9.0	10.0
IV	5.4	6.0	10.8	12.0

Normally categories I-III will be applied. Requirements in category IV will only be fulfilled by the use of high amounts of fibres having deformed surfaces or end anchorages.

Other suggestions are presented by Vandewalle, based on results from several large research and development contracts, as well as routine field quality control tests, TABLE 13. 6

TABLE 13. Suggested descriptions for steel fibre reinforced shotcrete according to /6/.

Category	Rating	I_{10}	I_{30}	$R_{30/10}$
I	Marginal	< 4	<12	< 40
II	Fair	4	12	40
III	Good	6	18	60
IV	Excellent	8	24	80

According to the Norwegian draft, the test of fiber reinforced shotcrete shall be carried out according to ASTM C 1018 but the evaluation is somewhat different. TABLE 14.

TABLE 14. Requirements on fiber reinforced shotcrete in different thoughness classes, according to the Norwegian draft/28/.

Thoughness class	Flexural strength,MPa, at deflection 1 mm	3 mm
0	Fiber type and amount specified	
1	2.0	1.5
2	3.5	3.0

4.5 Other properties

Denseness:
The denseness of the shotcrete is expressed in terms of requirements for porosity, density or watertightness.

Examples:

- Boiled absorbtion, (ASTM C642) 7 days: 3,5
  Without accelerator : 8 %
  With " : 9 %

- Volume of permeable voids, (ASTM C 642) 7 days: 3,5
  Without accelerator: 17 %
  With " : 19 %

- Density:
  According to Swedish standard: ≥2200 kg/m3 7,14

- Watertigthness:
  - Fullfilled according to Swedish standard. 7,14,16
  - Fullfilled for strength class ≥ SC 22,5 according to ÖNORM. 10
  - ≤ 50 mm and mean average ≤ 20 mm according to ISO 7031 29
  - Permeability ≤ 10^{-12} m/s, according to CEN 29

Other properties:
- Splitting tensile strength: 23

  7 d: 2 MPa
  28 d: 2.7 MPa

  Should not be used in design nor as reference parameter due to the sensitivity to specimen size and durability. 29

- Uniaxial tensile strength.
  - Related to the concrete grade according to TABLE 15. 29

TABLE 15. Requirements, Uniaxial tensile strength, according to EFNARC /29/.

Concrete Grade according to Section 9.1	Min. uniaxial tensile strength (MPa)
C25	1.5
C35	1.6
C45	2.1
C55	2.3

- Frost resistance:
  - Fullfilld for strength class ≥ SC 22,5 according to ÖNORM. 10

- Freeze-thaw resistance: 5

  Two alternatives according to ASTM C 1116:
  - A proven record of satisfactory freeze-thaw durability for concrete with or without fibres, the same air content, aggregates,and mixture proportions placed for, at least, two winters.
  - An average durability factor ≥ 80% for a set of three specimens tested according to ASTM C666.

- Bond:
  The bond should be higher than the tensile strength of the weakest material. 23

  Recommendations for bond strength and verification:
  - Shotcrete / rock:
    - ≥ 0.5 MPa 7,14,16
    - ≥ 0.5 MPa (structural) 29
      ≥ 0.1 MPa (non structural)
    - Possible up to 1.4 MPa to hard dry granite. 6
  - Concrete/ concrete:
    - ≥ 0.5 MPa (28 d, structural) 29
      ≥ 0.1 MPa (non structural)
    - ≥ 1.0 MPa 7,14,16
    - ≥ 2.0 MPa (28 d) 23

  If used in structural design, the bond shall, according to EFNARC, be specified as 29
  - average strength
  - characteristic or min value

- According to German guideline: 26
  - Average of 6 cores: ≥ 1.5 MPa
    If not: Additional 6 cores.
    If average < 1.5 MPa: Further investigation of the reason.
  - If single value < 1.0 MPa.
    Additional 3 cores within 1 m from the former.
    If the least value < 1.0 MPa.
    The area marked and concrete removed.

  Norwegian draft stress that the bond shall be secured by: 28
  - cleaning of surfaces
  - suitable concrete composition
  - effective curing

  and controlled by knocking.

5. BATCHING, MIXING AND TRANSPORT

5.1 Dry mix shotcrete

Addition of cement:
- Batched by mass or added by bag.
  Tolerance: ± 2 % 17
- Cement temperature: ≤ +50 °C. 10,29

Aggregate:
- Coarse and fine aggregates preferably batched by mass.
  Tolerance: ±3 % 17
- Alternatively by volume if volume batching conforms to ASTM C685 and the volumetric proportioning is checked at the start of every shift. 18

- Moisture content, fine aggregate: 2-6 %
  coarse aggregate: ≤ 4%.
  If drier aggregate is used, a pre-wetting system should be used, in order to get the preferred moisture content.

- Coarse and fine aggregates should be stockpiled and batched separately

- Temperature of aggregates: ≥ +5 °C. 10,29

Fibres:
- Batched by mass.
  Tolerance: ±3 % 17
- Alternatively added by whole bags, boxes etc, provided these packages are marked with the mass. 5

Additives:(fly ash, silica fume etc)
- Added by mass or preblended with the cement.
  Tolerance: ±5 % 17

Addmixtures:(setting accelerators, plasticizers etc)
- Mixed with the water.
  Tolerance: ± 5%. 17

Mixing equipment:
- Batch-mixer or a continuous mixer. The actual type must,for instance, comply to the requirements in ASTM C94 and C685 respectively. 5
- Correspondingly, there are requirements in DIN 1045, though for stiff concrete, as fiber reinforced concrete, the mixing time should be prolonged 0.5 min. 2

Water pressure:
- In order to get a complete wetting of the moist mix at the nozzle, the water pressure must be high enough. A pressure more than 1 kg/cm2 higher than the working pressure in the conveying line is recommended, that is, the desired pressure is ≥ 6 kp/cm^2. 3

- The best wetting is reached if the water ring is placed 1-3 m from the nozzle (semi-wet process).

Pot life:
- Mixed shotcrete (cement+moist aggregate) should be applied within 45-90 min at 20°C. At +10°C this time may be prolonged to 2-3hours. 11,17,18 29
- Dry bagged shotcrete , without accelerator, should be applied within 30 min of addition of mixing water in the predampener. 18
- The temperature before placing should not exceed +30 °C. 29
- In case of intermediate storage or long transport, the effect of partial hydration should be concidered. 29

5.2 Wet mix shotcrete

Requirements for wet-mix shotcrete normally refer to different national standards and recommendations for normal ready mix concrete, for instance, ÖNORM B 4200 (Austria) and ASTM C94.

The Norwegian draft prescribes that wet mix shotcrete shall be manufactured by a ready mix concrete supplier approved in high class (class A). For strength class $\geq$ 40 MPa and for shotcrete in very agressive environment, the ready mix concrete supplier shall be approved in an even higher class (class A1). 28
The use of automixer is only allowed for lower concrete qualities.

Addition of cement and aggregate:
If site-batced concrete is to be used then the required proportions of cement to aggregate should be determined by weigh-batching. For small scale project, volume-batching may be permitted. 30

Fiber addition:
Alternatively: 28
- added with the aggregate before addition of water and additives. To be concidered is the high resistance until the addition of water and admixtures have given effect. The mix capacity is reduced due to longer total mixing time.
- added to the ready mix concrete mass. To be concidered is that the fibers must be spread carefully into the mix. The consistency must be modified after addition of the fibers.

Transport:
Long time trombling under transport at low w/c-ratio increases the water evaporation which will decrease the slump. Besides, the friction in the concrete mass increases the heat evaluation which also will influence the slump reduction. 28

6. PREPARATION FOR SHOTCRETING

General:
Recommendations regarding precautions before shotcreting involve activities to control leaking water by drain systems and cleaning of rock surfaces by compressed air and water, as well as dampening too dry surfaces.

In general, whatever the nature of the substrate, it is according to AFTES, recommended that the surface is wetted just before spraying so that it does not absorb the water of the freshly sprayed concrete. This precaution is absolutely essential if the surface to be treated is dry. This also allows the elimination of dust recently settled on the surface 23

Direct spraying on work surface:

For direct spraying on the work surface, AFTES recommend that the wall be treated as soon as possible after excavation. The preparation of the excavation is limited to removal of unstable elements. If some time has passed since the baring of the wall, surface stripping may be necessary. 23

In very bad formations (lack of cohesion, intense fracturing), it may be necessary to consider a special mix design for the shotcrete to be used in the primary layer, called the "safety layer".

Spraying over a layer of early-age shotcrete:

If spraying takes place before hardening of the preceding layer of shotcrete, no surface preparation is necessary,according to AFTES, provided the latter has not been soiled. 23

Spraying over an existing structure:

On a concrete substrate where it is important in the supporting or strengthening process to obtain good bond of the shotcrete on to its substrate, spraying will be preceded if necessary by surface demolition or picking in order to dislodge the large unstable elements. Subsequeently, the preparation of the wall for cleaning and stripping consists generally in a mechanical action obtained by high pressure water or blasting.

Drainage of water:

It is, according to AFTES, essential to make arrangements to avoid any water underpressure on the newly treated surface. 23

7. REINFORCEMENTS

This section concerns the application of normal bar reinforcement of shotcrete.

Recommendations:

Minimum shotcrete thickness:	50 mm	23
" thickness of reinforcement bars:	3 mm	23
Maximum " " " :	25 mm	30
Minimum distance between bars(one layer):	100 mm	23
	4ϕ or 50 mm	30
" " " reinforcement layers:	50 mm	2,23
" concrete cover:	20 mm	23
	similar to normal concrete	30
" cover between excistant structure and reinforcement in the shotcrete:	3ϕ or 40 mm	30

EFNARC relate the requirements on the cover to the environmental class, according to TABLE 16. 29

TABLE 16. Cover to reinforcement, according to EFNARC /29/

Environmental class	Minimum cover (tolerance -0, + 15mm) (mm)
2a	30
3	40
5c	50
EA	60

Where two layers of reinforcement are incorporated, the bars on the front face should be in line with those on the rear face. In constricted areas it may be preferable to spray the rear layer of reinforcement to ensure good encapsulation of the steel prior to fixing the front layer. 30

It is desirable that reinforcement panels be fixed rapidly on a first layer of shotcrete of at least 20 mm thickness. 23

Several attachement points are to be provided per square meter on the working face or on a sublayer of the shotcrete. The distance between a reinforcement layer and the wall on which the shotcrete is applied shall be as small as possible. The optimum is 20 mm. After spraying, any movement or shifting of the reinforcements must be prevented, as this would lead to serious defects in the sprayed layer. 23

8. SHOTCRETE EQUIPMENT

8.1 Dry mix process

Recommendations:

Machine types:
- Bell type machines or Rotor type machines

Delivery line:
- inner diameter: 50-65 mm 23

Spraying lance:
- metal or rubber nozzle
- pre-wetting lance: should allow annular distribution of fluids (water, admixtures) 1-3 m from the discharge end. 23

Admixture proportioning:
- should be controlled by the operation rate. 23
- Powdery admixtures: added by machine mounted on feed conveyor. 23
  Equipment protected from dripped water,dirt atmospheric influence and dust. 29
- Liquid admixtures: added in lance disolveed in water 23

Water supply:
- prefarably an independant booster allowing over pressure 1-2 MPa.
  For higher pressure (5-10 MPa) special lance with small holes should be used. 23

Air supply:
- air rate, low output: 7 m^3/min
  " other cases: 10 " 23
- air pressure:
  - operating pressures ≤ 175 kPa when 30 m or less of material hose is used. Increased 35 kPa for each additional 15 m of hose or additional 8 m nozzle above the gun. 6
  - air pressure for hose diameter 65 mm according to Japanese recommendations 1

Pressure, bar	hose length, m
2.0-2.5	20
2.5-3.5	40
3.5-4.5	60
4.5-5.0	80

- compressor capacity and hose diameter according to TABLE 17. 6

TABLE 17. Compressor capacities and hose diameters /6/

material hose inside diameter (mm)	compressor capacity m^3/min at 700 kPa
25	10.0
32	12.5
38	17.0
51	21.0
64	28.0

8.2 Wet mix process

Recommendations:

Pump types:
- Screw pump:
  - Maximum pressure: 1.6 MPa 23
  - Rotation speed: 0-170 rev/min 23
  - Maximum rate: 286 l/min=17 m^3/h 23
  - " aggregate size: 8 mm 10
- Piston pump:
  - Maximum delivery: 24 m^3/h 23
  - " aggergate size: 12 mm 10
  - Consistency, normal slump: 160-200mm 28
    ≤ 100mm possible but increased rebound

Air supply:
- Required amount: 5 m^3/min 23
  ≥ 3 m^3/min at 700 kPa 6

Delivery hose:
- generally rubber
- diameter at outlet of pump: 100 mm 23
  " " " : 3 x max aggregate size 29
  " end near lance: 65 mm 23
  Distributed reduction in diameter
- bursting pressure: ≥ 3 times max pump pressure 29
- couplings 100 % tigth. Preferably with rubber sealings. 29

Lance:
- Metallic or rubber
- Outlet diameter: 50 mm 23
- Distribution of air and admixtures 200 mm from discharge end. 23

Admixture proportioning:
- Liquid admixtures added by built in propotioning pump controlled by the pump delivery rate. 23
  Changes in bulk density and viscosity must be taken into account. 10,14
- The total consumption of accelerators should be meassured. 11

8.3 Spray robots

Recommended for use in large section tunnels, ≥ 30 m^2. 23
Improve health and safety.

Types:
- complete robots: carrier with boom, operating station, pump and self contained operation.
- removable robot: boom, operating platform is attached to a carrier.

Operating conditions: 29
- the operator shall be able to watch the nozzle
- the robot shall admit as long reach as possible
- the operator shall be able to adjust the movment function
- the operator shall be able to controll/adjust water, concrete, accelerator/additives and air

9. HEALTH AND SAFETY

German documents gives regulations and limits for dust concentration at places of work. The limits are expressed as MAK-value (Maximale Arbeitsplatz Koncentration) for gas, steam or dust in the air, related to toxicologic and/or working medical experiences. 24,25

Regulation on dust concern both dust containing free mineralic silicon dioxid and different particles for air blasting.

The regulations state, for instance:

- If there are doubts concerning the occurrence and amount of silicon dust in the air of the working place, the contractor should examine if the MAK-values are exceeded.
- The contractor must guarantee that the air of the working place is free from silicon dust as far as there are technological possibilities, by for instance, ventilation technique.
- The contractor shall investigate if different additives, admixtures contain cristallinic silicon dioxide and if there are any possibilities to use less harmfull materials.
- If there are no technological possibilities to keep the working place free from silicon dust, the contractor shall provide access to respiratory protection.
- The contractor shall foresee that machines, equipments, as well as working clothes are cleaned regularly.
- The contractor shall foresee that the evaquated air is cleaned to the degree that it does not pass silicon dust to other working places.
- Air blasting material has limitations on free cristalinic silicon dioxide that must not be exceeded except
  - when special methods or equipments are used.
  - when the air blasting concern materials containing high amount of quartz

Special regulations are given on ventilation, stating, for working places and transport roads, during day time:

- every working place shall have an oxygen content > 19 % by volume.
- the limits on concentration of harmfull dust in the air must not be exceeded.
- no risk for explosion in the air
- the average air velocity shall be 0.2-6 m/s.
- when using mechanic ventilation
  - the amount of fresh air should be $2m^3$/min and worker and further $4m^3$/min and installed diesel-kW.
  - the working plant shall have self-closing doors or double doors (sluices)
- the dust shall be put down or exhausted near the source.

The Finnish guidelines give threshold limits fo mineral dust according to TABLE 18. 11

TABLE 18. Threshold limits for mineral dust according to Finnish guidelines /11/.

Quartz (fraction <5µm)	0,2 mg/m^3
Portland cement particles/cm^3	1000
Total dust content	10 mg/m^3

According to the Japanese guidelines the dust content should be $\leq$ 5 mg/m^3. 1

The Sprayed Concrete Association recommend that reasonable measure shall be adopted in accordance with the requirements of the Health & Safety at Work Act 1974, particularely concerning lighting, ventilation and protective clothing. 30

Some documents give quantitative requirements on the lighting during spraying, for instance, as a minimum lighting level of 50-70 lux. 17,18

ACI-506 states concerning health and safety: 15
- Eye glasses or shields shall be worn at all times during application.
- Crew should wear apropriate protective mask, gloves and clothing.
- An eye bath shall be readily available in the immediate vicinity of the application.

Other sources stress the need of a predetermined communication system and to regularly use 10-15 min for cleaning of equipment after each spraying shift. 27

The Sprayed Concrete Association recommend cleaning at least twice a day for wet mix equipment and at least once a day for dry mix equipment. 30

10. SHOTCRETING

General:

Requirements for the application process often refer to recommended practice such as ACI 506. 15

The Contractor should employ a full-time working Foreman on the project who should have had at least five years specialist spraying experience, including two years as a nozzleman. Also, he should have experience in concrete mix design and be fully conversant with the relevant codes of practice. 30

Recommendations:

Spraying procedure:

- spray lance shall be held perpendicular to the surface, except when spraying around reinforcement bars. 1,23
- spraying shall commence at bottom 10,30
- immediately prior to the spraying operation the surface shall be thoroughly cleaned and damped with a strong blast of air and water. 30
- voids shall not be left behind bars or steel mesh 1
- spraying downward vertical is difficult. Uncoated aggregate and rebound material are mixed with concrete. 23
- optimum nozzle distance: 1,10,16
  dry-mix: 1-2 m 23,2
  wet-mix: 0.5-1.8 m
- where an alignement similar to traditional concrete is required it is usual to place the shotcrete sligthly proud of the required alignement and carefully saw back with a timber straigth edge. After the shotcrete has reached its initial set a further layer (15-20 mm) is applied, aligned with a timber staigth edge and rubbed up with a wooden trowel. 30
- control of alignement and thickness shall be determined by the Contractor. Where sharp edges or accurate lines are required these should be set out by screed boards, guide wires and/or depth spacers. 30

Layer thickness:
- 20-30 mm typical for dry mix shotcrete. 11
  Normally ≤ 8 hours between first and second layer.
  Further 24 hours between second and third layer.
- the first layer must be allowed to take its 15
  initial set before spraying the next layer.
  Prior to spraying subsequent layer, loose
  materials shall be removed using strong blast
  of air. 30
- 50-100 mm layer dry mix shotcrete shall be built
  up by several passes. 10
- Wet-mix shotcrete: layer thickness and waiting time 11
  between layer depend on concrete mix and quantity of
  accelerator.
  The Contractor shall duly consider factors as
  position of reinforcement, plane of application,
  mix design and constituents including admixtures,
  that may contribute to slump and sag. 30

Construction joints:
- generally tapered to a thin edge over a with of
  about 300 mm or inclination 30 °. 15,30
- the entire joint should be thoroughly cleaned
  and damped prior to placement of adjacent
  sprayed concrete 30

Surface treatment:
- the surface shall be left as sprayed. If another
  texture is desired an additional layer shall be
  applied.(flash coat) 15,23,2
- other finnishing of the surface than very ligth
  trowelling will cause plastic cracking. On
  coatings ≤ 25 mm trowelling is undesirable. 30

Spraying in cold weather:
- the same rules as for normal concrete shall be
  regarded when spraying at temperature < +5 °C. 23
- sprayed concrete shall not be placed when air
  temperature falls below 3°C. It shall be
  maintained at not less than this temperature
  until the final set is achived. 30
- spraying must not be done against very cold or
  icy surfaces. 23
  The surface shall be heated or the working place
  protected by a heated shelter. 2

Spraying in hot weather:
- precausions shall be made that the surface
  temperature does not exceed +30 °C. 2

11. CURING

General:

Most documents indicate that the shotcrete should be treated according to the same rules as for normal concrete, that is, the shotcrete requires some kind of moist curing after application, particularly for thin section concrete, concrete with a textured surface and concrete with a low water/cement ratio.

Recommendations:

Conditions for curing:
- only necessary if the concrete has special properties (class SC III) or is exposed to special circumstances (e.g. rapid drying). 10
- only when the relative humidity ≤ 85-90 %. 6,7

"when possible" and in that case, by wet curing as long as possible. 17
- when the ambient temperature exceed 25 °C or the air movement may cause rapid drying, the surface shall not be exposed for longer time than 1 hour. 30

Time of curing:
- normally 3-7 days
- the time necessary to reach a certain degree of hydration or strength level, for instance
  - 60 % of the required strength 11
  - 80 % " (watertight) 11
  - 45 % " " 7,29
- protection against evaporation necessary during first and most critical hours/days. 29

Curing method:
- by repeated moist spraying since continous moist curing often is difficult to carry out in a tunnel Frequency: once every 4 hours. 1
- according to the Austrian standard (ÖNORM 4200), that is, by curtain-type moistened overlays (fibrous mats) or by acceptable curing membranes. 10

Use of curing membranes:
- recommended when drying conditions are not severe, when no additional shotcrete or paint is to be applied or when it is acceptable from an aesthetic standpoint. 15
- only on finished surfaces. 7
- prefered 11

- more frequently applied due to the effect of high surface roughness. When a further layer or other surface finnish is to be applied, bond test shall be carried out. Otherwise the curing compound should be removed by high water pressure, sand blasting etc. 11,29
- the rate of application of curing compounds may be the double compared to the use for paving, due to the increased surface roughness. 29

12 . QUALITY CONTROL

12.1 PRECONSTRUCTION TESTS

12.1.1 Conditions

The composition of the shotcrete is determined in the course of preconstruction tests in which the required properties of the shotcrete are checked. The need for such tests is often dependent on the utilization of the shotcrete, expressed as a minimum strength class or grade.

Examples:
- for strength grade $\geq$ SC 16, according to Austrian guidelines 10
- for strength classes I and II (out of four classes) according to Finnish recommendations 11
- in normal and extended controll class according to the Norwegan draft 28

AFTES relate the need for preconstruction tests to the available knowledge of the actual shotcrete composition and performance conditions. 23
- When the mix design is well known and there are references, test shall be done to check the capability of contractor (personal and equipment)
- When a prior study has been carried out in connection with a project but the shotcrete never has been applied, tests shall be done to ensure
  - feasability of concrete placement
  - compliance with specifications
  - capability of contractor

Tests shall be carried out on the site under placement conditions at least 10 days before start of work.

12.1.2 Extent

Preconstruction tests should comprise:
- According to the Austrian guidelines 10
  - two mixes with two binder contents and adequate dosage of admixtures.
  - one mix without accelerator

  The tests must be performed on site using the definite installations and concrete ingredients.
- According to the German guideline 2
  - two panels, one for tests on fresh concrete, the second for tests on hardened concrete.
- South-African documents prescribe 17,18,3
  - test panels should be made for each crew, for each mix and for each shooting orientation, at least in the beginning of a project. The number of specimens prescribed are, at least, 3-4 from each test panel.

Recommended tests on fresh concrete: 2,17,18
- Density
- Water content (dry mix process)
- Aggregate content < 0.25 mm
- Dosage of accelerator. Maximum dosage, not to be exceeded.

Recommended tests on hardened concrete: 17,18,23
- Compressive strength 3,7,28 days
- Splitting tensile strength 3,7,28 days
- Density on all cores
- Flexural strength and toughness
- Watertightness
- Bond, direct tensile test on test section, 3,28 days
- Uniformity and continuity: visual inspection of cores. Sclerometer and sonic inspection on test section at 7 and 28 days.

Norwegian draft for wet mix shotcrete relate the extent of tests to the actual controll class. 28
- Normal control class: Test on concrete mass and sprayed concrete:
  - water demand, workability, pumpability, sprayability/rebound.
  - material control: Slump, air content, compressive strength, density
  - dosage of accelerator

- Extended control class
  - Identification of demands on base material and consequences for material composition and performance
  - Choise of aggregate and ready mix concrete supplier
  - Mix design considerations
  - Test including material control, production control and , if necessary, property documentation.

12.1.3 Requirements

Conforming to normal concrete standards the requirements on preconstruction tests are higher than the requirements on construction tests.

Example:

- The Austrian guideline stipulates 25 % higher compressive strength value than the design strength, though not more than 8 MPa. 10
- according to South African document: 3
  - average compressive strength (3 samles) $\geq$ design strength, 28 days
  - single values $\geq$ 0.8x design strength, 28 days
- Swedish requirements on toughness stipulate 0.5-1.0 MPa higher residual stress values for preconstruction tests compared to the requirements on routine tests. 7,14

12.2 Routine tests

General:

According to the Norwegian draft the control extent is related to different control classes: 28

I : Minor control
II : Normal control
III: Extended control

The choise of control class should be done by the designer, based on
- type of project, (consequence of failure)
- degree of difficulty (strength and environment class)
- time schedule of project, that is, the possibility to carry out the control program (specially important in control class III)

Four types of control are specified:
- Production control
- Material control before spraying
- Control of hardened shotcrete
- Documentation of properties

The link between control class and control type is according to schedule below.

Control class	Production control	Material control	Control hardened shotcrete	Document of properties
Minor	x	x		
Normal	x	x	x	
Extended	x	x	x	x

In control class III (Extended control) there should be:
- a special organisation table for each project
- a special quality assurance Engineer

12.2.1 Test extent on constituents

The required extent of tests on constituents on site is extensive when using dry mix process shotcrete mixed on the site.

Cement:
Normally "tested" by checking the batch ticket at every delivery but Austrian guideline also stipulates more detailed tests, to be performed once every month regarding:
- fineness of grinding
- initial set
- strength
- sweating(bleeding)
- C_3A content, when applicable

Aggregate:
Beside batch ticket control of every delivery, there are different stipulations for testing
- grading curve of coarse and fine aggregates
  Frequency: 1/week-2/month or linked to the delivered volume as 1/100 m^3 natural fine or coarse aggregate and 1/50 m^3 fine crushed aggregates.

- moisture content
  Frequency: 2/week-2/month
  For wet mix shotcrete Norwegian draft prescribe 28
  1 test/shift in all control classes (minor, normal, extended) to be performed by the ready mix concrete supplier, independant of the concrete volume.
- type (deleterious substances)
  Frequency: every delivery- daily

Additives:
Normally "tested" by check of batch ticket every delivery but may also comprise, for instance
- fineness of grinding of fly ash
  Frequency: 1/month

Admixtures:
Normally "tested" by checking the batch ticket, marking etc every delivery or routine visual inspection but may also comprise:
- identity test
  Frequency: 1/ 2 month
- water-soluble aluminate content
  Frequency: 1/month
- decrease in strength, acceleration of setting of cement
  Frequency: by special direction
- resistance to sulfates (combined with cement)
  Frequency: 1/month

Water:
The influence on setting time and strength development is only tested if non-potable water is used and there are doubts concerning the occurence of harmful constituents.

12.2.2 Test extent on dry mix

The extent of routine tests performed on site on shotcrete mix before shotcreting is less when pre-bagged dry mix products are used compared to the situation when site-mixed dry mix shotcrete is used.

Pre-bagged dry mix products are tested by checking the batch ticket, marking etc. every delivery as well as routine visual inspection. More detailed control may be performed by checking the individual components.
Site-mixed dry mix shotcrete is, besides the individual components, tested with reference to
- composition
- moisture content
Frequency according to Austrian guideline: 4 /month 10

12.2.3 Test extent on fresh and hardening shotcrete

Tests on fresh concrete normally comprise, for dry-mix shotcrete,water content in the mix and for wet mix shotcrete, tests of consistency fresh density, temperature and, if prescribed, the air content.
For wet-mix shotcrete, the extent of tests performed on site is less when ready mix concrete is used compared with the situation when site mixed concrete is used.

A frequency for these kinds of tests is stipulated in the German guideline: 2

< 100 m^3 (500 m^2) shotcrete	: 1 test series
100-300 m^3 (500-1500 m^2)	: 1 series/100 m^3 (500 m^2)
> 300 m^3 (1500 m^2)	: 1 series at start and 1 series/250 m^3 (1250 m^2)

The frequency of these tests according to the Norwegian draft is related to the control class: 28

Concrete volume	Control class Minor	Normal	Extended
first 3 shift or 1/50 m^3	1/shift	-	-
≥ 3 shift	1/14 shift or 250 m^3	-	-
< 10 m^3 1)	-	1/shift, 3 or 50 m^3	1/3 shift 3 or 25 m^3
10-50 m^3 2)		1/6 shift 3 or 100 m^3	1/shift, 3 or 40 m^3
> 50 m^3 3)	-	1/3 shift 3 or 200 m^3	1/shift, 3 or 75 m^3

Notes: 1) Spraying by the rock front after each fire
2) " near the rock front to support a couple of excavation sections
3) Spraying for permanent support

For fibre-reinforced shotcrete, Swedish documents prescribe to check the fibre content and fibre distribution by wash out tests. The wash out tests are carried out on samples from the load and from the lining. 7,16
Frequency: 3 samples /load taken directly from the load
3 samples /load taken from the lining

The Japanese guidelines also specify the measurement of rebound carried out on, about 0.2 m^3 shotcrete, as well as measurement of the dust density. 1

Stipulations concerning tests on hardening shotcrete (young shotcrete) are given in the Austrian guideline. The hardening is tested by indirect methods calibrated to the strength development. 10
Frequency: 2 /month

12.2.4 Test extent on hardened shotcrete

Tests on hardened shotcrete are carried out by tests on
- concrete mass (standard tests)
- specimens from shotcrete panels
- cored specimens from the lining

Routine quality control programs also often comprise tests concerning
- thickness of the lining
- bond of the lining to the rock

The requirements for the type of samples in the Finnish guideline are linked to the actual shotcrete class (see TAB 6) and the shotcreting method according to TABLE 19. 11

TABLE 19. Methods for sampling in different shotcrete classes according to /11/.

	Samples	
Class	Wet-mix method	Dry-mix method
I	Standard tests	Shotcreted panels
	Shotcreted panels	Cores from the lining
	Cores from the lining	
II	Standard tests	Shotcreted panels
	Shotcreted panels	(Cores from the lining)[1)]
	(Cores from the lining)[1)]	
III & IV	Standard tests	(Shotcreted panels)[1)]
	(Shotcreted panels)[1)]	(Cores from the lining)[1)]

1) only if required in contract documents.

The frequency of making test panels and/or cored specimens is, according to the German guideline linked only to the volume or area of shotcrete, as presented above for preconstruction tests. 2

Other documents link the frequency of testing to the strength class or grade of the shotcrete. For instance the Finnish guideline, TABLE 20, or the Austrian guidline TABLE 21. 11 10

TABLE 20 Minimum number of shotcrete panels for compressive strength according to Finnish guideline /11/.

Nominal strength	Governmental inspection	Volume of the applied shotcrete V m^3	Number of samples
≤ K30	yes	< 900	6
	yes	> 900	V/150
	no	< 75	6
	no	75 - 675	9
	no	> 675	V/75
≥ K35	yes	< 600	6
	yes	> 600	V/100
	no	< 50	6
	no	50 - 450	9
	no	> 450	V/50

TABLE 21. Frequency of test according to Austrian guideline /10/

"Young" shotcrete acc. to item 8.1	SC(II),(III)	at least every seven working days
Strength grade, special requirements	SC(II)	every 2500 m^2 or 14 working days
	SC(III)	see ÖNORM B 4200, Part 10

In similarity to tests on fresh concrete, the Norwegian draft link the test on hardened concrete to both volume of concrete and the classification (control class) 28

- test of compressive strength and density, 7 and 28 days, on standardizized cubes cast on site. Frequency according to TABLE 22.
- test of srength and density of cores from the lining. Frequency according to TABLE 22.
- documentation of properties, such as, flexural strength and thoughness on beams sawn from shotcrete test panels. Frequency according to TABLE 23.

TABLE 22. Frequency of strength and density test from the lining according to Norwegan draft/28/

Concrete volume	Control class Minor	Normal	Extended
< 10 m^3	-	1/25 shift or 200 m^3	1/10 shift or 75 m^3
10-50 m^3	-	1/300 m^3	1/100 m^3
> 50 m^3	-	1/400 m^3	1/150 m^3

TABLE 23. Frequency of property documentation according to the Norwegian draft /28/

Concrete volume	Control class Minor	Normal	Extended
< 10 m^3	-	-	1/500 m^3
10-50 m^3	-	-	1/700 m^3
> 50 m^3	-	-	1/800 m^3

According to AFTES: Compressive strength 3,7,28 days. 23
Frequency 1/50 m^3

When summarizing the required test frequencies presented above and requirements in other documents, the frequencies vary between
- minimum: 1 sample (test panel)/250 m^3 of concrete
- maximum: " / 10 "

This difference is very much dependent on combinations with other quality control systems, as for instance, can be noticed in the Finnish guideline, TABLE 20. The requirements for test frequency are much lower if the shotcreting is performed under governmental inspection.
There is also an influence of the strength class. That is, a higher strength class requires more frequent tests.

Very approximately, the required test frequences may be divided in two frequency groups

1 sample/ 10-100 m^3 concrete.
Applied in -Finland (no governmental inspection)
- South Africa
- Sweden
- USA
- Canada

1 sample/ 100-250 m^3 concrete
Applied in - Finland (governmental inspection)
- Austria
- Germany

The test frequency requirements also comprise additional or complementary requirements, such as
- when fibre reinforcement is used, one test should be made each day 5
- the intended test specimen may be taken from the structure or from a test panel alternatively 5

The tests and number of specimens required at each test occasion normally comprise:
- compressive strength on 3-5 drilled cores or sawn cubes
- density measured on the compressive test specimens

Documents from Sweden and South Africa also prescribe the above frequency for toughness test according to ASTM C1018 on, at least 3 beams/test occasion. 14,17

Properties other than the above may be tested with other frequency requirements. For instance:

- splitting tensile strength 3,7,28 days:	1 test/ 100 m^3	23
- density:	on all cores	23
- watertightness:	2 specimen / 200 m^3	7
- toughness:	3 beams / 300 m	7
- modulus of elasticity:	no frequency stated	10
- bond:	3 tests / 50-100 m^3	7,16
" at 3,28 days:*	1 test/1000 m^2	23
- thickness: 1 test (5 points of measure)/ 50 m^3		16
	1 point of measure / m^2	17
	1 test (7 points)/ 20 m	1
- aggregate content: < 0.25 mm	no frequency stated	2
- uniformity in mass and continuity:	visual inspection of cores	23

* The scatter is great, according to experience, when testing in place due to influence of deviated traction, peelings,placement difficulties and weight of equipment. Test in laboratory is therefore recommended.

For fibre-reinforced shotcrete it is possible to use identity charts established for the actual fibre used, for instance, according to FIG 2. 6

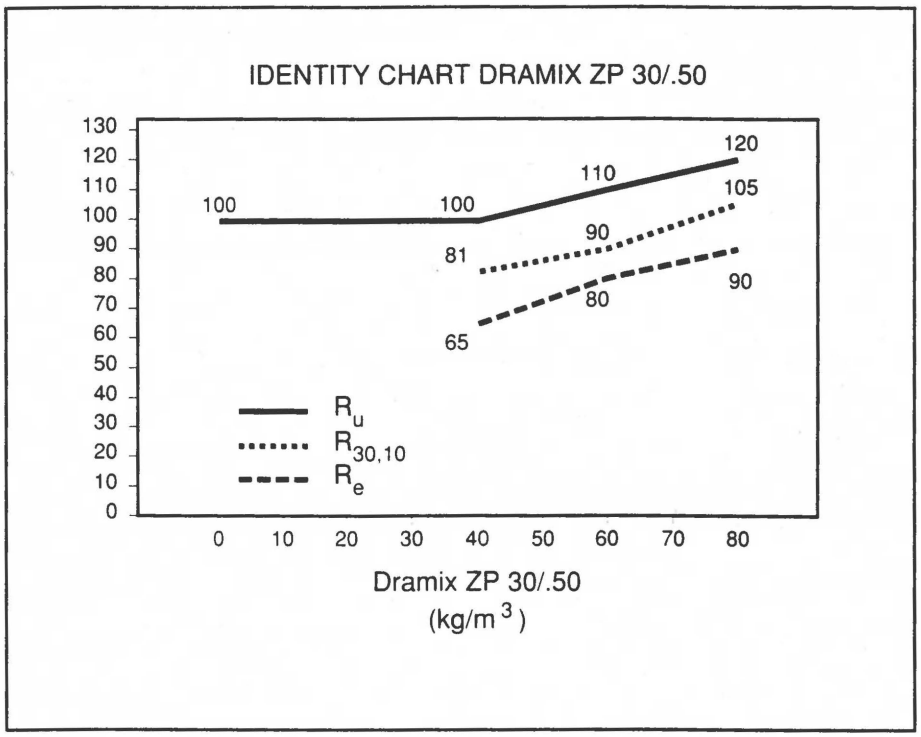


FIG 2. Identity chart for fibre type Dramix ZP 30/.50 /6/

The use of identity charts for routine quality control is based on the existence of a certain relation between the compressive and flexural strengths of plain concrete

$$fo = 0.4\sqrt[3]{fcc}$$

where: fo = ultimate flexural strength
fcc= compressive strength

Other quantities used are

Ru = 100 fu/fo expressing the relation between the ultimate flexural strength (fu) of fibre- reinforced concrete and the ultimate flexural strength of plain concrete (fo)

Re = 100 fe/fo expressing the relation between the equivalent flexural strength (fe) of fibre- reinforced concrete, tested according to the JCI method, and the ultimate flexural strength of plain concrete.

$R_{30,10}$ Residual strength factor established according to ASTM C 1018.

Using the identity charts and the above quantities, the routinely performed flexural tests on concrete beams, may be exchanged by tests on compressive strength only, which is more simple and less expensive. It is, however, important to consider that the basis of this proposal,that is, the existence of a relation between compressive and flexural strength of plain concrete, is very much dependent on the actual method of testing for compressive and flexural strength, the curing conditions etc.

12.2.5 Requirements

The requirements for shotcrete from routine tests are in agreement with the guidelines and recommendations presented in chapter 4. Thus, the recommendations and guidelines below focus on acceptable limits of variations, acceptance criteria etc

Cement:
See 3.1
Expected limits of variations for different properties of cement may be found in the specific cement standards applied. Some statements presented in the studied documents are:
- Fineness of grinding: Deviation: ± 5% 10
- Compressive strength of standard test: Standard deviation: ≤ 3.5 MPa 10

Aggregate:
Permissible deviation from a specific grading curve is presented in the Austrian guideline, TABLE 24. 10

TABLE 24. Permissible deviation from specified grading curve according to ÖNORM B 4200 /10/.

Sieve size mm	Permissible deviation % at max aggregate size < 16 mm	> 16mm
0.06	1.5	1.0
0.25 .	3.0	1.5
1.0	5.0	2.0
4.0	5.0	3.0
>8.0	5.0	3.0

Moisture content: Deviation ± 1 % from the designed. 2

Additives:
See 3.3
- Specific surface of
  fly ash: Deviation ± 250 cm2/g 10

Admixtures:
See 3.4

Fibres:
See 3.5

Composition of mix:
See 4.1
According to the Norwegian draft the mass ratio 28
m=v/(c+Kxp) must not exceed, by
- more than 15 % for single shotcrete areas or
  working shift
- more than 10 % for three following shotcrete areas
  or working shift.

Fresh concrete:
See 4.2
ASTM C 1116 /5/ gives acceptable tolerances for
workability of wet mix fiber-reinforced shotcrete
when measured as slump or "time of flow".

- slump specified as "maximum" or "not to exceed"

	Specified Slump	
	If 3 in. (75 mm) or less	If more than 3 in. (75 mm)
Plus Tolerance	0	0
Minus Tolerance	1½ in. (40 mm)	2½ in. (65 mm)

- slump not specified as "maximum" or "not to exceed"

Tolerances for Nominal Slumps

For Specified Slump of	Tolerance
2 in. (50 mm) and less	±½ in. (15 mm)
2 to 4 in. (50 to 100 mm)	±1 in. (25 mm)
more than 4 in. (100 mm)	±1½ in. (40 mm)

- time of flow specified as "maximum" or "not to exceed"

	Specified Time of Flow	
	If 15 s or less	If more than 15 s
Plus Tolerance	5 s	10 s
Minus Tolerance	0 s	0 s

- time of flow not specified as "maximum" or "not to exceed"

Tolerances for Time of Flow	
For Specified Time of Flow of	Tolerance
8 to 15 s	±3 s
more than 15 s	±5 s

Fiber-reinforced concrete shall be available within the permissible range of slump or time of flow for a period of 30 min starting either on arrival at the job site or after adjustment of the consistency at job site. The first and the last 0.25 m^3 are excluded from this requirement. 5

ASTM C 1116 also gives tolerances for air pore volume of fibre reinforced concrete: 5
- ± 1.5 % of the specified value

Young concrete:
See 4.3

Hardened concrete:
See 4.4
- Compressive strength:
  The Austrian guideline /10/ states a statistical method of evaluation if more than 30 results of quality tests are available for a particular strength grade. Then
  - the 10 % fractile of all test results must at least be in accordance with the required values.
  - < 10 % of the individual values may fall below 90 % of the required strength

  The guideline also states that the principle may also be applied to other characteristics e.g. watertightness etc
  Another document states that the single value must be > 0.8x required strength. 3

- Toughness:
  The evaluation of the shotcrete quality should be based on the 10 % fractile value.
  It is important to notice that the evaluation of toughness quantities according to ASTM C 1018 is very much dependent on the accuracy of the deformation measurement. That is , only well qualified laboratories should be used.

  The precision in measurement within laboratory is presented in ASTM C 1018. TABLE 25. 4

  TABLE 25. Within-Laboratory Precision for toughness test according to /4/. 1S=one-sigmalimit.

Parameter	Within-Batch 1S %	Overall 1S %[A]
First-crack strength	5	7
First-crack toughness	10	12
Toughness index I_5	12	13
Toughness index I_{10}	14	16
Toughness index I_{20}	16	20
Flexural strength	5 to 8[B]	8 to 10[B]

[A] Inclusive of batch-to-batch variability, but not variability due to changes in specimen geometry, test span, and mode of loading.

[B] Upper limit appears applicable to relatively high fiber concentrations, 200 lb/yd^3 (120 kg/m^3) or more of straight uniform fibers, or 70 lb/yd^3 (42 kg/m^3) or more of deformed fibers.

- Thickness:
  - the average measured thicknesss must not fall below: 16
    - 90 % of required thickness at nominal thickness $\leq$ 30 mm
    - 95 % of required thickness at nominal thickness $\geq$ 30 mm
  - $\pm$ 10% variation of the thickness is acceptable 14
  - If the thickness fall below the nominal at one measured point, new measurement should be carried out in the vicinity of the past in order to find out the extent of the area. 11
  - When shotcreting against a substrate at low temperature, frozen soil or rock, the nominal thickness shall be increased by 2-3 cm of shotcrete. 10
  - a tolerance of $\pm$ 10 mm over a 3 m length is readily attainable on a flat surface. 30

- Density:
  - The density may deviate < $\pm$ 2 % from the density evaluated during design and suiability tests. 23

13. TEST METHODS

13.1 Test panels

When testing shotcrete from test panels there are different recommendations concerning the dimensions of the test panels. Some recommended examples are:

- 500x500x150 mm 1
- 500x500x120 mm 11,2
- 600x600x100 mm 19
- 400x600x200 mm 10
- 600x600x120 mm 28
- 650x650x100 mm 17
- 750x750x150 mm 3
- 600x600x100 mm for dry mix shotcrete
  750x750x100 mm " wet " " 30
- 450x450x100 mm for construction test
  though 750x750x100 for preconstruction test 18
- (nx125+100)x550 mm n=number of beams 13
- 800x800x160 mm 29
- surface area $\geq$ 0.25 m^2. Thickness $\geq$ 150 mm 23

The choice of panel dimensions is important both from the practical point of view (difficult to handle) as well as from the technical point of view in order to get a realistic measure of the actual concrete structure.

When using robot the test panels should be made by spraying on a loading stool, without the normal incleaned sides, provided with a laminate plate. 28

According to EFNARC the filling of receptacles by robot is difficult, due to high rate (10-20 m^3/hour). Thus, sampling by in-place coring is recommended. 23

Making test panels: 28
- the mould shall be placed against the tunnel wall with inclenation $\leq$ 45° to the vertical plane.
- spraying to minimum thickness 120 mm. Concrete thickness > 170 mm shall be removed immediately.
- the panel shall be cured similar with the lining and be remained at the test place for 12-18 hours
- the concrete surface shall be protected by plastic sheet or moist cloth before transport to test laboratory earliest after 4 days.

13.2 Fresh shotcrete

Test methods for fresh shotcrete, that is, normally wet mix shotcrete or dry mix shotcrete without accelerator (or tested before adding the accelerator) also often refer to standard test methods for normal concrete. Special attention should, however, be paid to some tests on fibre- reinforced concrete. Workability of fibre- reinforced shotcrete tested by slump will have a lower slump value than the slump of an otherwise identical concrete without fibres. Thus it is recommended that trial mixes be made with the actual types and amounts of fibres to ensure that the specific slump requirements are met. 5

Fibre content and fiber distribution may be tested by wash out methods from fresh shotcrete.
Recommendations:
- minimum 2 litres of concrete 16
- " 10 " " 28,23
- at least 8 kg (4 litres) for dry mix shotcrete 10
- the analysis shall be carried out on a sample from a mix of concrete from 3 different zones. 23

Mass ratio:
Calculated, for wet mix shotcrete, from production data in ready mix concrete factory combined with measured consumption of accelerator on site. 28

Rebound:
- of shotcrete:
  - measured by weighing of shotcrete rebound on a tarpaulin. Drop-of of already applied concrete shall not be included.
- of fibers in rebound:
  - measured by wash out from at least 5 kg rebounded material.

13.3 Hardening (young) shotcrete

Methods to test the properties of young shotcrete are presented in the Austrian guideline and different measuring ranges are specified for different test methods. FIG 3. 10

The test methods specified are:
- modified penetration test
  - with flat-ended 9 mm needle used immediately after placing of shotcrete
  - with pointed-ended (60 °), 3mm needle for maximum strength 1.5 N/mm2.
    Strength is recorded at time intervalls 2,4,6,8, 10 20, 30 min according to EFNARC. 29

- powder actuated fastening process:
  Bolts are driven into the concrete and subsequently extracted again by measuring the pull-out force. The parameter for determining the compressive strength is the ratio of pull-out force to depth of penetration.
- pull-out test:
  An insert consisting of a threaded shaft is encasad in shotcrete and then pulled from the concrete for assessing the strength corresponding to the respective state of hardening.

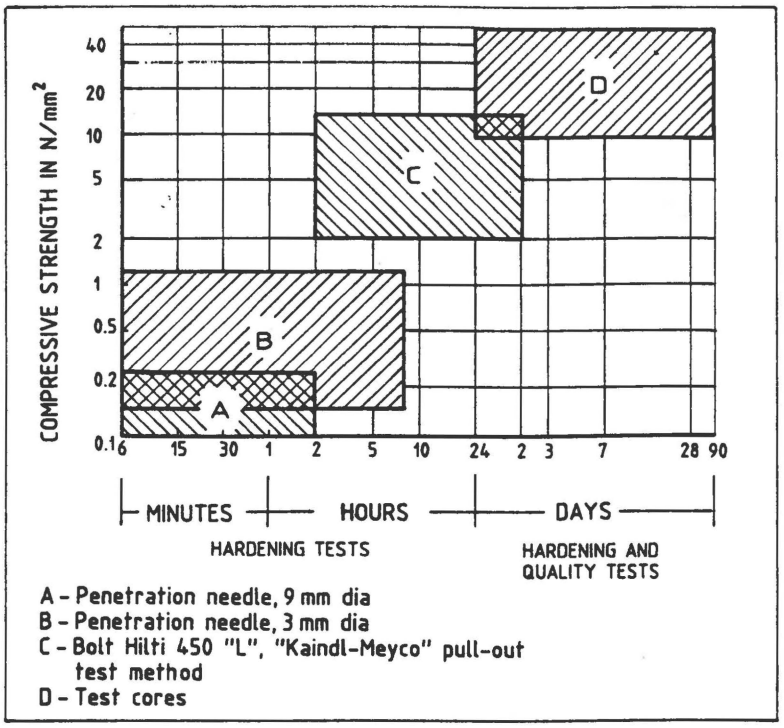


FIG 3. Measuring ranges for the test methods of "young" shotcrete compressive strength. /10/

Coring technique is possible for strength ≥ 5 MPa.
For strength 1-5 MPa sawing of specimens is prefered.

13.4 Hardened shotcrete

13.4.1 Compressive strength

The recommended dimensions of specimens:
- drilled cores:
  - diameter: ϕ60-100 mm
  - length/diameter ratio: 1:1-1:2.
    1:1.5-1:1.7 (prefered) 28
- sawn cubes:
  - side dimensions: 75-100 mm
    ≥ 60 mm 29

According to The Sprayed Concrete Association the quality of in-situ sprayed dry mix shotcrete may be confirmed by the taking of 25 mm cores. 30

The drilling of cores or sawing of cubes should be done when sufficient strength has been reached, that is,
- about 10-15 MPa.(after 2-3 days). 3,10
- after at least 7 days 23

The curing of specimens prior to tests is in agreement with the treatment of specimen for normal concrete compressive strength test according to most national standards. Normally at site 7-10 days.

13.4.2 Toughness

Flexural toughness can be expressed in energy terms as absolute values. This requires very strict definitions of specimen sizes, loading geometry and other test conditions, if the values are to be used generally in evaluation, control or design.
Another approach has been to describe the toughness as a dimensionless index in relation to an "ideal" material behaviour, e.g. linear elasto-plastic, or to a reference material.That is, by this relative value description one part of the response to the external loading of an element is compared with another part of the response of the same specimen.

The group of absolute descriptions includes propositions presented by the Japan Concrete Institute (JCI) and RILEM.
The most applied method, belonging to the second group, is the method according to ASTM C 1018.

Method according to ASTM C 1018:

A test beam, cut from a shotcrete test panel, is subjected to third point loading in flexure and a load vs deformation curve is plotted. The flexural strength f_o and the crack deflection are defined at the first crack and subsequently the various toughness indices I_j. A toughness index is the ratio of the absorbed energy up to a given deflection to the absorbed energy up to the first crack. The area below the load-deflection curve is a measure of the absorbed energy.
In the standard, toughness indices $I_5, I_{10}, I_{20}, I_{30}$ are defined for deflections up on to 3δ ,5.5δ ,$10,5^{\delta}$,15.5δ.
FIG 4.

Recommendations concerning beam dimensions are:
- 100x100x350 mm (thick sections)
  equal to the actual thickness used (thin sections) 4
- 75x125xmin550 mm 28
- 75x125x600 mm 29

According to EFNARC, 29
- I_{10} and I_{20} shall primarely be used for rock support.
- I_5 and I_{10} shall be used for other applications.

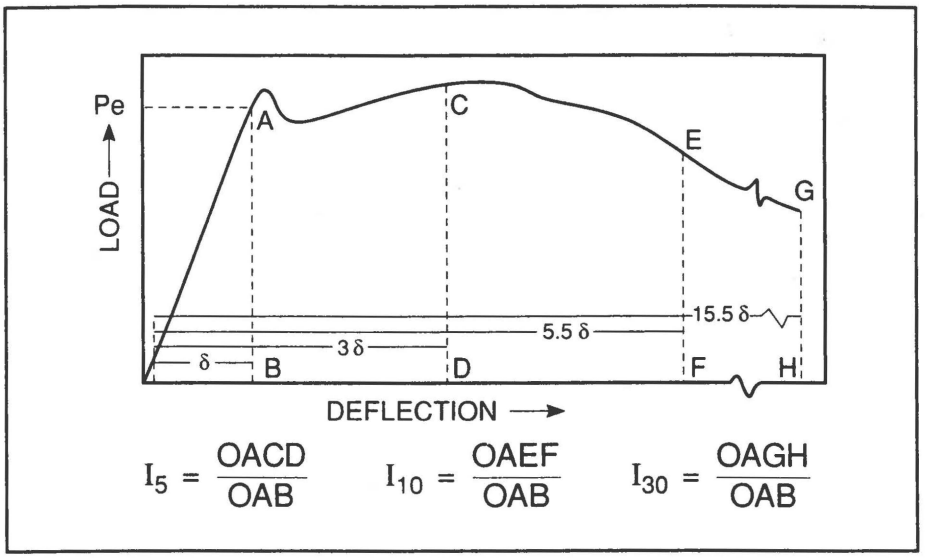


FIG 4 .Load-deflection curve and toughness indices according to ASTM C 1018./6/

It should be observed that the estimation of toughness indices is very much dependent upon the accurate registration of δ .This value is very small, of the order of 0.05-0.1 mm and small variations in the estimation result in great influence on the estimation of the deflection value corresponding to the actual toughness index. Thus, the accuracy in estimation is very much dependent on the laboratory equipment used.

Besides toughness indices, design values for toughness can be defined by residual strength factors such as:

$$R_{10,30} = 5(I_{30}-I_{10})$$

This value would be 100 for an elasto-plastic material.

In Sweden the residual strength factors have been used to characterize two stress levels to be exceded in acceptance tests. 7

$\frac{R_{5,10}}{100} \times f_s$ Expressing the average stress level in the deflection range corresponding to toughness indices I_5 and I_{10}.

$\frac{R_{10,30}}{100} \times f_s$ Average stress level in the deflection range corresponding to toughness indices I_{10} and I_{30}.

(fs= first crack stress)

Method according to JCI:

According to this standard, flexural strength is defined with reference to the maximum load. As a measure of toughness an "equivalent flexural strength f_e" is defined, matching a flexural strength derived from an average load value over a given area. The standard sets the maximum deflection equal to 1/150 of the span.FIG 5.

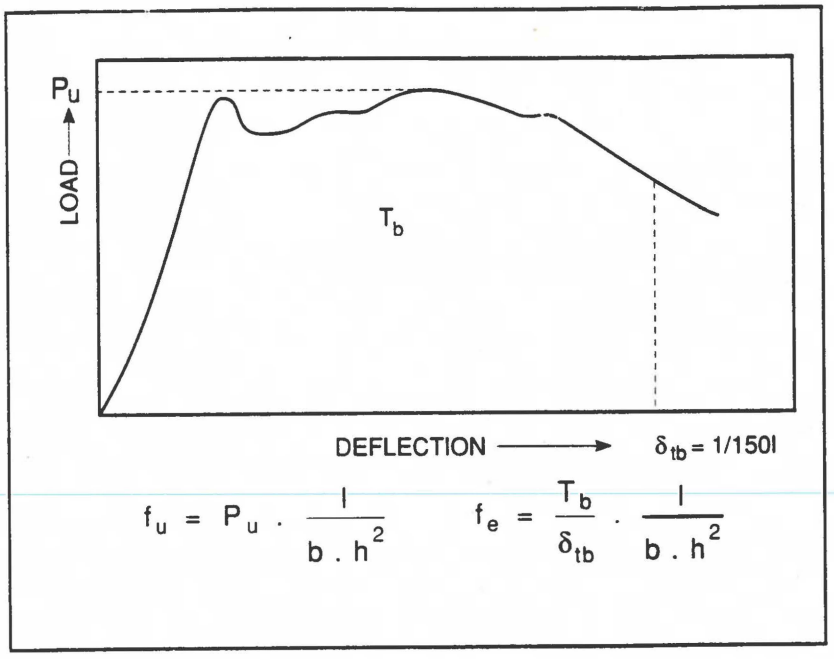


FIG 5. Definition of equivalent flexural strength according to JCI /6/.

This absolute description neglects the resemblance of the material to an elastic-plastic ideal material. While it tells how much energy must be used for a certain standard specimen to be deformed to a certain extent, the form of destruction (brittle or ductile) is not indicated. 8

Comparison of methods:

The methods based on relative values have most merits. 8
Among the positive features of the ASTM method are:
- it gives information on a first crack stress level as well as an index based on energy, thus making distinction between matrix strengthening and toughening of the composite.
- the toughness index value refers directly to an idealized material, thus the meaning of the value is easily understood.
- it allows the choice between different indices based on different deformations, which is relevant since failure criteria can be different for different applications.
- the residual strength factors facilate the use of the toughness property in design.
- the specimen dimensions are chosen in relation to the main dimensions of the product to be evaluated. Thus fibre orientation effects, size effects, etc. are taken into account.

A summary of various toughness descriptions is presented in TABLE 26.

TAB 26. Summary of various toughness descriptions according to /8/.

Name (year,[ref])	Toughness description	Toughness Index [1] symbol	Formula [2]	Reference F-δ diagr.	F or δ limits in index value estimation [1)4)]
RILEM 1982 [25]	absolute	-	$\int F d\delta$	-	span/10 or $0.4F_{max}$
JCI-SF4 1983 [18]	absolute	-	$\int F d\delta$	-	span/150
ACIComm.544 1978 [1]	relative	I_{075}	(A+B)/A	the same specimen	1.91 mm or $0.8F_{max}$
ACI Comm.544 1988 [2]	relative	I_t [5]	(A+B)/A	plain concr. specimen	entire response
Austin,Robins 1986 [7]	relative	I_{AR}	(A+B)/A	plain concr. specimen	$0.8F_{max}$ or $0.5F_{max}$ or 2.3 mm
Barr et al. 1982 [12]	relative	(I_{B4}) [3]	(A+B)/(4A)	the same specimen	$2\delta_0$
Barr, Hasso 1985 [9]	relative	I_{B3}	100B/(3A)	the same specimen	$2\delta_0$
ASTM C1018 1985,89 [5]	relative	I_5	(A+B)/A	the same specimen	$3\delta_0$ or $3\delta_0'$
Mobasher,Shah 1989 [22]	absolute [3]	(G_f) [3]	$\int F d\delta$ (net sect)	-	entire response
Fanella,Naaman 1985 [15]	relative [3]	I_σ	$\int \sigma d\varepsilon / (\int \sigma d\varepsilon)_{plain}$	plain mortar specimen	compress. strain 0.0154
Otter,Naaman 1988 [24]	relative [3]	$I_{\sigma cycl}$	$\int \sigma d\varepsilon / (\int \sigma d\varepsilon)_{plain}$	plain concr. specimen	compress. strain 0.020
Shah, et al. 1987 [26]	relative [5]	TI_{aging}	(A+B)/(A'+B')	un-aged specimen	entire response

13.4.3 Other properties

Splitting tensile strength:
- the "Brazilian" test on cores ϕ60 mm. It is important that the surfaces are straigth without undulations. 23

Direct tensile test:
- on cores ϕ60 -80 mm. Preferably 80 mm to reduce the scatter. 23
- on samples 100x100x600 mm (28d) 29

Density:
- by weighing and hydrostatic weighing after application of paraffin. 23

Thickness:
- tested by drilling holes. The placing may be specified using a template, according to Swedish standard, FIG 6.
- alternatively: 28
  - by sticking a pricker through the fresh shotcrete
  - by applying distance pins in the first shotcrete layer

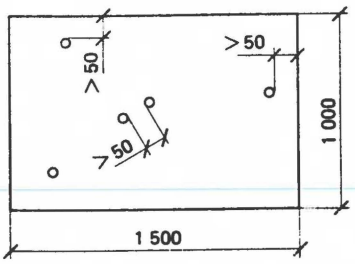


FIG 6. Template used when testing thickness of shotcrete lining, according to Swedish standard /20/.

Bond:

- preferably performed in laboratory on cores o80 mm.	23
- measured on a random 1 m^2 surface area of the tunnel lining. 6 cores are tested earliest after 10 days. The cores are wrapped in plastic sheet before being taken to a laboratory. The mean centric tensile strength are measured at age $\geq$ 14 days.	26
- measurement of bond may be stopped if the bond strength > 1.5 MPa.	2
- controlled by knocking. If there are non-bonded areas, the reason shall be investigated and the need of additional support evaluated.	28

Watertigthness:

- tested on cores, ϕ150 mm and h=120 mm, from shotcrete panels according to DIN 1048.	2

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/2/ DIN 18551- Shotcrete, production and quality control. March 1992.

/3/ SANCOT Working Group- Shotcrete specification on Inanda-Wiggins Aqueduct, South Africa. Corresp Aug-1991

/4/ ASTM C 1018-89 - Standard Test Method for Flexural Toughness and First Crack Strength of Fiber Reinforced Concrete

/5/ ASTM C 1116.89 - Standard Specification for Fiber Reinforced Concrete and Shotcrete

/6/ Vandewalle M, N.V Bekaert S.A, Tunneling the world,1991

/7/ Swedish Railroad Department- Tender document on railway tunnel project "Hallandsåsen" - 1991

/8/ Kasperkiewicz J, Skarendahl Å - Toughness estimation in FRC composites. CBI Report 4:90, Stockholm 1990

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/25/ Tiefbau- Berufsgenossenschaft. Unfallsverhütungsvorschrift. Bauarbeiten. Aprill 1985.

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/30/ The Sprayed Concrete Association - Guidelines and Specifications. Okt.1986. Re-printed Sept.1990.

/31/ The Swedish National Resque Service Board - Tender document.

APPENDICES

There are few documents which really describe a relevant basis for design of shotcrete lining in cases where it is not obviously working as an ordinary structural member, like an arch, a beam or a plate with defined supports. Still it is of interest to illustrate this compliation with some references to publications on this issue.
Different approaches for design of shotcrete and examples of correlations to different rock classification systems, are presented in Appendix 1 and 2.
Appendix 3 and 4 give some examples for items and tender documents.

APPENDIX 1

DESIGN MODELS AND SHOTCRETE CLASSIFICATIONS

According to Wandevalle, the most important effect of lining construction is to secure full, continous contact between the lining and the ground movements, and not to carry ground loads. The most efficient tunnel lining is one that mobilises the strength of the ground, permitting controlled ground deformations. For multistage linings, the initial construction support is very flexible compared to ground, and can absorb large flexural deformations associated with redistribution of ground stresses. 6
Selection of the type of lining depends on excavation methods that are suited to ground characteristics and design must account for large uncertainties and variations in ground conditions, construction procedures and ground behaviour during construction.

Two models for lining function depending on the rock quality are presented in based on the comprehensive tests performed on wet-process shotcrete in Norway. 6 22

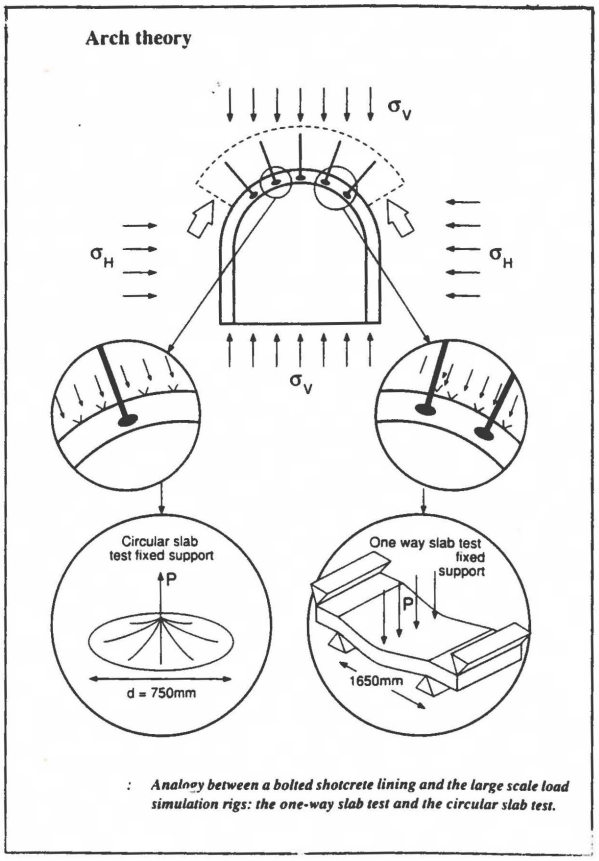
- The arch theory (in medium-bad rock) FIG 7. Important shotcrete properties are high flexural strength and great ductility e g NATM.
- The falling block theory (in hard rock when good bonding is achieved) FIG 7. Important shotcrete properties are good bond and high shear strength.

In both cases a fast development of the required properties is essential.

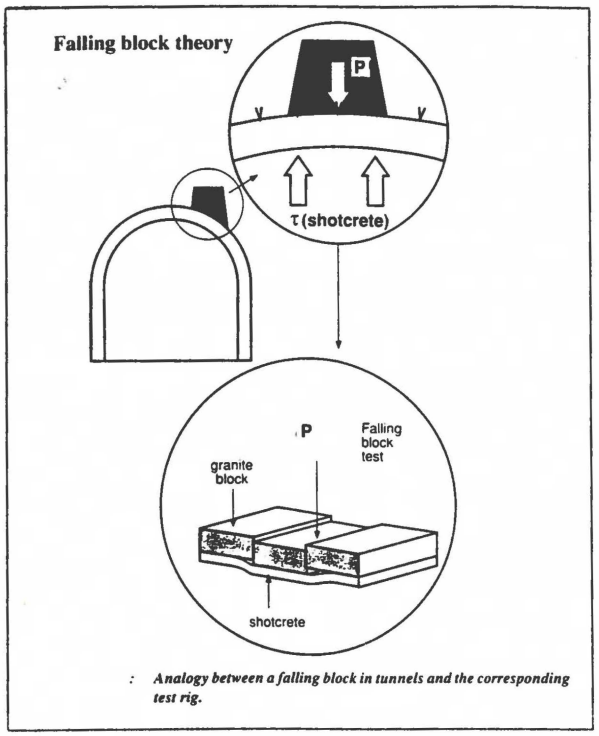
The requirements on bond and ductility are also discussed by Stille et al, who stated that 12

- no requirements on bond are necessary if the strength and ductility properties, that is the bearing capacity, of the lining exceeds the actual loads and deformation situations after the primary adhesive failure.
- on the contrary- if the bond is complete, then there is no need for reinforcement or ductility.

The safety margin against adhesive failure and bending failure is illustrated in FIG 8.



: *Analogy between a bolted shotcrete lining and the large scale load simulation rigs: the one-way slab test and the circular slab test.*



: *Analogy between a falling block in tunnels and the corresponding test rig.*

FIG 7. Principles for the arch theory and the falling block theory according to /6/ and /22/.

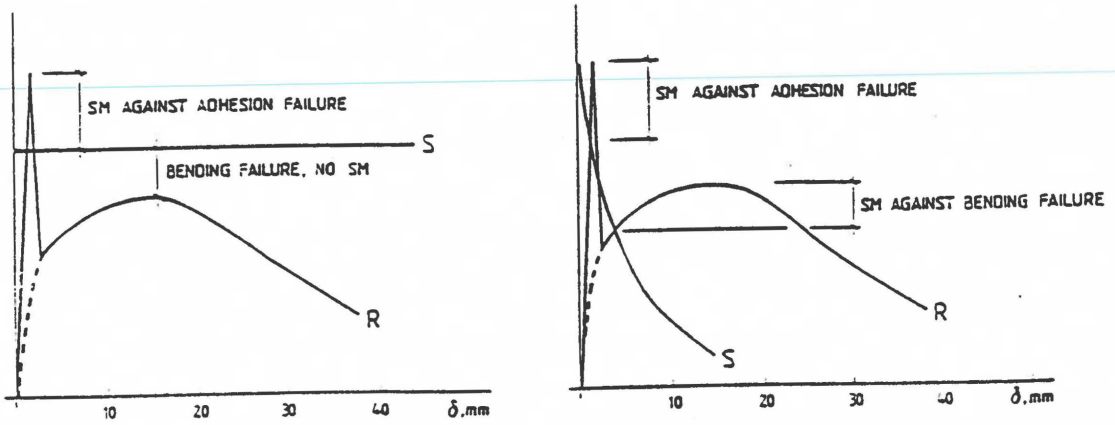


FIG 8. Safety margins (SM) depending on the development of the load (S) with increasing deformation./12/.

Vandewalle also gives some examples of design of fibre-reinforced shotcrete linings compared with normally reinforced linings for linings combined with systematic rock bolts, thus supposing 6
- the bearing capacity is independant of the bond properties
- the calculation may be made according to the same principles as slabs and pillars
- systematic bolting is also required for other reasons

The examples are presented in Appendix 2.

Recommendations linking the actual load situation to the design of the shotcrete lining are few, but some empirical rules of design are presented in /6/ TABLE 28.

According to the Norwegan draft, the application of shotcrete shall be advised by the tunnel geologist, that is, the place and the thickness. 28

There is also a table from an actual contract where both normally reinforced and fibre reinforced linings are linked to different rock qualities and rock bolt placing. The rock qualification was based on the Norwegian Geotechnical Institute "Q" system. TABLE 27.

TABLE 27. Different rock support designs for different rock quality classes and bolt placing./6/

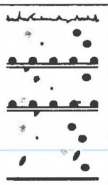
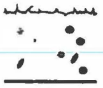
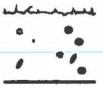
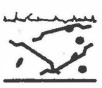
Category	C2	C1	B2	B1*	B0*	A
Q value	1-0,1	4-1	10-4	40-10	40-15	>40
Bolt c/c (m)	1.0	1.0	1.5	1.5	2.0	As necessary
Shotcrete thickness (mm)	 200+mesh	 100+mesh	 100+mesh	 50	 50	As necessary
SFRS thickness (mm)	 135	 65	 65	Not used	Not used	Not used
* Category Bo if $\frac{RQD}{jn}$ > 10 over 90% of arch						

TABLE 28. Empirical rules for design of shotcrete linings in loosening ground /6/

Alberts 1965	
Swedish rules from local experience	
Criteria	**Thickness**
Initial application immediately after blasting if the rock is heavily jointed.	3-8 cm
Total thickness applied if roof falls or deterioration is observed	10-15 cm

Kobler (1966)	
Experience from large highway tunnels	
Condition	**Applied Shotcrete Thickness**
Normal	15 cm thick at crown and tapered out below springline.
Slide pressures	Same as above plus 5-10cm carried down the walls.

Cecil (1970)		
Rock quality parameter		
RQD	**Average discontinuity spacing**	**Support requirements**
60 %	< 30cm	**Maximum**: multiple shotcrete application (1); cast concrete arches; combinations with spot bolts.
60-80%	30cm-1m	**Intermediate**: medium (2-5 m) to closely (<2m) spaced spot bolts; single shotcrete application; combined spot bolts and one shotcrete application.
80%	> 1m	**Minimum**: unsupported or medium (2-5m) to widely (>5m) spaced spot bolts.

(1) A single shotcrete application is a 4-6cm thickness; multiple applications refer to a repeated application of layers of this same thickness.

Heuer (1974)	
Temporary support under loosening loads(1)	
Ground condition	**Shotcrete application**
1. **Good ground:** where support problems are minimal, but for one reason or another a "bald-headed" tunnel is considered unacceptable. RQD commonly > 75%.	5 cm shotcrete in arch above springline.
2. **Fair ground:** Where the rock is more closely jointed or broken and the arch definitely needs some support, but sidewalls are stable. Ground allows good bond of shotcrete to excavation perimeter. RQD commonly 50 to 75 %.	7-8 cm shotcrete in arch, feather out below springline.
3. **Poor ground:** Where tunnel walls tend to travel some, or where a good shotcrete bond to rock cannot be archieved. RQD commonly 25 to 50%.	8-10 cm shotcrete in arch. 7-8cm shotcrete on walls. Carry to base of walls in horseshoe tunnels. On circular tunnels, wall coverage required depends on quality of shotcrete bond to rock. If bond is of fair quality, may need only upper 270° shotcrete coverage. If bond is very poor, need full 360° coverage.
4. **Very poor ground:** If support problems are truly loosening loads, treat as above for poor ground but add another 2-3 cm of shotcrete, giving 10-12 cm in arch. ±10 cm on walls.	

(1) For tunnel diameters of 4-6 m

Other documents classify the shotcrete quality for different applications wihout any reference to a rock classification.
The Austrian guideline classify the shotcrete in three classes

- SC I : For surface finish and for rock mass sealing
- SC II : For stabilization and support of temporary outer linings and for slope stabilization. The concrete cover of reinforcement is determined according to purpose of use. The "young" shotcrete must fulfill the ranges J1 or J2 (see 4.3) and attention should be paid to the degree of strength loss.
- SC III: For structural functions according to ÖNORM. Requirements mainly concern strength, but other properties as watertightness, chemical resistance etc may also be important. Special measures have to be taken to ensure the denseness and homogenity of the shotcrete. Liquid accelerators should be used. Aggregate size 12 mm is recommended The concrete cover must not be less than 3 cm.

The guideline also gives examples concerning the way of defining the grades of shotcrete, TABLE 29.

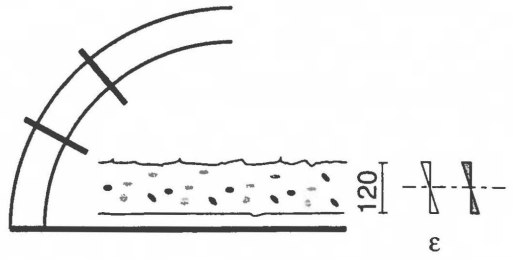
TABLE 29. Examples for grades of shotcrete /10/
WU=watertightness, GK=maximum size
FTB=resistance to frost thaw cycles
TST=sulfate atac

Purpose and requirements	Concrete grade according to ÖNORM B 4200, Part 10
1. Shotcrete for the temporary outer lining of a road tunnel (medium rock mass conditions)	SC 19/II/J_1
2. Shotcrete for the permanent lining of a headrace tunnel	SC 22.5 (90)/III/WU
3. Shotcrete for the outer lining of an underground railway with sulfate attack	SC 25 (56)/III/J_2/ WU/TST/GK11
4. Shotcrete as a base for sealing strips	SC 12/I/GK11
5. Shotcrete for repair work of bridges, reprofiling mortar	SC 30/III/FTB/GK4

APPENDIX 2

EX 1: Comparative design: Plain shotcrete layer vs Dramix reinforced shotcrete layer./6/

Design of the plain shotcrete layer



$$M_p = \frac{f_u}{s} \cdot b \cdot \frac{d^2}{6}$$

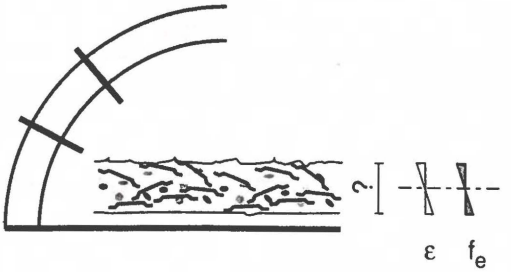
whereby M_p = bending moment (Nm/m)
f_u = plain shotcrete flexural strength (N/mm²)
s = safety factor
b = width of loaded area (mm)
d = total shotcrete layer thickness (mm)

for f_u = 4 N/mm²
s = 3
b = 1.000 mm
d = 120 mm

$$M_p = \frac{4}{3} \cdot 1000 \cdot \frac{120^2}{6}$$

= 3.200.000 Nmm/m
= 3.200 Nm/m

Design of Dramix reinforced shotcrete layer



$$M_{D,p} = f_e \cdot b \cdot \frac{d^2}{6}$$

whereby $M_{D,p}$ = M_p = bending moment (Nm/m)
f_e = equivalent flexural strength of Dramix shotcrete (N/mm²)
b = width of loaded area (mm)
d = total layer thickness (mm)

for $M_{D,p}$ = 3.200 Nm/m
b = 1.000 mm
f_e = 0.65 f_u for 40 kg/m³ Dramix ZP 30/.50 (Fig. 2)
f_u = 4 N/mm²
f_e = 0.65 x 4 = 2.6 N/mm²

$$d^2 = \frac{6 \cdot M_{D,p}}{f_e \cdot b} = \frac{6 \times 3\,200\,000}{2.6 \times 1\,000}$$

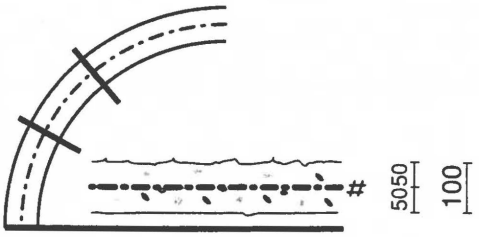
= 7.385 mm²

d = 86 mm

APPENDIX 2

EX 2: Comparative design: 1 mesh reinforced layer vs Dramix reinforced layer /6/

Design of the 1 mesh reinforced layer



Due to the irregular position of the wire mesh within the shotcrete layer, it is recommended to consider the mesh position in the center of the layer. In this case only half the layer thickness can be taken into account, as the upper part will be working when compressive stresses act in the outer half and the lower part in case compressive stresses are induced in the inner half.

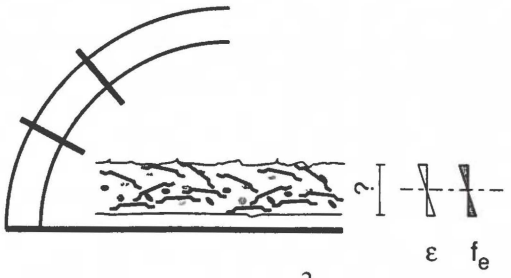
$$M_{m.u} = 0.9 \cdot \frac{d}{2} \cdot A_s \cdot \sigma_{s.u}$$

whereby

$M_{m.u}$ = ultimate bending moment (Nm/m)
d = total layer thickness (mm)
A_s = steel wire mesh cross section (mm^2/m)
$\sigma_{s.u}$ = ultimate tensile strength of mesh steel wires (N/mm^2)

for d = 100 mm
A_s = 31 mm^2 (# 150/5)
$\sigma_{s.u}$ = 460 N/mm^2
$M_{m.u}$ = 0.9 x 50 mm x 131 mm^2/m x 460 N/mm^2
= 2.711.700 Nmm/m
= 2.712 Nm/m

Design of Dramix reinforced shotcrete layer



$$M_{D.1m} = f_e \cdot \frac{b \cdot d^2}{6}$$

whereby

$M_{D.1m} = M_{m.u}$ = bending moment (Nm/m)
f_e = equivalent flexural strength of Dramix shotcrete (N/mm^2)
b = width of loaded area (mm)
d = total layer thickness (mm)

for $M_{D.1m}$ = 2.712 Nm/m
b = 1.000 mm
f_e = 0.65 f_u for 40 kg/m^3 Dramix ZP 30/.50 (Fig. 2)
f_u = 4 N/mm^2
f_e = 0.65 x 4 = 2.6 N/mm^2

$$d^2 = \frac{6 \cdot M_{D.1m}}{f_e \cdot b} = \frac{6 \times 2.712.000}{2.6 \times 1.000}$$

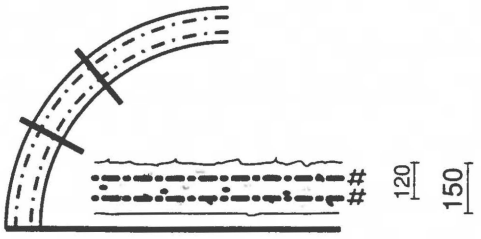
$$= 6.258 \text{ mm}^2$$

d = 80 mm

APPENDIX 2

EX 3: Comparative design: 2 mesh reinforced layer vs Dramix reinforced layer./6/

Design of the reinforced shotcrete layer



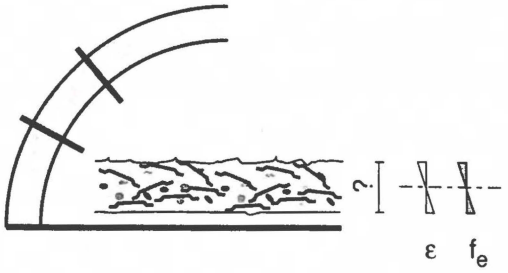
$$M_{2m.u} = 0.9 \cdot h \cdot A_s \cdot \sigma_{s.u}$$

whereby
- $M_{2m.u}$ = ultimate bending moment (Nm/m)
- h = d - a (mm)
- d = shotcrete layer thickness (mm)
- a = shotcrete cover of wire mesh (mm)
- A_s = steel wire mesh cross section (mm^2/m)
- $\sigma_{s.u}$ = ultimate tensile strength of steel mesh wires (N/mm^2)

for
- d = 150 mm
- a = 30 mm
- h = 150 - 30 = 120 mm
- A_s = 126 mm^2/m (# 100/4)
- $\sigma_{s.u}$ = 460 N/mm^2

$M_{2m.u}$ = 0.9 x 120 mm x 126 mm^2/m x 460 N/mm^2
= 6.259.680 Nmm/m
= 6.260 Nm/m

Design of Dramix reinforced shotcrete layer



$$M_{D,2m} = f_e \cdot b \cdot \frac{d^2}{6}$$

whereby
- $M_{D,2m}$ = $M_{m.u}$ = bending moment (Nm/m)
- f_e = equivalent flexural strength of Dramix shotcrete (N/mm^2)
- b = width of loaded area (mm)
- d = total layer thickness (mm)

for
- $M_{D,2m}$ = 6.260 Nm/m
- b = 1.000 mm
- f_e = 0.65 f_u for 40 kg/m^3 Dramix ZP 30/.50 (Fig. 2)
- f_u = 4 N/mm^2
- f_e = 0.65 x 4 = 2.6 N/mm^2

$$d^2 = \frac{6 \cdot M_{D,2m}}{f_e \cdot b} = \frac{6 \times 2.260.000}{2.6 \times 1.000}$$

$$= 14.446 \text{ mm}^2$$

d = 120 mm

APPENDIX 3

EX 1: Item "Shotcrete" for tunnel driving in rock /10/

Shotcrete **SC 22.5/II/J2/GK11,** minimum thickness: 10 cm, must be produced using cement in accordance with item 3.1 of this guideline as a binder, and placed as a support of the excavation.

The costs of cleaning the substrate by compressed air or pressure water - wherever necessary - and of filling unavoidable overbreak as well as difficulties deriving from the spraying of system-related reinforcement must be included in the unit price.

All auxiliary work according to ÖNORM B 2203, the costs of the preliminary, quality and hardening tests according to the enclosed table (examples are given in Appendix 2) as well as the costs of refilling drill holes after coring must also be included in the unit price.

The specified shotcrete thickness is the minimum thickness (with the exception of firm rock edges).

Arris and edges of the rock surface must be rounded by shotcrete.

The payment of shotcrete work is based on the theoretical surface area according to the drawings or the Client's instructions. With curved surfaces, the theoretical excavation line is taken account of.

For checking the shotcrete thickness, one drilling must be executed every 50 m². No separate payment for this work.

If the shotcrete falls short of the specified strength, the theoretical thickness "d" of the shotcrete must be increased by the value "d_1" without separate payment according to the following formula:

$$d_1 = (\frac{F}{m} - 1) \cdot d$$

with F being the specified strength in N/mm², m being the measured strength in N/mm², d being the specified shotcrete thickness in cm, d_1 being the extra thickness in cm.

If the shotcrete falls short of the specified strength, it will be left to the Client's discretion either to demand an extra concrete thickness or to reduce the payment for the shotcrete work, namely by 2 % of the unit price for every percentage point the shotcrete falls short of the specified strength, based on the values determined from test cores.

labor cost .....

product cost .....

..... m² unit price .....

APPENDIX 3

EX 2: Item "Shotcrete" for tunnel driving in loose ground /10/

Shotcrete **SC 22.5/III/J_1**, minimum thickness: 12 cm, must be produced using cement in accordance with item 3.1 of this guideline as a binder, and placed as a support of the excavation slopes.

The costs of the required scaffolding, the preparation of the substrate as well as difficulties deriving from the spraying of system-related reinforcement must be included by the Contractor in the unit price.

All standard auxiliary work, the costs of the preliminary, quality and hardening tests according to the enclosed table (examples are given in Appendix 2) as well as the costs of refilling drill holes after coring must also be included in the unit price.

Concrete curing by means of a curing agent in accordance with RVS 11.064, sheet 2 must be included in the price.

The payment of shotcrete work is based on the theoretical surface area according to the drawings or the Client's instructions. With curved surfaces, the theoretical excavation line is taken account of.

For checking the shotcrete thickness, one pin must be placed and sprayed every 20 m². No separate payment for this work.

The supply and installation of reinforcement will be remunerated separately.

labor cost .....

product cost .....

..... m² unit price .....

EX 3: Item "Shotcrete" for open caisson foundation and slope stabilization /10/.

Shotcrete **SC 25 (56)/II/J2/WU/TST/GK11,** minimum thickness: 15 cm, must be produced using cement with strong resistance to sulfate attack, liquid AC and fly ash in accordance with item 3.1 of this guideline, and placed as a support of the excavation.

The costs of additional concrete cubage due to overbreak (unless ordered) as well as difficulties deriving from the spraying of system-related reinforcement must be included by the Contractor in the unit price.

All auxiliary work according to ÖNORM B 2203, the costs of the preliminary tests according to the enclosed table (examples are given in Appendix 1) as well as the costs of refilling drill holes after coring must also be included in the unit price.

The Client will bear the expenses for the quality and hardening tests.

The payment of shotcrete work is based on the theoretical surface area according to the drawings or the Client's instructions. With curved surfaces, the theoretical excavation line is taken account of.

For checking the shotcrete thickness, two pins must be placed and sprayed every 50 m². No separate payment for this work.

labor cost .....

product cost .....

..... m² unit price .....

APPENDIX 4

Details to be included in tender specifications according to Austrian guideline /10/

- The pertinent Austrian standards (ÖNORM) and the guideline "Shotcrete" are valid.
- By means of appropriate control measures, it must be ensured that the tender specifications regarding the clearance of the underground opening are complied with including a certain tolerance.
- Additional concrete cubage due to overbreak, unless ordered or as a result of the geological conditions, as well as difficulties deriving from the spraying of system-related reinforcement (wire mesh, steel arches, liner plates, rock bolts, etc.) must be included by the contractor in the tender price.
- Defects of structural shotcrete (unless system-related) must be repaired.
- Projecting, firm rock edges being part of the rock mass must be covered with only one third of the specified shotcrete thickness.
- The number of preliminary, quality and hardening tests must be adapted to the volume of shotcrete work (details should be presented in tables, see *Appendices 1* and *2*).
  It must be stated who will bear the costs of the preliminary, quality and hardening tests.
- The following details should be included in the specifications (see *Appendices 4, 5* and *6*):
  - type of concrete
  - shotcrete thickness, minimum thickness and checks (e.g. by means of pins incorporated in the shotcrete or drillings)
  - special specifications with regard to the concrete composition, e.g. types of cement, additives, accelerator and other admixtures
  - details on curing
  - definition of the payable surface (e.g. measured from the excavation line)
  - arrangements in case of inferior quality and insufficient concrete thickness (Note: RVS 8.25 is currently being revised)
  - concrete cover
  - dimensional units considered for settling the accounts (m^2 or m^3, in special cases also the quantity of the dry mix)

APPENDIX 4

Example on shotcrete specification according to Swedish tender document /14/

Swedish tender documents /14/ specify the following shotcrete alternatives

- unreinforced shotcrete. Nominal thickness 30 mm (one layer) or 50 mm (two layers)
- reinforced shotcrete. Nominal thickness 80 mm
- reinforced shotcrete. Nominal thickness 100-120 mm
- reinforced shotcrete beam. Nominal thickness 250 mm
- fibre reinforced shotcrete with possible adhesion to rock. Nominal thickness 60 mm.
- fibre reinforced shotcrete without adhesion. Nominal thickness 90 mm.

Requirements are defined on

- compressive strength: > 40 MPa
- density: >2200 kg/m^3
- watertightness: According to Swedish standard
- thickness: acceptable variation $\pm$ 10%.
- adhesion: Shotcrete-rock: $\geq$ 0.5 MPa
  Between layers= tensile strength: $\geq$1.0 MPa

For fibre- reinforced shotcrete as well

- toughness, tested according to ASTM C 1018 Swedish praxis:

$R^{5,10}_{100}$ xf_s $\geq$5.0 MPa (preconstruction test)

$\geq$4.5 MPa (routine tests)

$R^{10,30}_{100}$ xf_s $\geq$3.0 MPa (preconstruction tests)

$\geq$2.5 MPa (routine tests)

- fibre content: by wash out method. To be documented.