[Editor's note: *As the national Swedish group of the International Tunnelling Association (ITA), SveBeFo (the Swedish Rock Engineering Research) has compiled a report of different countries' regulations and recommendations with regard to shotcrete for rock support.* ***This report is not to be regarded as a scientific evaluation of the material provided by the different countries, nor should it be viewed as recommendations, by the ITA or the author, regarding shotcrete use.*** *Rather, it is a compilation of the most important parts of some selected references, and is intended as a reference source for those who are to make specifications for shotcrete support.*

The report as published herein ***does not*** *include several appendices that are provided in the full report (83 pp.), which is available from the Swedish Rock Engineering Research - SveBeFo, P.O. Box 49153, S-100 29 Stockholm, Sweden. The cost of the report is SEK 400.-.*]

Shotcrete for Rock Support: a Summary Report on the State of the Art in 15 Countries

International Tunnelling Association Working Group on Shotcrete Use
Prepared by Swedish Rock Engineering Research (Bo Malmberg, author)

Abstract—*This ITA Report is a compilation of guidelines from 15 countries on materials and mix design, production and performance of shotcrete, as well as national guidelines concerning quality control and test methods. The report also deals with the extent and requirements of both preconstruction tests and routine tests, and applicable test methods. It should be observed that although the report itself does not put forth recommendations, it presents a summary of what is generally official recommended or suggested practice in different countries today.*

Résumé—*Ce rapport de l'AITES est un recueil de directives de 15 pays sur le sujet du dimensionnement des matériaux et du mortier, la production et la qualité du béton projété, ainsi que les directives concernant des méthodes d'essais et de contrôle de la qualité. Le apport traite aussi des besoins, à la fois en tests de préconstruction et de routine et en méthodes de test d'application. Il sera intéressant de noter que bien que le rapport en lui-même n'avance aucune recommandation, il présente un consensus pratiques actuelles officiellement recommandées ou suggérées dans divers pays.*

Foreword

The International Tunnelling Association (ITA) Working Group on Shotcrete Use was formed at the ITA meeting in Toronto, Canada, in 1989. The group's first task was to implement a status report on shotcreting technology in different countries.

Two years later, the report "Shotcrete in Tunnelling—Status Report 1991" was published. The primary aim of the 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 also were 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. This would be valuable, for example, with regard to possible normative work within the EC (European Community) norms in the construction area.

The Swedish national group of the ITA, the Swedish Rock Engineering Research Foundation (BeFo; now SveBeFo) took on the responsibility for this work. The task was entrusted to Bo Malmberg, M.Sc., of the Swedish firm AB Jacobson & Widmark. Mr. Malmberg has many years of experience in the field of shotcreting technology, particularly with regard to the composition of shotcrete mixtures, including additives and fibres.

This report is not be regarded as a scientific evaluation of the material provided by the 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 includes a few personal comments.

It also should be noted that some of the references used were in the draft stage (e.g., the Norwegian guidelines and specifications of the European Federation of the National Association of Special Repair Contractors and Material Suppliers [EFNARC]), whereas

Present address: T. Franzén, Swedish Rock Engineering Research - SveBeFo, P.O. Box 49153, S-100 29 Stockholm, Sweden.

0886-7798/93 $6.00 + .00

some others are officially established national regulations.

This compilation is intended to serve as a reference for those who are involved in making specifications for shotcrete support, as well as to inspire and inform 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, also involving concrete technology. Thus far, no technical committee on shotcrete has been established within the CEN [Commité Européen de Normalisation] organization. Therefore, it is vitally important that the tunnelling community be aware of and participate in any planned work in this respect.

It is the hope of the ITA Working Group on Shotcrete Use that this report will serve as a basis for further enhancement of shotcrete technology, and the exchange of information in this field within the international tunnelling community.

—*Tomas Franzén, Animateur, ITA Working Group on Shotcrete Use*

1.0 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 performed at the request of the ITA Working Group on Shotcrete Use.

The aim of the work is to present a summary of what is generally considered officially recommended practice in different countries today.

This compilation is mainly based on documents received from different members of the Working Group at the request of BeFo in 1991, and on complementary documents received at and after the ITA conference in Acapulco in May 1992.

The author has primarily compiled and put in order different quantified and, preferably, measurable recommendations or standards for a variety of properties of shotcrete, without attempting any deeper analysis concerning the reasons for the reported values.

The list of references is as extensive as possible, so that readers may find further information in current publications.

It is hoped that this compilation will serve as a basis for further discussions concerning reasonable recommendations and standards on shotcrete.

2.0 National Work in Progress on Shotcrete

Before examining the various recommendations, it may be useful to provide an overview of the work on shotcrete that is now underway or that has been recently carried out, as well as existing guidelines for different countries. This overview is mainly based on information provided in the Working Group's status report to the International Tunnelling Association in 1991 (ITA 1991).

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

Austria. The Austrian Concrete Society has established 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, reference is made to documents presented by ASTM, ACI and CSA (Canadian Standards Association).

Finland. Finland has no permanent working group on shotcrete. Working groups are established for special purposes when the need arises. Finland's "Guidelines for Shotcreting" (1991) are intended for shotcreting in rock engineering applications. The Guidelines represent the measures by which a good technical and economical result can be obtained; and also deal with aspects of working safety. The Guidelines can be included in contract documents, but do not replace specifications for an actual job. They consist of recommendations, which are not official standards.

France: Working Group No. 6 ("Shotcrete") of the Association Française des Travaux en Souterrain (AFTES), drafted the AFTES "Recommendations on Technology and Application of Shotcrete" in 1974. In 1989, the Working Group was asked to update existing texts and to draft a recommendation on the use of fibre-reinforced shotcrete. The group's recommendations were published by AFTES in 1992.

Germany: Existing working groups are:

- The Working Group Shotcrete-DIN 18551, of the German Committee on Concrete (DAfStb);
- Committee for National Railway Standards-DS 853 Shotcrete, of the Central Department of the National Railway (BZA);
- Working Group "Steel-Fibre-Reinforced Shotcrete" of the German Concrete Institute (DBV).

The most recently presented German guideline is the handbook "Stahlfaserbeton", which was published in 1991. This reference was not available for use in this compilation.

Italy: Società Italiana Gallerie (SIG) has established a working group on shotcrete. The group has been divided into five subgroups, dealing with the following topics:

1. Characteristics of shotcrete for structural use;
2. Mix design (criteria): aggregate, cement, tests, and research on the behaviour of green concrete;
3. Additives, admixtures and fibres;
4. Equipment and safety in works;
5. Items for contract and tender specifications.

Japan: The Japan Tunnelling Association has a working group on shotcrete. Existing standards and guidelines are:

- "Tunnelling Standard Specification", published by the Society of Civil Engineers (JSCE) in 1986 (in Japanese);
- "Standard Specifications for the Design and Construction of Concrete Structures", published by the JSCE in 1986 (in English);
- "Recommendations for the Design and Construction of Steel-Fibre-Reinforced Concrete", published by the JSCE in 1983 (in Japanese);
- "NATM Guideline for Design and Construction", published by the Japan Railway Construction Public Corporation in 1983 (in Japanese);
- Construction Manual for Civil Engineering Work, published by the Japan Highway Public Corporation (JHPC) in 1989 (in Japanese);
- "Guideline for Construction", published by the JHPC in 1987 (in Japanese);
- "Guidelines for Steel-Fibre-Reinforced Concrete", published by the Japan Tunnelling Association (JTA) in 1980 (in Japanese).

Norway: A 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; it is expected to be adopted as an official recommendation in 1993.

South Africa. The South African National Council on Tunnelling (SANCOT) has 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 workers from rebound material, insufficient lighting, and dust levels. The latter specifications are mainly based on specifications of the ACI, ASTM and certain Canadian sources, though existing specifications of the South African Bureau of Standards (SABS) have been substituted where possible.

Sweden: No national working group exists with particular interest in shotcrete. Nor does any formally adopted guideline exist, although some major clients have established their own routines and guidelines. In addition, there are some recommendations in the Swedish "Concrete Handbook".

A new "Handbook on Shotcrete", prepared by the Swedish State Power Board, was published in 1992 (in Swedish).

Switzerland: The SIA Standard 198 is currently undergoing revision.

U.K. No standards exist in the U.K. with regard to shotcrete technology. Each contract has its own specification, based on those developed on the Channel Tunnel project.

U.S.A. The most active organization is the Shotcrete Committee of the American Concrete Institute (ACI-506), which has developed numerous standards and guidelines on shotcrete. In addition, the ASTM has established a subcommittee to:

- assemble and study shotcrete properties;
- develop test methods; and
- formulate standards for shotcrete.

In 1992, the Underground Technology Research Council (UTRC) of the American Society of Civil Engineers, together with ACI-506, created a UTRC-ACI Underground Shotcrete subcommittee, which will work closely with the ITA Working Group on Shotcrete, in addition to addressing shotcrete issues in the U.S.

Work of Other Organisations. A draft publication concerning shotcrete was published by EFNARC-TC-Sprayed Concrete Committee in 1992.

The Sprayed Concrete Association has presented separate general recommendations for wet process sprayed concrete and dry process sprayed concrete (Sprayed Concrete Association 1990).

The following compilation of shotcrete recommendations is based on information from some of the countries listed above. A general view of the types of documents received from the different countries is given below:

- Guidelines from Japan, Austria, Finland, Germany, the U.S.A., and Norway.
- Standards from Germany, South Africa, and U.S.A.
- Tender documents from Sweden and South Africa.
- Articles and literature from Canada, Belgium and Sweden.

3.0 Materials

3.1 Cement

Cements for shotcreting generally should fulfill demands for normal standard or rapid-hardening Portland cement according to national standards, as, for example:

- DIN 1164
- ÖNORM B 3310 (Austria)
- ASTM C 150
- SABS 471 (South Africa)
- CEN standard EN 197 or national standard, according to EFNARC draft (1992).

Other types of cements may also be used, e.g., according to ASTM C595 (Blended Hydraulic Cements).

Some quantified data concerning cement for shotcrete are given in Tables 1 and 2.

Table 2. Guidelines for standard compressive strength of cement, in MPa, according to the Japan Tunnelling Association (1986); and the Austrian Concrete Society (1990).

Days	Austria*	Japan
1	≥ 7	-
	≥ 9**	-
3	-	≥ 7
7	-	≥ 15
28	≥ 39	≥ 30
90	≥ 50	-

* 5% fractile
** (normal shotcrete)

The American Concrete Institute (ACI 1983) recommends:

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

The Norwegian draft for shotcrete guidelines prescribes the use of sulfate-resistant cement when there is a risk of sulfate attacks, but only if there is no simultaneous risk of chloride attacks (Norwegian Concrete Association 1992).

Swedish tender documents prescribe the use of sulfate-resistant cement only (Swedish Railroad Department, 1991a

Table 1. Austrian Concrete Society and Japan Tunnelling Society guidelines on cement specifications for shotcrete.

Specification		Reference Source
Start of setting time:	1.5–4 hrs.	(Austrian Concrete Society 1990)
Start of setting time:	≥ 1 hr.	(Japan Tunnelling Association 1991)
Fineness of grind:	3500–4500 cm^2/g	(Austrian Concrete Society 1990)
Fineness of grind:	≥ 2500 cm^2/g	(Japan Tunnelling Association 1991)
Bleeding:	≥ 20 cm^3	(Austrian Concrete Society 1990)
C_3A content: • ≤ 3% if SO_4^{2-} content of water exposed to concrete > 400 mg/l • As low as possible (highly sulfate-resistant cement) if SO_4^{2-} content > 1000 mg/l		(Austrian Concrete Society 1990)
Alcali content ($Na_2O + 0.65K_2O$): ≤ 0.6%		(Japan Tunnelling Association 1991)
If required: Test influence of the temperature and of the chemical composition of the cement on the reaction time.		(Austrian Concrete Society 1990)
Cement temperature ≤ +70°C when filled into silo on site		(Austrian Concrete Society 1990)

and 1991b). Other documents prescribe the use of sulfate-resistant cement or, alternatively, rapid-hardening cement, although the latter is not sulfate-resistant (Stockholm City Streets and Traffic Administration 1990).

French recommendations (AFTES 1992) prescribe that the validity of the cement selected should be demonstrated in the presence of:

- Acid water.
- Water that is not highly mineralized.
- Polluted water.

3.2 Aggregates

Most recommendations concerning aggregate refer to ordinary national standards for concrete aggregates (cf. DIN 4226, ASTM C33, C330, C637, SABS 1083 [South Africa], and BS 822).

In Austria (Austrian Concrete Society 1990), the choice of aggregate is linked to the type of shotcrete used, i.e.:

- For types SCII (supporting concrete) and SC III (structural concrete), only segregated aggregates are allowed. The segregation should take place every 4 mm. Maximum size recommended to 16 mm, although 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.

Other specific recommendations regarding aggregates suitable for shotcreting are given in Table 3 and Table 4.

According to the EFNARC draft (1992), the chloride content is regulated by CEN standard ENV 206, and the alcali content by national standards.

3.3 Additives

3.3.1 Fly ash

In 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 (JCI 1991). Recommendations regarding fly ash are given in Table 5.

Table 3. Recommended aggregate gradation, according to different sources.

Sieve (mm)	Percent, by Weight, Passing Sieve Size (mm)				
	Wet Mix		Dry Mix	Not Specified[1]	
	8	16	16	8	16
32	100[2]	100[3]	100[3] 100[4]	100[5] 100[6]	100[5] 100[6]
16	100	85–100	80–100 85–97	100 100	100 100
8	90–100	70–100	56–100 66–81	100 100	60–88 71–88
4	73–100	58–99	40–100 46–66	61–85 68–80	36–74 51–69
2	55–90	42–78	28–58 20–50	36–71 48–63	21–62 38–52
1	37–72	30–56	18–32 18–30	21–57 32–48	12–49 28–40
0.5	22–50	19–38	10–20 8–20	14–39 20–30	8–34 18–30
0.25	11–26	10–25	4–11 7–18	5–21 10–16	3–18 10–19
0.125	4–12 4–6[7]	8–15	3–10 3–10	3–9 5–10	1–9 7–10

(1) Probably for dry mix shotcrete.
(2) According to Norwegian draft (Norwegian Concrete Association 1992).
(3) According to Swedish Concrete Handbook.
(4) According to American Concrete Institute 1983.
(5) According to DIN 1045.
(6) According to AFTES 1992.
(7) According to Japanese guidelines (Japanese Tunnelling Association 1991).

Table 4. Specifications for coarse aggregate and sand used for shotcrete.

Coarse Aggregate	Specification	Reference Source
• Maximum aggregate size:		
Dry mix shotcrete:	16 mm	Japan Tunnelling Association 1991
	normally 10 mm (possibly 20 mm)	Sprayed Concrete Association 1990
Wet mix shotcrete:	8 mm	Japan Tunnelling Association 1991
	16 mm	Sprayed Concrete Association 1990
No single fraction > 30% of total aggregate		Norwegian Concrete Association 1992
Specific gravity	≥ 2.5 kg/dm^3	Japan Tunnelling Association 1991
Water absorption:	≥ 3.0%	Japan Tunnelling Association 1991
Loss by washing:	≥ 1.0%	Japan Tunnelling Association 1991
Clay:	≥ 0.25%	Japan Tunnelling Association 1991
Sand	**Specification**	**Reference Source**
Fineness modulus:	2.8–3.2	Japan Tunnelling Association 1991
Surface water:	4–6%	Japan Tunnelling Association 1991
	Recommended 2–4%	AFTES 1992
	Maximum 7%	AFTES 1992
Specific gravity:	≥ 2.5 kg/dm^3	Japan Tunnelling Association 1991
Water absorption	≤ 3.0%	Japan Tunnelling Association 1991
Loss by washing:	≤ 5.0%	Japan Tunnelling Association 1991

3.3.2 Silica fume

Condensed silica fume may be added to provide the mix with good adhesion/cohesion characteristics for overhead application. This provides the possibility of building up full thickness in one layer, and to significantly reduce rebound, according to South African tender documents (JCI 1991). According to the ITA Status Report (1991), it is possible to use condensed silica fume together with fly ash.

Recommendations regarding the addition of silica fume are given in Table 6.

3.3.3 Blast furnace slag

South African specifications, referred to in the ITA's status report on shotcrete (1991), do not recommend the use of blast furnace slag cement, because of its slow early strength gain.

However, Japanese guidelines recommend the use of 30–60% addition of blast furnace slag in the cement (Japan Tunnelling Association 1991); and the EFNARC draft (1992) recommends at least 30%.

3.4 Admixtures

Requirements for admixtures for shotcrete mainly concern the use of accelerating admixtures. Their use should be approved by the Engineer, but the method of introduction and concentration should be left to the discretion of the Specialist Contractor (Sprayed Concrete Association 1990).

Specifications concerning other admixtures often refer to specifications or standards for normal concrete additives—e.g., DIN 1045 (DIN 18551, 1992)—or, as in Finland, certified by national concrete associations (Püllä 1991). Their use should be approved by the Engineer (Sprayed Concrete Association 1990).

The admixtures used (normally water glass) must be adapted to the cement with regard to their effect on:

- Setting time;
- Early strength; and
- Decrease in strength at advanced ages (Austrian Concrete Society 1990, EFNARC draft 1992).

The use of accelerators shall also guarantee:

- Good adhesion;
- No corrosive effects on steel;
- Effective operation even at water inflow; and
- Harmlessness to humans.

A typical dosage should be specified, including the detrimental effects of overdosing, especially with regard to long-term durability (Sprayed Concrete Association 1990).

According to the Norwegian draft document (Norwegian Concrete Association 1992), the use of high amounts of accelerators may be compensated for by high strength in the concrete mix design.

Table 7 gives recommendations for accelerators.

Calcium chloride or admixtures containing chlorides either must not be used (JCI 1991); or the chloride content must be limited in reinforced structures, e.g., as according to Austrian guidelines (Austrian Concrete Society 1990).

When cement containing fly ash is used, special consideration must be given before accelerators can be used (SANCOT 1991).

Other admixtures are used for shotcrete. According to Morgan (1991), the normal dosage rates are:

- Water-reducing agents: 0.5%, by weight of cement.
- Superplasticizers: 1–1.5%, by weight of cement.

When air-entraining agents are used, the air pore volume should be expected to be:

- 10–12% by the pump.
- 4–6% after shotcreting.

Air-entraining agents should not be used without approval of the contractor because high air content may reduce

Table 5. Recommendations regarding addition of pulverized fly ash.

Characteristic	Recommendation	Reference Source
Maximum allowable addition:		
• for Portland cement:	≤ 15%	Austrian Concrete Society 1990
	≤ 30%	ITA 1991; EFNARC 1992
• for PFA cement:	≤ 15%	EFNARC 1992
• for blast-furnace slag cement:	≤ 20%	Austrian Concrete Society 1990; EFNARC 1992
Specific surface:	≥ 450 m^2/kg According to BS 3892	Austrian Concrete Society 1990 SANCOT 1991
Carbon content:	≤ 5%	SANCOT 1991
SO_3 content:	≤ 2.5% (Total SO_3 content in cement + PFA: ≤ 4%)	SANCOT 1991

Table 6. Recommendations for addition of silica fume to shotcrete mix.

Feature/Specification		Reference Source
Recommended addition (wet mix shotcrete):		
• 3–5% drift support on front		Norwegian Concrete Assoc. 1992
• 4–8% combination with PFA cement and for permanent support		Norwegian Concrete Assoc. 1992
• 6–10% combination with Portland or SR cement for permanent support		Norwegian Concrete Assoc. 1992
• 8–13%		Morgan 1992
Allowable limits of addition (wet mix):		Norwegian Concrete Assoc. 1992
• 3% ≤ addition ≤ 15%		
Surface area:		
• ≥ 1800 m^2 /kg (densified)		SANCOT 1991
• ≥ 1200 m^2 /kg (BET)		EFNARC 1992
Particle size:	average 0.2 micron	Norwegian Concrete Assoc. 1992
SiO_2 content:	≥ 85–90%	SANCOT 1991; Specification for Lesotho Highlands Project 1991; EFNARC 1992
Carbon content:	≤ 5%	SANCOT 1991; Specification for Lesotho Highlands Project 1991
Total alkali:	≤ 1%	SANCOT 1991
Soluble SO_3:	≤ 1%	Austrian Concrete Society 1990
Loss on ignition:	≤ 4%	EFNARC 1992
Chloride content:	≤ 0.1%	EFNARC 1992
Free CaO:	≤ 1.0%	EFNARC 1992
Hydraulic effectiveness:	100% (ÖNORM B 3320)	Austrian Concrete Society 1990
Activity index:	≥ 95% (28 d)	EFNARC 1992

Table 7. Recommendations for accelerators to be added to shotcrete mixes.

Feature/Specification		Reference Source
Recommended amount:		
• Powdery type:	6–8%	Austrian Concrete Society 1990
	average 6%	EFNARC 1992
• Liquid type:	4–6%	Austrian Concrete Society 1990
	6–8%	EFNARC 1992
• Water glass	10–15%	Austrian Concrete Society 1990
• Not specified:	2–5%	Morgan 1991
• Dry mix:	4–7%	Japan Tunnelling Association 1991
• Wet mix:	5–10%	Japan Tunnelling Association 1991
Allowable amount:		
• Powdery type:	≤ 10%	Austrian Concrete Society 1990
• Liquid type:	≤ 8%	Austrian Concrete Society 1990
• Not specified	≤ 3% (documented experience ≥ 5 years)	SANCOT 1991
Allowable decrease of strength:	≤ 45%, powdery accelerators ≤ 30%, liquid accelerators	Austrian Concrete Society 1990
Approval test:		
• Proctor test 10 min.:	≥ 130 N	EFNARC 1992
Water-soluble aluminate:	≤ 0.6% if shotcrete exposed to water with SO_4^{2-} content > 600 mg/l	Austrian Concrete Society 1990

the pumpability of the shotcrete (Norwegian Concrete Association 1992).

When several admixtures are contemplated, a compatibility study should be carried out before the suitability trial (AFTES 1992).

3.5 Fibres

The use of steel fibres as reinforcement in shotcrete (SFRS) is well established in many countries, including the U.S.A., Canada, South Africa, Germany, Sweden, and Norway.

Other countries regard the fibre-reinforcement technique as a special method (Austria) or as a technique to be used only after sufficient structural tests have been performed (Finland).

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

- 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 for Type I fibre are given in Table 8.

Other, not quantified, recommendations are as follows:

1. Fibres must be dry, free from corrosion, oil, grease, or other contaminants or surface coating (JCI 1991).
2. Fibres should be high strength, deformed, drawn or slit sheet steel fibres (Morgan 1991).
3. A particular product should be specified (e.g., Fibrex HC 25 or Dramix ZC 30/.50).

Rebound reduces the effective amount of fibres in dry-mix shotcrete to about 50–70% of the amount in the mix. For wet-mix shotcrete, the amount of fiber rebound is approximately 5–10% (EFNARC draft 1992).

Galvanized fibers, which are sometimes used in aggressive environments, give very good bond to the concrete; however, there is a risk of gas generation in reaction with de-chromatized cement. The use of de-chromatized cement is prescribed in some countries, e.g., Sweden and Norway (Norwegian Concrete Association 1992).

Other types of fibres, such as glass, polymer and carbon fibres, may be used if the requirements are fulfilled according to applied guidelines (Austrian Concrete Society 1990).

Synthetic fibres contribute to the stability of shotcrete material (AFTES 1992). Their excessively low mechanical properties can modify the rheological behaviour of the fresh concrete and of the concrete during hardening (e.g., improved cohesion and shearing resistance). Their contribution to improving the hardened properties is negligible. The normal dosage is 1–2 kg/m³.

4.0 Mix Design and Performance

4.1 Composition

The contractor should be free to design the mix to achieve the specified characteristic strength (Sprayed Concrete Association 1990).

According to the Austrian guidelines (Austrian Concrete Society 1990), shotcrete without special requirements, up to certain strength levels (SC 16), can be produced without any trial mix tests, using mix proportions for dry or wet mix.

The composition of the shotcrete mix normally is determined by long experience or by trial mix tests. One example of recommended trial mix proportions is presented in Table 9.

Recommendations concerning composition normally refer to "designated" composition. It should be noted that the *in-situ* composition, i.e., in the lining, deviates from the original composition, due to rebound. This is especially important for dry-mix shotcrete (DIN 18551, 1992).

According to AFTES (1992), the result is an average increase of the order of 10 to 20% in cement proportioning for spraying of an area approximately 70 mm thick, and a transfer towards

Table 8. Recommendations for steel-fibe reinforcement in shotcrete. The type of fibre used often refers to ASTM 820, e.g., Type I fibres.

Characteristic	Recommendation	Reference Source
Equivalent diameter:	0.5 mm (Type I, ASTM 820)	
Fiber length:	• ≤ 30 mm for dry mix • ≤ 20 mm for wet mix • < 0.7 x internal dia. of pipes and hoses used	Austrian Concrete Society 1990 Austrian Concrete Society 1990 EFNARC 1992
Aspect ratio l/d:	• 40–60 (Type I, ASTM 820) • 65–100	JCI 1991
Ultimate elongation:	12–22%	JCI 1991
Fiber amount:	• Normally 50–80 kg/m³ • < 5–6% (weight) or 120–140 kg/m³, adapted to pumpability • Related to fiber length (l): ≥ 65 kg/m³ for 1≤ 20 mm ≥ 50 kg/m³ for 21 ≤ 1 ≤ 39 mm ≥ 40 kg/m³ for 1≥ 40 mm	 EFNARC 1992 Norwegian Concrete Assoc. 1992

Table 9. Trial mix batch proportions for 1 m^3 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

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 this increase in proportioning will be, for ceiling applications.

Japanese guidelines (Japan Tunnelling Association 1991) state that the rebound, when tested, should be less than 25%.

According to Vandewalle (1991), rebound may be reduced for wet mix shotcrete by:

- Increasing the cement content.
- Adding fines.
- Decreasing the maximum size of aggregate.
- Attaining the proper moisture content for the aggregate.
- Achieving finer gradation.
- Including fly ash or silica in the mix.

Rebound may be reduced for dry-mix shotcrete by:

- Increasing fines.
- Process-controlled pre-dampening.
- Reducing air pressure.

The cement content should be higher than for normal concrete in order to improve pumpability and shotcrete production (Norwegian Concrete Association 1992).

The ready-mix concrete supplier must not reduce the cement content due to high-strength margins without the consent of the shotcrete contractor.

Other quantified recommendations regarding shotcrete composition are given in Table 10.

According to the Norwegian draft document (Norwegian Concrete Association 1992), the shotcrete should be classified according to the aggressiveness of the current environment, which regulates the maximum mass ratio and the minimum cement content as shown in Table 11.

The mass ratio is as follows:

$$m = \frac{v}{c + Kxp}$$

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% of Portland clinker content.

A similar classification is proposed by the EFNARC draft (1992). As shown in Table 12, requirements for air content also are considered, in order to guarantee freeze-thaw durability on shotcrete that is used primarily for repair work.

When calculating water content for wet-mix shotcrete, consideration should be given to the water content in admixtures and additives (Norwegian Concrete Association 1992). If no special agreement exists between the contractor and the concrete supplier, it should be assumed that 25–30 l/m³ of accelerator will be used. This means that the concrete recipe must have a margin for addition of 25 litres of water at the site.

4.2 Performance—Fresh Shotcrete

Properties of fresh concrete to be considered are:

Table 10. Quantified recommendations for shotcrete composition.

Composition Aspect	Recommendation	Reference Source
Cement content:		Vandewalle 1991
• Fine shotcrete, 0–4 mm:	450–600 kg/m³	
• Shotcrete, 0–8 mm:	350–450 kg/m³	
• Coarse shotcrete, 0–15 mm:	330–350 kg/m³	
Water/cement ratio:		
• For dry mix shotcrete:	0.3–0.4	Morgan 1991
	0.45–0.55	Japan Tunnelling Assoc. 1991
	≤ 0.5*	DIN 18551, 1992
• For wet mix shotcrete:	0.4–0.5	Morgan 1991
	0.50–0.65	Japan Tunnelling Assoc. 1991
• For fibre-reinforced shotcrete:	≤ 0.5	Austrian Concrete Society 1990
Sand/aggregate ratio:	0.55–0.60	Japan Tunnelling Assoc. 1991
Aggregate/cement ratio	3.5:1–4.0:1	Sprayed Concrete Assoc. 1990

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

- Consistency or workability.
- Air pore volume.
- Setting time or workability time.

Recommendations for each of these aspects are given below.

Consistency (wet mix):

- Class KP-KF for dense-flow conveying according to DIN 18551 (1992),.
- Class KS-KP for thin-flow conveying (DIN 18551, 1992).
- Slump:
  60–100 mm (Japan Tunnelling Assoc. 1986; Morgan 1991).
  100–150 mm (AFTES 1992).

Air pore volume. The use of air-entraining agents for shotcrete is not very common. Thus, there are only a few recommendations concerning air pore volume, and they are concentrated on wet-mix shotcrete where freeze/thaw durability is important.

The following two recommendations regarding air pore volumes are cited in DIN 18551 (1992):

- 10–12% air pore volume at the discharge pump.
- 4–6% air pore volume as shot.

Setting time. The setting time often refers to tests according to ASTM C403. Recommended time ranges for plain or steel-fibre-reinforced shotcrete with an accelerator are:

- Initial set: 3–10 min. (SANCOT 1991; Vandewalle 1991; Morgan 1991).
- Final set: 9–30 min. (Wood 1992).

Table 11. Environmental classes and corresponding specifications of concrete composition according to Norwegian draft guidelines for shotcrete (Norwegian Concrete Association 1992).

Environment Class	Environment	Max. Mass Ratio	Min. Binder Content (kg)
NA	Somewhat aggressive	0.60	360
NMA	More aggressive	0.50	420
MA	Very aggressive	0.45	470
MMA	Extremely aggressive	0.40	530

Table 12. Environmental classes, according to the EFNARC draft (1992).

Class Environment	Max. W/(C+)	Min. Cement (kg/m³)	Fresh Air Content (%)
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	6
Frost	0.40	450	

4.3 Performance—Young Shotcrete

The term "young concrete" refers to the state of hardening of concrete to a strength level of approximately 10 MPa.

Requirements for young concrete are prescribed when there is a need to protect against:

- The influence of blasting near the shotcreting site; and/or

Table 13. Permissible impact from blasting near shotcrete structures of different ages.

Shotcrete age (days)	Max. Peak Particle Velocity (mm/s)
0–3	10
3–7	35
>7	110

- The influence of early freezing.

4.3.1. Recommendations

Finnish guidelines (Pöllä 1991) recommend that young concrete have a strength level approximately 60% that of the final strength, in order to withstand blasting near the shotcreting site (given a normal design strength of 30 MPa). Permissible peak particle velocities for shotcrete structures of different ages are given in Table 13.

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

Austrian guidelines (Austrian Concrete Society 1990) classify young shotcrete in three strength development ranges: J_1, J_2 and J_3, as described below:

J_1: Applicable when shotcrete must be placed as quickly as possible in thick layers, inflow of water is observed, and stresses occur as a result of operations following immediately after concrete placement.

J_2: Applicable when early active rock pressure is present.

J_3: Applies only to exceptional cases (e.g., high early strength generally leads to reduced strength increase at later age).

Strength development for the three classifications is shown in Figure 1.

Other recommendations regarding young shotcrete are as follows:

- Required strength: ≥ 5 MPa at 8 hours (SANCOT 1991, Vandewalle 1991).
- Required strength: ≥ 5 MPa before influence of frost (Swedish Railroad Department 1991b, EFNARC draft 1992).
- Concrete temperature must be kept above +5°C until it reaches the freezing strength, normally 3–4 days (Pöllä 1991).

4.4 Performance—Hardened Shotcrete

4.4.1. Compressive strength

The requirements for compressive strength are often related to different strength classes or grades. The three grades recommended by the Sprayed Concrete Association (1990) are shown in Table 14.

More detailed grades are presented in the Austrian guidelines (Austrian Concrete Society 1990), as shown in Table 15. The Finnish guidelines (Pöllä 1991) associate the strength class with different applications (see Table 16).

Examples of requirements for compressive strength given in other documents are shown in Table 17.

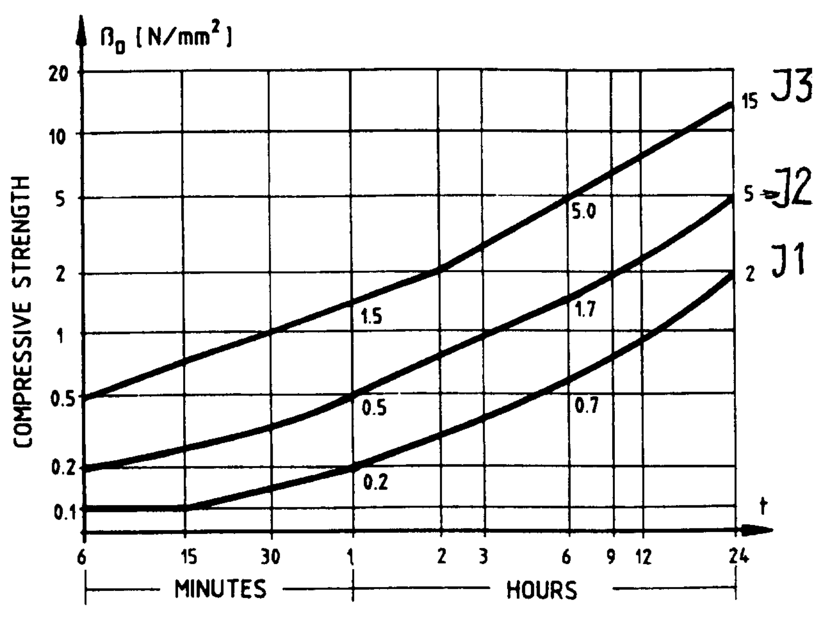


Figure 1. Young shotcrete strength requirements, according to Austrian guidelines (Austrian Concrete Society 1990).

Table 14. Three grades of shotcrete specified by the Sprayed Concrete Association (1990).

Grade	Characteristic Strength at 28 Days
30	30 MPa
40	40 MPa
50	50 MPa

Compressive strength is classified by the EFNARC draft (1992) as shown in Table 18.

Although the Norwegian draft document (Norwegian Concrete Association 1992) does not specify any particular compressive strength, it states that the evaluation of compressive strength shall be based on cores from the lining, and specifies the minimum strength of the cores for different strength classes (see Table 19).

If no other agreement exists, the relationship between the compressive strength of the concrete tested before spraying and the strength of the shotcrete in the lining should fulfill strength classes according to Table 20.

Other special recommendations for fibre-reinforced concrete are as follows:

- Strength grade ≥ SC 22.5 (Austrian Concrete Society 1990).
- Strength class ≥ C 25 (preferably ≥ C 35) to ensure sufficient bond between fibres and the matrix (EFNARC draft 1992).

4.4.2 First crack and/or ultimate flexural strength

Examples of requirements for first crack strength and/or ultimate flexural strength are given in Table 21. All tests refer to ASTM C 1018, and apply only to fibre-reinforced shotcrete.

The Norwegian draft document (Norwegian Concrete Association 1992) relates the flexural strength to the actual compressive strength class, as shown in Table 22.

4.4.3 Toughness

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

All requirements presented concerning toughness refer to tests according to ASTM C1018-89 or modifications thereof. However, other test methods have been proposed—for example, the test prescribed by the Japan Concrete Institute (JCI). These two methods are discussed in section 13.4.2.

Table 15. Strength grades of shotcrete, based on Austrian guidelines (Austrian Concrete Society 1990). The strength grades may refer to an age of 28, 56, or 91 days.

Grade	Minimum Average Value of Compressive Strength (MPa)	Notes
SC12	12	
SC16	16	
SC19	19	With requirements J_1 or J_2, GENERALLY obtainable strength at 28 days
SC22.5	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 SC 40	30 40	Without special requirements for the "young" shotcrete (e.g., reinforced concrete for repair work)

Examples of values presented for the toughness quantities are given in Table 23. In addition to the requirements presented in the table, the EFNARC draft (1992) also presents requirements on toughness indices for various concrete grades. These are given in Table 24.

According to ASTM C1116-89, the requirements for toughness may be linked to various performance levels, as shown in Table 25.

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

Other suggestions, presented by Vandewalle (1991), are based on results from several large research and development contracts, as well as routine field quality control tests. These are given in Table 26.

According to the Norwegian draft document (Norwegian Concrete Institute 1992), the test of fibre-reinforced shotcrete should be carried out according to ASTM C1018; however, the evaluation is somewhat different (see Table 27).

4.5 Other Properties

Denseness: The denseness of shotcrete is expressed in terms of requirements for porosity, density or watertightness. Examples are given in Table 28.

Splitting tensile strength: Recommendations from AFTES (1992) are as follows:

7 days: 2 MPa
28 days: 2.7 MPa

These figures should be used neither in design nor as reference parameters, due to the sensitivity to specimen size and durability.

Uniaxial tensile strength: These requirements are related to the concrete grade (EFNARC draft 1992), as shown in Table 29.

Frost resistance: This is fulfilled for strength class ≥ SC 22.5, according to ÖNORM (Austrian Concrete Society 1990).

Freeze-thaw resistance: ASTM C1116 (1989) gives two alternatives for meeting this requirement:

1. A proven record of satisfactory freeze-thaw durability for concrete, with or without fibres, with the same air content and mixture proportion, placed for at least two winters.

2. 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 (AFTES 1992). Recommendations for bond strength and verification are given in Table 30.

According to EFNARC draft (1992), if shotcrete is used in structural design, the bond shall be specified by:

- Average strength; or
- Characteristic or minimum value.

The German guideline (Maidl 1992), gives the following bond specifications:

- Average of 6 cores: ≥ 1.5 MPa. If not: take an additional 6 cores. If average < 1.5 MPa: further investigation of the reason.
- If single value < 1.0 MPa: An additional 3 cores must be taken within 1 m from the previous ones. If the least value < 1 MPa, the area must be marked and the concrete removed.

The Norwegian draft document (Norwegian Concrete Association 1992)

Table 16. Shotcrete classes according to Finnish guidelines (Pöllä 1991)

Class	Min. Compressive Strength	Application
I	K30	Sites with strict structural requirements, e.g., bridges
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.

Table 17. Examples of requirements for compressive strength based on other documents.
[Note: It may be observed that there is a great difference between the requirements according to the Japan Tunnelling Association (1986) and the Swedish tender documents (Swedish Railroad Department 1991a). The reasons may, to a certain extent, depend on the influence of different test standards, that is, the effect of specimen type, size, and curing conditions. Other reasons are probably related to different national practices, including the influence of the national geotechnical conditions.]

Age of Shotcrete	Compressive Strength (MPa)	Reference Source
8 hours	5	Wood 1992
1 day	5	Japan Tunnelling Assoc. 1991
	8*	AFTES 1992
	10	Morgan 1991, SANCOT 1991, Wood 1992, EFNARC 1992
3 days	20	Wood 1992
7 days	17*	AFTES 1992
	25	EFNARC 1992
	30	Morgan 1991, Wood 1992
28 days	18	Japan Tunnelling Assoc. 1991
	25**	AFTES 1992
	30	JCI 1991, EFNARC 1992
	35	Stockholm City Streets and Traffic Admin. 1990
	35***	Maidl 1992
	40*	Maidl 1992
	40	Morgan 1991, SANCOT 1991, Swedish Railroad Dept. 1991, Specs. for Lesotho Highlands Project 1991, Wood 1992
	45	Swedish Railroad Dept. 1991
90 days	35	EFNARC 1992

* Arithmetic mean
** Characteristic strength
*** Single value

stresses that the bond should be ensured by:

- Cleaning of surfaces.
- Suitable concrete composition.
- Effective curing.
- Controlled by knocking.

5.0 Batching, Mixing and Transport

5.1 Recommendations for Dry-mix Shotcrete

5.1.1 Addition of cement

- Batched by mass or added by bag. Tolerance: ±2% (JCI 1991).
- Cement temperature: ≤+50°C (Austrian Concrete Society 1990, EFNARC draft 1992).

5.1.2 Aggregate

- Coarse and fine aggregates, preferably batched by mass.
  Tolerance: ± 3% (JCI 1991).
- Alternatively, batched by volume, if volume batching conforms to ASTM C685, and the volumetric proportioning is checked at the start of every shift (Specification for Lesotho Highlands Project 1991).
- Moisture content:
  Fine aggregate: 2–6%.
  Coarse aggregate: ≤ 4%.
  If drier aggregate is used, a prewetting system should be used, in order to obtain the preferred moisture content.
- Coarse and fine aggregates should be stockpiled and batched separately.

Table 18. Strength classes for sprayed concrete tested on sawed 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

Table 19. Minimum strength of concrete cores in different concrete strength classes, according to the Norwegian draft document (Norwegian Concrete Association 1992).

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

Table 20. Relationships between strength classes for sprayed concrete and concrete before spraying, according to the Norwegian draft document (Norwegian Concrete Association 1992).

Strength Class, Sprayed Concrete	C30	C35	C40	C45	C50	C55
Minimum strength class before spraying	C38	C43	C48	C54	C60	C65

Table 21. Examples of requirements for first crack strength and/or ultimate flexural strength.

Age (in days)	First crack strength and/or ultimate flexural strength (in MPa)
7	4
28	6

Table 22. Minimum flexural strength in different compressive strength classes, according to Norwegian draft document (Norwegian Concrete Association 1992) and the EFNARC draft (1992).

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		

Table 23. Example of values presented for shotcrete toughness quantities.

Quantity	Age (in days)	Value	Reference Source
I_5	7	3.5	SANCOT 1991; Specs. for Lesotho Highlands Project 1991; Wood 1992
	- *	3.5	Morgan 1991
	28	5.0	JCI 1991
I_{10}	7	5.0	SANCOT 1991; Specs. for Lesotho Highlands Project 1991; Wood 1992
	-*	5.0	Morgan 1991
	-*	7.0 (for C25)	EFNARC 1992
	28	7.0	Swedish National Rescue Services Board
	28	8.0	JCI 1991
I_{20}	- *	10.0 (for C25, 35, 45)	EFNARC 1992
I_{30}	- *	14.0	Morgan 1991
	28	19.0	JCI 1991
	28	21.0	Swedish Natlional Resque Service Board
$\frac{R_{5,10}}{100} x f_s$	- *	4.0 MPa**	Swedish Railroad Department 1991b
$\frac{R_{10,30}}{100} x f_s$	- *	2.5MPa**	Swedish Railroad Department 1991b

* Not specified.
** Requirements for routine tests. Corresponding requirements for preconstruction tests: 5MPa and 3 MPa.

- Temperature of aggregates: ≥ 5°C (Austrian Concrete Society 1990, EFNARC draft 1992).

5.1.3 Fibres

- Batched by mass.
  Tolerance: ± 3% (JCI 1991).
- Alternatively, added by whole bags, boxes, etc., provided these packages are marked with the mass (ASTM C1116.89).

5.1.4 Additives (fly ash, silica fume, etc.)

- Added by mass or preblended with the cement.
  Tolerance: ± 5% (JCI 1991).

5.1.5 Admixtures (setting accelerators, plasticizers, etc.)

- Mixed with the water.
  Tolerance: ± 5% (JCI 1991).

5.1.6 Mixing equipment

- Batch mixer or a continuous mixer. The actual type must, for example, comply with the requirements in ASTM C94 and C685, respectively (ASTM C1018, 1989).
- There are corresponding requirements in DIN 1045, although for stiff concrete, such as fibre-reinforced concrete, the mixing time should be prolonged by 0.5 min. (DIN 18551, 1992).

5.1.7 Water pressure

- In order to achieve complete wetting of the moist mix at the nozzle, the water pressure must be sufficiently high. A pressure greater than 1 kp/cm² higher than the working pressure in the conveying line is recommended, i.e., a desired pressure of ≥ 6 kp/cm² (SANCOT 1991).

Table 24. Requirements, flexural strength and toughness in bending according to the EFNARC draft (1992).

Concrete Grade	C25	C35	C45
Average flexural strength, MPa	3.5	4.2	4.6
Average toughness indices:			
• I_{10}	6	6	6
• I_{20}	12	12	12

Table 25. Toughness values for various performance levels, according to ASTM C116 (1989).

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

Table 26. Suggested descriptions for steel-fibre-reinforced shotcrete, according to Vandewalle (1991).

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

Table 27. Requirements of fibre-reinforced shotcrete in different toughness classes, according to the Norwegian draft document (Norwegian Concrete Association 1992).

Toughness 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

Table 28. Examples of requirements for porosity, denseness, or watertightness.

Example	Specification	Reference Source
Boiled absorption (ASTM C642), 7 days: • Without accelerator: • With accelerator:	 8% 9%	SANCOT 1991, ASTM C1116.89
Volume of permeable voids (ASTM C642), 7 days: • Without accelerator: • With acceleator:	 17% 19%	SANCOT 1991, ASTM C1116.89
Density: According to Swedish standard:	 ≥ 2200 kg/m	Swedish Railroad Dept. 1991a and 1991 b
Watertightness: • Fulfilled according to Swedish standard • Fulfilled for strength class > SC 22.5, according to ÖNORM • ≤ 50 mm and mean average ≤ 20 mm, according to ISO 7031 • Permeability ≤ 10^{-12} m/s, according to CEN		 Swedish Railroad Dept. 1991a and 1991b, Stockholm City Street and Traffic Admin. 1990 Austrian Concrete Society 1990 EFNARC 1992 EFNARC 1992
Other properties: • Splitting tensile strength: 7 days: 2 MPa 28 days: 2.7 MPa Should not be used in design nor as reference parameter, due to sensitivity to specimen size and durability. • Uniaxial tensile strength: Related to the concrete grade, according to Table 29.		 AFTES 1992 AFTES 1992

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

5.1.8 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 2–3 hours (Pöllä 1991; JCI 1991; Specific. for Lesotho Highlands Proj. 1991; EFNARC draft 1992).
- Dry-bagged shotcrete without accelerator should be applied within 30 min. of the addition of mixing water in the predampener (Specification for Lesotho Highlands Project 1991).
- The temperature before placing should not exceed +30°C (EFNARC draft 1992).
- In case of intermediate storage or long transport, the effect of partial hydration should be considered (EFNARC draft 1992).

5.2 Wet-mix Shotcrete

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

Table 29. Requirements for uniaxial tensile strength, according to the EFNARC draft (1992).

Concrete Grade, according to Section 9.1	Minimum Uniaxial Tensile Strength (MPa)
C25	1.5
C35	1.6
C45	2.1
C55	2.3

The Norwegian draft document (Norwegian Concrete Association 1992) prescribes that wet-mix shotcrete shall be manufactured by a ready-mix concrete supplier approved in high class (class A). For strength class ≥ 40 MPa and for shotcrete in very aggressive environments, the ready-mix concrete supplier shall be approved in an even higher class (class A1).

The use of automatic mixers is allowed only for lower-quality concretes.

5.2.1 Addition of cement and aggregate

If site-batched concrete is to be used, then the required proportions of cement to aggregate should be determined by weight-batching. For small-scale projects, volume-batching may be permitted (Sprayed Concrete Association 1990).

5.2.2 Fibre addition

There are two options for addition of fibres (Norwegian Concrete Association 1992):

1. The fibres can be added to the aggregate before the addition of water and additives. To be considered in such a case are the high resistance until water is added, and the given

Table 30. Recommendations for bond strength and verification.

Type of Bond	Recommendation	Reference Source
Shotcrete/rock:	• ≥ 0.5 MPa	Swedish Railroad Dept. 1991a and 1991b, Stockholm City Streets and Traffic Administration 1990
	• ≥ 0.5 MP (structural) ≥ 0.1 MPa (non structural)	EFNARC 1992
	• Possible up to 1.4 MPa to hard dry granite	Vandewalle 1991
Concrete/concrete:	• ≥ 0.5 MPa (28 days, structural) ≥ 0.1 MPa (non structural)	EFNARC 1992
	• ≥ 1.0 MPa	Swedish Railroad Dept. 1991a and 1991b, Stockholm City Streets and Traffic Administration 1990
	• ≥ 2.0 MPa (28 days)	AFTES 1992

effect of the admixtures. In addition, the mix capacity is reduced because of the longer total mixing time.

2. The fibres can be added to the ready-mix concrete mass. It is important to consider that the fibres must be spread carefully into the mix. The consistency must be modified after the fibres are added.

5.2.3 Transport

Long-term mixing under transport at a low w/c-ratio increases the water evaporation, which will decrease the slump. In addition, the friction in the concrete mass increases the heat evaluation which, in turn, will influence the slump reduction (Norwegian Concrete Association 1992).

6.0 Preparation for Shotcreting

6.1 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 of surfaces that are too dry.

In general, according to AFTES (1992), whatever the nature of the substrate, it is recommended that the surface be wetted just before spraying so that it does not absorb the water of the freshly sprayed concrete. This precautionary measure is absolutely essential if the surface to be treated is dry; and it also eliminates dust that has recently settled on the surface.

6.2 Direct Spraying on the Work Surface

For direct spraying on the work surface, AFTES (1992) recommends 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.

In very bad formations (e.g., characterized by lack of cohesion or 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".

6.3 Spraying over a Layer of Young Shotcrete

According to AFTES (1992), if spraying takes place before the preceding layer of shotcrete has hardened, no surface preparation is necessary, provided that the latter has not been soiled.

6.4 Spraying over an Existing Structure

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

6.5 Drainage of Water

According to AFTES (1992), it is essential to make arrangements to avoid any water underpressure on the newly treated surface.

7.0 Reinforcements

This section concerns the application of normal bar reinforcement of shotcrete. Recommendations on this process are given in Table 31.

The EFNARC draft (1992) relates the requirements concerning the concrete cover to the environment class, as shown in Table 32.

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 (Sprayed Concrete Association 1990).

It is desirable that reinforcement panels be fixed rapidly on a first layer of shotcrete at least 20 mm thick (AFTES 1992).

Several attachment points should be provided per square meter on the working face or on a sublayer of the shotcrete (AFTES 1992). The distance between a reinforcement layer and the wall on which the shotcrete is applied should 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.

8.0 Shotcrete Equipment

8.1 Dry Mix Process

Below are given the recommendations from the various countries concerning shotcrete equipment used in the dry-mix process.

Machine types:
- Bell-type machines or Rotor-type machines.

Delivery line:
- Inner diameter: 50–65 mm (AFTES 1992).

Spraying lance:
- Metal or rubber nozzle.
- Pre-wetting lance: should allow annular distribution of liquids (water, admixtures) 1–3 m from the discharge end (AFTES 1992).

Admixture proportioning:
- Should be controlled by the operation rate (AFTES 1992).
- *Powdery admixtures*: should be added by machine mounted on feed conveyor (AFTES 1992). Equipment must be protected

Table 31. *Recommendations for application of normal bar reinforcement of shotcrete.*

Feature	Recommendation	Reference Source
Minimum shotcrete thickness:	50 mm	AFTES 1992
Minimum thickness of reinforcement bars:	3 mm	AFTES 1992
Maximum thickness of reinforcement bars:	25 mm	Sprayed Concrete Association 1990
Minimum distance between bars (one layer):	100 mm 4ϕ or 50 mm	AFTES 1992 Sprayed Concrete Association 1990
Minimum distance between reinforcement layers:	50 mm	DIN 18551. 1992, AFTES 1992
Minimum concrete cover:	20 mm Similar to normal concrete	AFTES 1992 Sprayed Concrete Association 1990
Minimum cover between existing structure and reinforcement in the shotcrete:	3ϕ or 40 mm	Sprayed Concrete Association 1990

from dripped water, dirt, atmospheric influences, and dust (EFNARC draft 1992).

- *Liquid admixtures*: should be added in lance dissolved in water (AFTES 1992).

Water supply:

- Preferably an independent booster allowing overpressure of 1–2 MPa. For higher pressure (5–10 MPa), a special lance with small holes should be used (AFTES 1992).

Air supply:

- Air rate, low output: 7m³/min. Air rate, other cases: 10 m³/min. (AFTES 1992)
- Air pressure:
  - Operating pressures ≤ 175 kPa when 30 m or less of material hose is used (Vandewalle 1991). Increased 35 kPa for each additional 15 m of hose or additional 8 m nozzle above the gun.
  - Air pressure for hose diameter 65 mm, according to Japanese recommendations (Japan Tunnelling Association 1991), given in Table 33.
- Compressor capacity and hose diameter, according to Table 34.

8.2 Wet-Mix Process

Recommendations for the wet-mix process are given in Table 35.

8.3 Spray Robots

Spray robots are recommended for use in large-section tunnels, i.e., ≥ 30 m² (AFTES 1992).

Two types of robots are used:

1. *Complete robots*—self-contained operations that comprise a carrier with a boom, operating station, and pump.
2. *Removable robots*—also include a boom, in which the operating platform is attached to a carrier.

The following operating conditions are recommended in the EFNARC draft (1992):

- The operator must be able to watch the nozzle.
- The robot should be capable of as long a reach as possible.
- The operator must be able to adjust the movement function.
- The operator must be able to control/adjust the amounts of water, concrete, accelerator/additives, and air.

9.0 Health and Safety

German documents give regulations and limits for dust concentration at work sites (Tiefbau-Berufsgenossenschaft 1985 and 1988). The limits are

Table 32. *Required concrete cover to reinforcement, according to the EFNARC draft (1992).*

Environmental Class	Minimum Cover (Tolerance -0, + 15 mm) (in mm)
2a	30
3	40
5c	50
EA	60

Table 33. *Air pressure for hose diameter 65 mm, according to Japanese recommendations (Japan Tunnelling Association 1986).*

Pressure (bar)	Hose length (m)
25	10.0
32	12.5
38	17.0
51	21.0
64	28.0

Table 34. *Compressor capacity and hose diameter, according to Vandewalle (1991).*

Material Hose inside dia. (mm)	Compressor Capacity (m /min. at 700 kPa)
25	10.0
32	12.5
38	17.0
51	21.0
64	28.0

expressed as MAK-value (Maximale Arbeitsplatz Koncentration) for gas, steam or dust in the air, related to toxicologic and/or working medical experience.

Regulation of dust concerns both dust containing free mineralic silicon dioxide and different particles for air blasting.

Some of these regulations are listed below.

- If there are doubts concerning the occurrence and amount of silicon dust in the air of the workplace, the contractor should determine whether the MAK values have been exceeded.
- The contractor must guarantee that the air of the workplace is free from silicon dust as far as is technologically possible, e.g., by ventilation techniques.
- The contractor shall investigate whether different additives or admixtures contain crystalline silicon dioxide and, if so, whether it is possible to use less harmful materials.
- If it is technically impossible to keep the workplace free from silicon dust, the contractor shall provide access to respiratory protection of workers.
- The contractor shall ensure that machines, equipment, and work clothes are cleaned regularly.
- The contractor shall foresee that the evacuated air is cleaned to the degree that it does not pass silicon dust to other work sites.
- Air blasting material has limitations on free crystalline silicon dioxide that must not be exceeded, except when:
  - special methods or equipment are used; or
  - the air blasting involves materials containing a large amount of quartz.

The following German special regulations also apply to ventilation for work places and transport roads during daytime:

- Every work place shall have an oxygen content >19% by volume.
- The limits on concentrations of harmful dust in the air must not be exceeded.
- There must be no risk of explosion in the air.
- The average air velocity shall be 0.2–6 m/s.
- When using mechanical ventilation:

Table 35. Summary of guidelines regarding the wet-mix process.

Feature	Recommendations	Reference Source
PUMP TYPES: Screw pump: • Maximum pressure: • Rotation speed: • Maximum rate: • Maximum aggregate size: Piston pump: • Maximum delivery: • Maximum aggregate size: • Consistency, normal slump:	 1.6 MPa 0–170 rev/min. 286 l/min. = 17 m^3 /h 8 mm 24 m^3 /h 12 mm 160–200 mm ≤ 100 mm possible, but increased rebound	 AFTES 1992 AFTES 1992 AFTES 1992 Austrian Concrete Society 1990 AFTES 1992 Austrian Concrete Society 1990 Norwegian Concrete Assoc. 1992
AIR SUPPLY: • Required amount	 5 m^3 /min. ≥ 3 m^3 /min. at 700 kPa	 AFTES 1992 Vandewalle 1991
DELIVERY HOSE: • Diameter at outlet of pump: Diameter at outlet of pump: Diameter at end near lance: • Bursting pressure:	• Generally rubber 100 mm 3 times maximum aggregate size 65 mm • Distributed reduction in diameter • ≥ 3 times maximum pump pressure • Couplings 100% tight, preferably with rubber	 AFTES 1992 EFNARC 1992 AFTES 1992 EFNARC 1992 EFNARC 1992
LANCE: • Outlet diameter: • Distribution of air and admixtures:	• Metallic or rubber 50 mm 200 mm from discharge end	 AFTES 1992 AFTES 1992
ADMIXTURE PROPORTIONING: • Liquid admixtures:	 • Added by built-in proportioning pump controlled by the pump delivery rate. • Changes in bulk density and viscosity must be taken into account. • Total consumption of accelerators should be measured.	 AFTES 1992 Austrian Concrete Society 1990; Swedish Railroad Dept. 1991a Pöllä 1991

- the amount of fresh air should be 2 m³/min. per worker; and 4 m³/min. per diesel-kW.
- the working plant shall have self-closing doors or double doors (sluices).

• The dust shall be laid down or exhausted near the source.

Finnish guidelines (Pöllä 1991) give threshold limits for mineral dust, as shown in Table 36.

According to Japanese guidelines, the dust content should be ≤5 mg/m³. (Japan Tunneling Association 1986).

The Sprayed Concrete Association (1990) recommends that reasonable measures should be adopted in accordance with the requirements of the Health and Safety at Work Act of 1974, particularly concerning lighting, ventilation and protective clothing.

Some documents (JCI 1991, Specifications for Lesotho Highlands Project 1991) give quantitative requirements regarding lighting during spraying, e.g., a minimum lighting level of 50–70 lux.

Concerning health and safety, U.S. regulation ACI-506 (1983) states that:

- Eyeglasses or shields shall be worn at all times during application.
- The crew should wear appropriate protective mask, gloves and clothing.
- An eye bath shall be readily available in the immediate vicinity of the application.

Other sources (Wood 1992) stress the need for a predetermined communication system, and the need to regularly clean the equipment for 10–15 min. after each spraying shift.

The Sprayed Concrete Association (1990) recommends cleaning at least twice a day for wet-mix equipment, and at least once a day for dry-mix equipment.

Table 36. Threshold limits for mineral dust, according to Finnish guidelines (Pöllä 1991).

Type of Mineral Dust	Threshold Limits
Quartz (fraction < 5µm)	0,2 mg/m³
Portland cement particles/cm³	1000
Total dust content	10 mg/m³

10.0 Shotcreting

10.1 General

Requirements for the application process often refer to recommended practice, such as U.S. regulation ACI 506 (1983).

The contractor should employ a full-time working foreman on the project. The foreman should have had at least five years of specialist spraying experience, including two years as a nozzleman. In addition, the foreman should have experience in concrete mix design, and be fully conversant with the relevant codes of practice (Sprayed Concrete Association 1990).

10.2 Recommendations

Below are given recommendations from the various countries for shotcreting application.

10.2.1 Spraying procedure

- The spray lance shall be held perpendicular to the surface, except when spraying around reinforcement bars (Japan Tunnelling Association 1991; AFTES 1992).
- Spraying shall commence at the bottom (Austrian Concrete Society 1990; Sprayed Concrete Association 1990).
- Immediately prior to the spraying operation, the surface shall be thoroughly cleaned and damped with a strong blast of air and water (Sprayed Concrete Association 1990).
- Voids shall not be left behind bars or steel mesh (Japan Tunnelling Association 1991).
- For spraying in the downward vertical direction, which is difficult, uncoated aggregate and rebound material should be mixed with the concrete (AFTES 1992).
- Optimum nozzle distance (Japan Tunnelling Association 1991; Austrian Concrete Society 1990; Stockholm City Streets and Traffic Administration 1990):
  - Dry mix: 1–2 m (AFTES 1992; DIN 18551,1992).
  - Wet mix: 0.5–1.8 m.
- Where an alignment similar to traditional concrete is required, it is usual to place the shotcrete slightly proud of the required alignment, and to carefully saw back with a timber straight-edge. After the shotcrete has reached its initial set, a further layer (15–20 mm) is applied, aligned with a timber straight-edge, and rubbed up with a wooden trowel (Sprayed Concrete Association 1990).
- Control of alignment and thickness shall be determined by the contractor. Where sharp edges or accurate lines are required, they should be set out by screed boards, guide wires and/or depth spacers (Sprayed Concrete Association 1990).

10.2.2 Layer thickness

- 20–30 mm is typical for dry-mix shotcrete (Pöllä 1991). Normally ≤ 8 hours should be allowed between the first and second layers. A further 24 hours should be allowed between the second and third layers.
- The first layer must be allowed to take its initial set before the next layer is sprayed (ACI 506-66, 1983). Prior to spraying the subsequent layer, loose material should be removed using a strong blast of air.
- A 50–100-mm layer of dry mix shotcrete should be built up by several passes (Austrian Concrete Society 1990).
- For wet-mix shotcrete, the layer thickness and waiting period between layers depend on the concrete mix and quantity of accelerator used (Pöllä 1991).
- The contractor shall duly consider factors such as position of reinforcement, plane of application, mix design and constituents, including admixtures, that may contribute to slump and sag (Sprayed Concrete Association 1990).

10.2.3 Construction joints

- Construction joints generally should be tapered to a thin edge over a width of approximately 300 m or inclination 30° (ACI 506-66, 1983; Sprayed Concrete Association 1990).
- The entire joint should be thoroughly cleaned and damped prior to placement of adjacent sprayed concrete (Sprayed Concrete Association 1990).

10.2.4 Surface treatment

- The surface shall be left as sprayed. If another texture is desired, an additional layer (flashcoat) shall be applied (ACI 506-66, 1983; AFTES 1992; DIN 18551, 1992).
- Finishing of the surface other than with very light trowelling will cause plastic cracking. On coatings ≤ 25 mm, trowelling is undesirable (Sprayed Concrete Association 1990).

10.2.5 Spraying in cold weather

- The same rules as for normal concrete shall be applied when spraying at a temperature ≤ +5°C (AFTES 1992).
- 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 achieved (Sprayed Concrete Association 1990).
- Spraying must not be done against very cold or icy surfaces (AFTES 1992).
- The surface shall be heated or the workplace protected by a heated shelter (DIN 18551, 1992).

10.2.6 Spraying in hot weather

- Precautions shall be taken to ensure that the surface temperature does not exceed +30°C (DIN 18551, 1992).

11. Curing

11.1 General

Most documents indicate that the shotcrete should be treated according to the same rules as those for normal concrete. The shotcrete will require 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.

11.2 Recommendations

Below are recommendations from the various countries concerning curing of shotcrete.

11.2.1 Conditions for curing

- Curing is only necessary if the concrete has special properties (class SC III) or is exposed to special circumstances, such as rapid drying (Austrian Concrete Society 1990).
- Curing should be done only when the relative humidity ≤ 85–90% (Vandewalle 1991; Swedish Railroad Department 1991b).
- Curing should be done "when possible", and in that case, by wet curing as long as possible (JCI 1991).
- When the ambient air temperature exceeds 25°C or the air movement may cause rapid drying, the surface shall not be exposed for longer than 1 hour (Sprayed Concrete Association 1990).

11.2.2 Curing time

- The normal time required for curing is 3–7 days.
- The time of curing varies with the time necessary to reach a certain degree of hydration or strength level (see Table 37).
- Protection against evaporation is necessary during the first and most critical hours/days (EFNARC draft 1992).

11.2.3 Curing method

- Because continuous moist curing often is difficult to carry out in a tunnel, curing by repeated moist spraying is recommended (Japan Tunnelling Association 1991). Frequency: once every 4 hours.
- Curing should be done according to the Austrian standard (ÖNORM 4200), which dictates the use of curtain-type moistened overlays (fibrous mats) or acceptable curing membranes (Austrian Concrete Society 1990).

11.2.4 Use of curing membranes

- Curing membranes are recommended when drying conditions are not too severe; when no additional shotcrete or paint is to be applied; or when it is acceptable from an aesthetic standpoint (ACI 506-66, 1983).
- Curing membranes should be used only on finished surfaces (Swedish Railroad Department 1991b).
- Use of curing membranes is "preferred", according to Finnish guidelines (Pöllä 1991).
- Curing membranes are more frequently applied because of the effect of high surface roughness. When a further layer or other surface finish is to be applied, bond testing shall be carried out. Otherwise, the curing compound should be removed by high water pressure, sand blasting, etc. (Pöllä 1991, EFNARC draft 1992).
- Because of the increased surface roughness, the rate of application of curing compounds may be double the rate of application when they are used for paving (EFNARC draft 1992).

12. Quality Control

12.1 Preconstruction Tests

12.1.1 Conditions of testing

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 often depends on the use of the shotcrete, expressed as a minimum strength class or grade. For example, tests are needed:

- For strength grade ≥ SC 16, according to Austrian guidelines (Austrian Concrete Society 1990).
- For strength classes I and II (out of four classes), according to Finnish recommendations (Pöllä 1991).
- In normal and extended control classes, according to the Norwegian draft (Norwegian Concrete Association 1992).

AFTES (1992) relates the need for preconstruction tests to the available knowledge of the actual shotcrete composition and performance conditions. For example:

- When the mix design is well known and there are references, testing shall be done to check the capability of the contractor (personnel and equipment).
- When a prior study has been carried out in connection with a project but the shotcrete has never been applied, tests shall be performed to ensure:
  - feasibility of concrete placement;
  - compliance with specifications; and
  - capability of the contractor.

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

Table 37. Degree of hydration or strength required, as related to time required for curing of shotcrete.

Degree of Hydration or Strength Required, in Relation to Curing Time	Reference Source
60% of required strength	Pöllä 1991
80% of required strength (watertight)	Pöllä 1991
45% of required strength (watertight)	Swedish Railroad Dept. 1991b, EFNARC 1992

12.1.2 Extent of testing

According to the Austrian guidelines (Austrian Concrete Society 1990), *preconstruction tests should comprise:*

- Two mixes with two binder contents and an adequate dosage of admixtures.
- One mix without accelerator.

The tests must be performed on site using the same equipment, installations, concrete ingredients, and procedures used in production shotcreting.

German guidelines (DIN 18551, 1992) call for two panels: one for tests on fresh concrete; and the second, for tests on hardened concrete.

South African documents (JCI 1991; Specifications for Lesotho Highland Project 1991; SANCOT 1991) prescribe that test panels should be made for each crew; for each mix; and for each shooting orientation, at least at the beginning of a project. A minimum of three or four specimens from each test panel is prescribed.

The following tests on fresh concrete are recommended (DIN 18551, 1992; JCI 1991; Specifications for Lesotho Highland Project 1991):

- Density.
- Water content (dry-mix process).
- Aggregate content (< 0.25 mm).
- Dosage of accelerator. Maximum dosage, not to be exceeded.

The following tests on hardened concrete are recommended (JCI 1991; Specifications for Lesotho Highland Project 1991; AFTES 1992):

- 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.

For wet-mix shotcrete, the Norwegian draft document (Norwegian Concrete Association 1992) relates the extent of testing to the actual control class, as follows.

For normal control class, tests on concrete mass and sprayed concrete:

- Water demand, workability, pumpability, sprayability/rebound.
- Material control: slump, air content, compressive strength, density.
- Dosage of accelerator.

For extended control class:

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

12.1.3 Requirements

Conforming to normal concrete standards, the requirements for preconstruction tests are higher than those for construction tests.

For example, the Austrian guideline (Austrian Concrete Society 1990) stipulates 25% higher compressive strength value than the design strength, although not more than 8 MPa.

Requirements given in the South African document (SANCOT 1991) are:

- Average compressive strength (3 samples) ≥ design strength, 28 days.
- Single values ≥ 0.8 x design strength, 28 days.

Swedish requirements on toughness stipulate 0.5–1.0 MPa higher residual stress values for preconstruction tests in comparison to requirements for routine tests (Swedish Railroad Department 1991a and 1991b).

12.2 Routine Tests

According to the Norwegian draft (Norwegian Concrete Association 1992), the extent of control is related to different control classes, as follows:

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

The choice of control class should be made by the designer, based on:

- The type of project (consequence of failure).
- The degree of difficulty (strength and environment class).
- The time schedule of the project, that is, the possibility of carrying out the control program (especially important for control class III).

Four types of control are specified:

1. Production control.
2. Material control before spraying.
3. Control of hardened shotcrete.
4. Documentation of properties.

The relationship between control class and control type is shown in the schedule in Table 38.

For shotcrete in control class III (Extended control), there should be:

- A special organisation table for each project; and
- A special quality-assurance Engineer.

12.2.1 Extent of testing on constituents

Extensive testing of constituents on-site is necessary when dry-mix process shotcrete is mixed on the site.

Cement is normally "tested" by checking the batch ticket at every delivery. However, the Austrian guideline (Austrian Concrete Society 1990) also stipulates more detailed tests, to be performed once a month, pertaining to:

- Fineness of grinding.
- Initial set.
- Strength.
- Sweating (bleeding).
- C_3A content, where applicable.

For *aggregate*, in addition to batch ticket control of every delivery, there are different stipulations for testing, including:

- **Grading curve of coarse and fine aggregates.**
  Frequency: 1/week–2/month; or linked to the delivered volume as 1/100 m^3 for natural fine or coarse aggregate, and 1/50 m^3 for fine crushed aggregates.
- **Moisture content.**
  Frequency: 2/week–2/month.
  For wet-mix shotcrete, the Norwegian draft prescribes 1 test/shift in all control classes (minor, normal, extended), to be performed by the ready-mix concrete supplier, independent of the concrete volume (Norwegian Concrete Association 1992).
- **Type** (deleterious substances): Frequency: every delivery–daily.

Additives are normally "tested" by checking the batch ticket for every delivery. However, they may also require, for example, testing of the fineness of grinding of the fly ash (frequency: 1/month).

Admixtures are normally "tested" by checking the batch ticket, marking every delivery, or by routine inspection. Admixture testing may also include:

- Identity testing.
  Frequency: 1/2 months.
- Testing of water-soluble aluminate content.
  Frequency: 1/month.
- Testing to determine decrease in strength, or acceleration of setting of cement.
  Frequency: by special direction.
- Test of resistance to sulfates (combined with cement).
  Frequency: 1/month.

Table 38. Relationships between control class and control type (Norwegian Concrete Association 1992).

Control Class	Production Control	Material Control	Control Hardened Shocrete	Document of Properties
Minor	x	x		
Normal	x	x	x	
Extended	x	x	x	x

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

12.2.2 Extent of testing on dry-mix shotcrete

Less routine testing must be performed on-site on the shotcrete mix before shotcreting when pre-bagged dry-mix products are used, in comparison to the amount of testing required when site-mixed dry-mix shotcrete is used.

Pre-bagged dry-mix products are tested by checking the batch ticket, and by marking, etc., every delivery, as well as by routine visual inspection. More detailed control may be performed by checking the individual components.

In addition to testing of the individual components, site-mixed dry-mix shotcrete is tested with reference to composition and moisture content (frequency, according to Austrian guideline: 4/month [Austrian Concrete Society 1990]).

12.2.3 Extent of testing on fresh and hardening shotcrete

Fresh concrete for dry-mix shotcrete is normally tested for water content in the mix. Wet-mix shotcrete is normally tested for consistency, fresh density, temperature, and, if prescribed, air content.

For wet-mix concrete, less extensive on-site testing is required when ready-mix concrete is used, as compared to the extent of testing required when site-mixed concrete is used.

The frequency of these kinds of tests, as stipulated in the German guideline 18551 (1992), is shown in Table 39.

The Norwegian draft (Norwegian Concrete Association 1992), relates the frequency of these tests to the control class, as shown in Table 40.

For fibre-reinforced shotcrete, Swedish documents (Swedish Railroad Department 1991a, Stockholm City Street and Traffic Administration 1990) prescribe checking 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. The recommended frequency is: three samples taken directly from the load, and another three samples taken from the lining.

The Japanese guidelines (Japan Tunnelling Associaton 1986) also specify the measurement of rebound, carried out on approximately 0.2 m³ shotcrete, as well as measurement of the dust density.

Stipulations concerning tests on hardening shotcrete (young shotcrete) are given in the Austrian guideline (Austrian Concrete Society 1990). The hardening is tested by indirect methods calibrated to the strength development. Recommended frequency: 2/month.

12.2.4 Extent of testing 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 Finnish guideline (Pöllä 1991) links the requirements for the type of samples to the actual shotcrete class (see Table 16) and the shotcreting method, as shown in Table 41.

According to the German guideline (DIN 18551, 1992), the frequency of making test panels and/or cored specimens is related only to the volume or area of shotcrete, as presented above for preconstruction tests.

Table 39. Frequency of testing on fresh and hardening shotcrete, according to German standard DIN 18551 (1992).

Volume of shotcrete	Type of Testing
< 100 m³ (500 m²) shotcrete:	1 test series
100–300 m³ (500–1500 m²):	1 series/100 m³ (500 m²)
> 300 m³ (1500 m²):	1 series at start and 1 series/250 m³ (1250 m²)

Table 40. Frequency of tests on fresh and hardening shotcrete, according to Norwegian draft document (Norwegian Concrete Association1992).

Control Volume	Control Class		
	Minor	Normal	Extended
First 3 shift or 1/50 m³	1/shift	-	-
≥ 3 shift	1/14 shift or 250 m³	-	-
< 10 m³ *	-	1/shift or 50 m³	1/3 shift or 25 m³
10–50 m³ **		1/6 shift or 100 m³	1/shift or 40 m³
> 50 m³ ***	-	1/3 shift or 200 m³	1/shift or 75 m³

* Spraying by the rock front after each fire.
** Spraying near the rock front to support a couple of excavation sections.
*** Spraying for permanent support.

Other documents link the frequency of testing to the strength class or grade of the shotcrete. Examples are shown in Table 42 (Finnish guideline [Pöllä 1991]) and Table 43 (Austrian guideline [Austrian Concrete Society 1990]).

Similar to tests on fresh concrete, the Norwegian draft (Norwegian Concrete Association 1992) relates the test on hardened on concrete to both the volume of concrete and the classification (control class), as follows:

- Test of compressive strength and density, 7 and 28 days, on standardized cubes cast on-site. Frequency as shown in Table 44.
- Test of strength and density of cores from the lining. Frequency as shown in Table 44.
- Documentation of properties such as flexural strength and toughness on beams sawn from shotcrete test panels. Frequency as shown in Table 45.

According to AFTES (1992), compressive strength should be tested at intervals of 3, 7 and 28 days (frequency 1/50 m^3).

In summarizing the required test frequencies presented above and requirements in other documents, the frequencies vary between the following:

- Minimum: 1 sample (test panel)/ 250 m^3 of concrete.
- Maximum: 1 sample (test panel)/ 10 m^3 of concrete.

This difference is highly dependent on combinations with other quality control systems, as noted, e.g., in the Finnish guideline (Pöllä 1991) shown in Table 42. The requirements for test frequency are much lower if the shotcreting is performed under governmental inspection.

The strength class also influences the testing, in that a higher strength class requires more frequent testing.

Very approximately, the required test frequencies may be divided into two frequency groupings, as follows:

1 sample/10–100 m^3 concrete:

Applied in: Finland (no governmental inspection)
South Africa
Sweden
U.S.A.
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 (ASTM C1018, 1989), e.g.:

- When fibre reinforcement is used, one test should be made each day.

Table 41. Methods for sampling in different shotcrete classes, according to Finnish guideline (Pöllä 1991).

Class	Samples	
	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)*
	(Cores from the lining)*	
III & IV	Standard tests	(Shotcreted panels)*
	(Shotcreted panels)*	(Cores from the lining)*

* Only if required in contract documents.

Table 42. Minimum number of shotcrete panels for compressive strength, according to Finnish guideline (Pöllä 1991).

Nominal Strength	Governmental Inspection	Volume of the Applied Shotcrete V m^2	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 43. Frequency of testing, according to Austrian guideline (Austrian Concrete Society 1990).

Shotcrete Class or Grade		Frequency of Testing
"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 B4200, Part 10

- The intended test specimen may be taken from the structure or, alternatively, from a test panel.

The tests and the 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 (Swedish Railroad Department 1991b, JCI 1991) also prescribe the above frequency for toughness testing, i.e., according to ASTM C1018 (1989), on at least 3 beams per test occasion.

Properties other than the above may be tested with other frequency requirements, as shown in Table 46.

For fibre-reinforced shotcrete, it is possible to use identity charts established for the actual fibre used. Such a chart is shown in Figure 2.

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

$$f_o = 0.4\sqrt[3]{f_{cc}}$$

where: f_o = ultimate flexural strength
f_{cc} = compressive strength

Other quantities used are:

R_u = $100 f_u/f_o$, expressing the relationship between the ultimate flexural strength (f_u) of fibre-reinforced concrete, and the ultimate flexural strength of plain concrete (f_o).

R_e = $100 f_e/f_o$, expressing the relationship between the equivalent flexural strength (f_e) 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 C1018 (1989).

Using the identity charts and the above quantities, the routinely performed flexural tests on concrete beams may be exchanged for tests on compressive strength only, which are simpler and less expensive. However, it is important to consider that the basis of this proposal—i.e., the existence of a relationship between the compressive and flexural strength of plain concrete—is greatly dependent on the actual method of testing for compressive and flexural strength, curing conditions, etc.

12.2.5 Requirements

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

Table 44. Frequency of strength and density testing from the lining, according to Norwegian draft document (Norwegian Concrete Association 1992).

Control 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 45. Frequency of property documentation, according to Norwegian draft document (Norwegian Concrete Association 1992).

Control 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

Cement. See Section 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 given below:

- Fineness of grinding: Deviation ± 5%.
- Compressive strength of standard test: Standard deviation ≤ 3.5 MPa.

Aggregate: Permissible deviation from a specific grading curve is presented in the Austrian guideline (Austrian Concrete Society 1990), as shown in Table 47.

Moisture content. Deviation ±1% from the designed (DIN 18551, 1992).

Additives. See Section 3.3.

- Specific surface of fly ash: Deviation ± 250 cm^2/g.

Admixtures. See Section 3.4.

Fibres. See Section 3.5.

Composition of mix: See Section 4.1. According to the Norwegian draft (Norwegian Concrete Association 1992), the mass ratio m = v/(c + Kxp) must not be exceeded:

- By more than 15% for single shotcrete areas or working shift.
- By more than 10% for three following shotcrete areas or working shifts.

Fresh concrete: See Section 4.2. ASTM C1116 (1989) gives acceptable tolerances for workability of wet-mix fibre-reinforced shotcrete when measured as slump or "time of flow".

- For slump specified as "maximum" or "not to exceed", see Table 48.
- For slump not specified as "maximum" or "not to exceed", see Table 49.
- For time of flow specified as "maximum" or "not to exceed", see Table 50.
- For time of flow not specified as "maximum" or "not to exceed", see Table 51.

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

ASTM C 1116 (1989) also gives tolerances for air pore volume of fibre-reinforced concrete as ±1.5% of the specified value.

Young concrete: See Section 4.3.

Hardened concrete: See Section 4.4.

- **Compressive strength**: The Austrian guideline (Austrian

Table 46. Properties that may be tested with other frequency requirements.

Property	Frequency Requirement(s)	Reference Source
Splitting tensile strength 3, 7, 28 days:	1 test/100 m^3	AFTES 1992
Density:	On all cores	AFTES 1992
Watertightness:	2 specimens/200 m^3	Swedish Railroad Dept. 1991b
Toughness:	3 beams/300 m	Swedish Railroad Dept. 1991b
Modulus of elasticity:	No frequency stated	Austrian Concrete Society 1990
Bond: • at 3, 28 days*:	3 tests/50–100 m^3 1 test/1000 m^2	Swedish Railroad Dept. 1991a, Stockholm City Streets and Traffic Admin. 1990 Austrian Concrete Society 1990
Thickness:	1 test (5 points of measure)/50 m^3 1 point of measure/m^2 1 test (7 points)/20 m	Stockholm City Streets & Traffic Admin. 1990 JCI 1991 Japan Tunnelling Association 1991
Aggregate content:	< 0.25 mm; no frequency stated	DIN 18551, 1992
Uniformity in mass and continuity	Visual inspection of cores	AFTES 1992

*The scatter is great, depending on experience, when testing in place, due to the influence of deviated traction, peelings, placement difficulties, and weight of equipment. Therefore, testing in laboratory is recommended.

Concrete Society 1990) 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 be applied to other characteristics, e.g., watertightness, etc.

Another document states that the single value must be ≥ 0.8 x required strength (SANCOT 1991).

- **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 C1018 (1989) is very dependent on the accuracy of the deformation measurement. Therefore, only well-qualified laboratories should be used.

The precision in measurement within laboratory is presented in ASTM C1018 (1989), as shown in Table 52.

- **Thickness:**
  - The average measured thickness must not fall below:
    - 90% of required thickness at nominal thickness ≤ 30 mm; or
    - 95% of required thickness at nominal thickness ≥ 30 mm

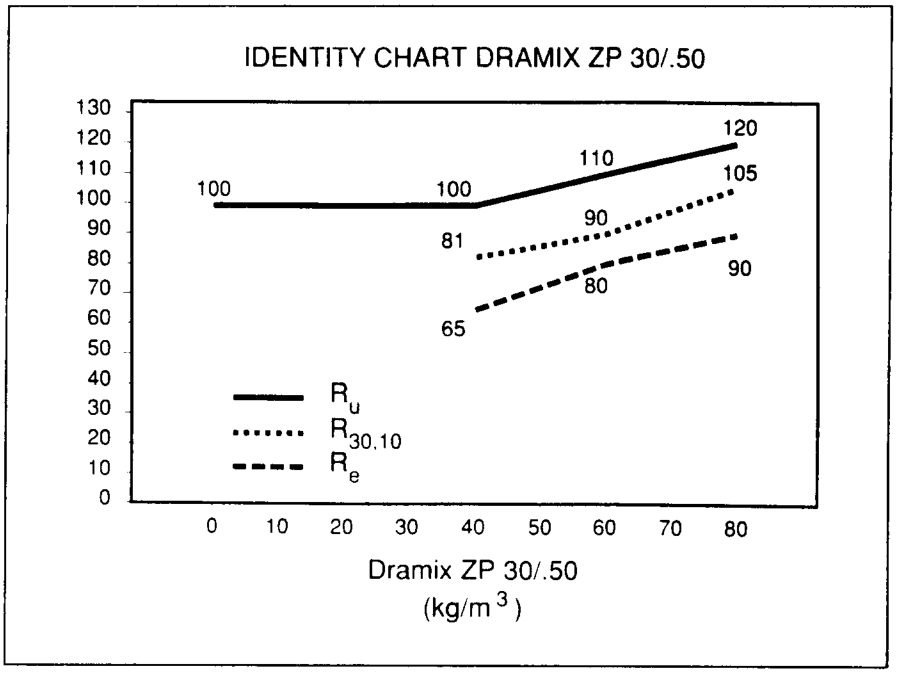


Figure 2. Identity chart established for fibre type Dramix ZP 30/.50 (Vandewalle 1991).

Table 47. Permissible deviation from specified grading curve, according to ÖNORM B4200 (Austrian Concrete Society 1990).

Sieve Size (mm)	Permissible Deviation % at Max. Aggregate Size	
	< 16 mm	> 16 mm
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

Table 48. Acceptable tolerances for workability of wet-mix fibre-reinforced shotcrete when measured for slump specified as "maximum" or "not to exceed".

Type of Tolerance	Specified Slump	
	If 3 in. (75 mm) or less	If more than 3 in. (75 mm)
Plus tolerance	0	0
Minus tolerance	1.5 in. (40 mm)	2.5 in. (65 mm)

Table 49. Acceptable tolerances for workability of wet-mix fibre-reinforced shotcrete for slump not specified as "maximum" or "not to exceed".

Tolerances for Nominal Slumps	
For Specified Slump of	Tolerance
2 in. (50 mm) and less	± .5 in. (15 mm)
2 to 4 in. (50 to 100 mm)	± 1 in. (25 mm)
More than 4 in. (100 mm)	± 1.5 in. (40 mm)

Table 50. Acceptable tolerances for workability of wet-mix fibre-reinforced shotcrete when measured for time of flow specified as "maximum" or "not to exceed".

Type of Tolerance	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

Table 51. Acceptable tolerances for workability of wet-mix fibre-reinforced shotcrete when measured for 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

(Stockholm City Streets and Traffic Administration 1990).
- ± 10% variation of thickness is acceptable (Swedish Railroad Department 1991b).
- If the thickness falls below the nominal at one measured point, new measurement should be carried out in the vicinity of the past in order to determine the extent of the area (Pöllä 1991).
- When shotcreting against a substrate at low temperature, frozen soil or rock, the nominal thickness shall be increased by 2–3 cm of shotcrete (Austrian Concrete Society 1990).
- A tolerance of ± 10 mm over a 3-m length is readily attainable on a flat surface (Sprayed Concrete Association 1990).

- **Density**: The density may deviate <±2% from the density evaluated during design and suitability tests (AFTES 1992).

13.0 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 given in Table 53.

The choice of panel dimensions is important—both from the practical point of view, because of the difficulty of handling the panels; and from the technical point of view, because of the necessity of obtaining a realistic measure of the actual concrete structure.

When using robots, the test panels should be made by spraying on a loading stool, without the normal inclined sides, provided with a laminate plate (Norwegian Concrete Association 1992).

According to the 1992 EFNARC draft, the filling of receptacles by robot is difficult because of the high rate of filling (10–20 m^3/hr). Therefore, sampling by in-place coring is recommended.

In making test panels, the following guidelines should be observed (Norwegian Concrete Association 1992):

- The mold shall be placed against the tunnel wall with inclination ≤ 45° to the vertical plane.
- The panels should be sprayed to a minimum thickness of 120 mm. A concrete thickness > 170 mm shall be removed immediately.
- The panel shall be cured similarly to the lining, and shall remain at the test place for 12–18 hours.
- The concrete surface shall be protected by a plastic sheet or moist cloth before transport to the test

laboratory after a minimum period of four days.

13.2 Fresh Shotcrete

Test methods for fresh shotcrete, i.e., normally wet-mix shotcrete or dry-mix shotcrete without accelerator (or tested before adding the accelerator), also refer to standard test methods for normal concrete. However, special attention should be paid to some tests on fibre-reinforced concrete.

The workability of fibre-reinforced shotcrete tested by slump will have a lower slump value than the slump of an otherwise identical concrete without fibres. Therefore, 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 (ASTM C1116, 1989).

Fibre content and fibre distribution may be tested on fresh shotcrete by wash-out methods, following the recommendations given below.

- Minimum 2 litres of concrete (Stockholm City Streets and Traffic Admin. 1990).
- Minimum 10 litres of concrete (Norwegian Concrete Association 1992; AFTES 1992).
- At least 8 kg (4 litres), for dry-mix shotcrete (Austrian Concrete Society 1990).
- The analysis shall be carried out on a sample from a mix of concrete from three different zones (AFTES 1992).

For wet-mix shotcrete, the mass ratio can be calculated from production data in the ready-mix concrete factory, combined with measured consumption of accelerator on-site (Norwegian Concrete Association 1992).

Rebound of shotcrete should be measured by weighing the shotcrete rebound on a tarpaulin. Drop-out of already applied concrete should not be included in the measurement.

Rebound of fibres in the rebound should be measured by wash-out from at least 5 kg of rebounded material.

Table 52. Within-laboratory precision for touchness test according to ASTM C1018 (1989). 1s = one-sigma limit.

Parameter	Within-Batch 1S%	Overall 1S%*
First-crack strength	5	7
First-crack toughness	10	12
Toughness index$_5$	12	13
Toughness index$_{10}$	14	16
Toughness index$_{20}$	16	20
Flexural strength	5 to 8**	8 to 10**

* Inclusive of batch-to-batch variability, but not variability due to changes in specimen geometry, test span, and mode of lining.

** 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.

Table 53. Examples of recommended dimensions for test panels for testing shotcrete.

Recommended Dimensions of Test Panels	Reference Source
500 x 500 x 150 mm	Japan Tunnelling Association 1991
500 x 500 x 120 mm	Pöllä 1991; DIN 18551, 1992
600 x 600 x 100 mm	Skurdal 1989
400 x 600 x 200 mm	Austrian Concrete Society 1990
600 x 600 x 120 mm	Norwegian Concrete Association 1992
650 x 650 x 100 mm	JCI 1991
750 x 750 x150 mm	SANCOT 1991
600 x 600 x 100 mm for dry-mix shotcrete 750 x 750 x 100 mm for wet-mix shotcrete	Sprayed Concrete Association 1990
450 x 450 x 100 m for construction test; 750 x 750 x 100 for preconstruction test	Specification for Lesotho Highlands Project 1991
(n x 125 + 100) x 550 mm n = number of beams	CBI 1990
800 x 800 x 160 mm	EFNARC 1992
Surface area ≥ 0.25 m^2. Thickness ≥ 150 mm	AFTES 1992

13.3 Hardening (young) Shotcrete

Methods to test the properties of young shotcrete are presented in the Austrian guideline (Austrian Concrete Society 1990), and different measuring ranges are specified for different test methods (see Figure 3).

The test methods are specified below.

- **Modified penetration test:**
  - With a flat-ended 9-mm needle used immediately after placing of shotcrete.
  - With a pointed-ended (60°), 3-mm needle for maximum strength 1.5 N/mm².

  Strength is recorded at time intervals 2, 4, 6, 8, 10, 20, and 30 minutes, according to the EFNARC draft (1992).
- **Powder-activated fastening process:**
  Bolts are driven into the concrete and subsequently extracted 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 encased in shotcrete and then pulled from the concrete for assessing the strength corresponding to the respective state of hardening.

Coring technique is possible for concrete strength ≥ 5 MPa. For strength 1–5 MPa, sawing of specimens is preferred.

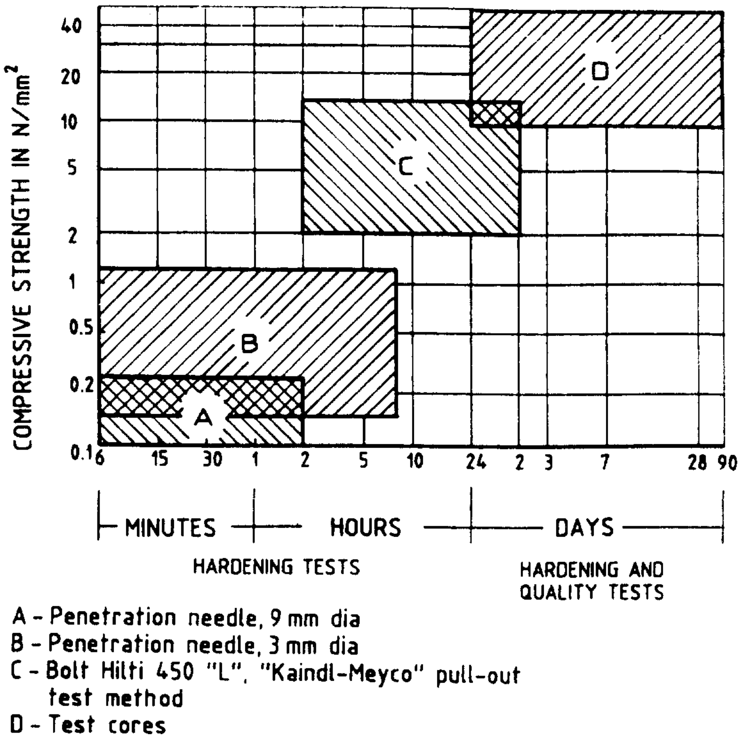


Figure 3. Measuring ranges for methods of testing the compressive strength of "young" shotcrete (Austrian Concrete Society 1990).

13.4 Hardened Shotcrete

13.4.1 Compressive strength

Recommended dimensions of specimens are given in Table 54.

According to the Sprayed Concrete Association (1990), the quality of *in-situ* sprayed dry-mix shotcrete may be confirmed by taking 25-mm cores.

The drilling of cores or sawing of cubes should be done when sufficient strength has been achieved, i.e.:

- Approximately 10–15 MPa, after 2–3 days (SANCOT 1991; Austrian Concrete Society 1990).
- After at least 7 days (AFTES 1992).

The curing of specimens prior to tests is in agreement with the treatment of specimen for normal concrete compressive strength testing, according to most national standards. Normally this testing is done at the site within 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.

The group of absolute descriptions includes propositions presented by the Japan Concrete Institute (JCI).

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. This type of relative value description compares one part of the response to the external loading of an element with another part of the response of the same specimen.

The most applied method from this group is the method according to ASTM C1018 (1989). In this method 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 the first crack. The area below the load-deflection curve is a measure of the absorbed energy.

In the ASTM standard, toughness indices I_5, I_{10}, I_{20}, and I_{30} are defined for deflections up to 3δ, 5.5δ, 10.5δ, and 15.5δ. The load deflection curve and toughness indices are shown in Figure 4.

Recommendations concerning beam dimensions are given in Table 55.

According to the 1992 EFNARC draft:

- I_{10} and I_{20} shall primarily be used for rock support.
- I_5 and I_{10} shall be used for other applications.

It should be observed that the estimation of toughness indices is highly 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 depends greatly on the laboratory equipment used.

In addition to 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 exceeded in acceptance tests (Swedish Railroad Department 1991a):

$$\frac{R_{5,10}}{100} \times f_a$$

expressing the average stress level in the deflection range corresponding to toughness indices I_5 and I_{10}. (f_a = first crack stress)

Table 54. Recommended dimensions of specimens of hardened shotcrete.

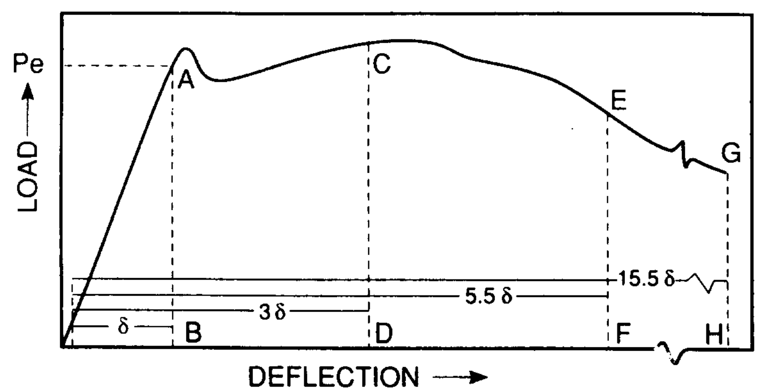
Recommended Dimensions of Specimens		Reference Source (if given)
DRILLED CORES:		
• Diameter:	60–100 m	
• Length/diameter ratio:	1:1–1:2 1:1.5–1:1.7 (preferred)	Norwegian Concrete Association 1992
SAWN CUBES: • Side dimensions:	75–100 m ≥ 60 mm	EFNARC 1992

$$\frac{R_{10,30}}{100} x f_s$$

average stress level in the deflection range corresponding to toughness indices I_{10} and I_{30}. (f_s = first crack stress)

According to the JCI (1991) standard, flexural strength is defined with reference to the maximum load. As a measure of toughness, an "equivalent flexural strength f″" 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 (see Fig. 5).

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 (Kasperkiewicz and Skarendahl 1990).



$$I_5 = \frac{OACD}{OAB} \quad I_{10} = \frac{OAEF}{OAB} \quad I_{30} = \frac{OAGH}{OAB}$$

Figure 4. Load-deflection curve and toughness indices, according to ASTM C1018 (Vandewalle 1991).

13.4.3 Other properties

Splitting tensile strength: The "Brazilian" test on cores ϕ60 mm. It is important that the surfaces are straight, without undulations (AFTES 1992).

Direct tensile test:

- On cores ϕ60–80 mm (preferably 80 mm to reduce the scatter) [AFTES 1992].
- On samples 100 x 100 x 600 mm (28d) [EFNARC draft 1992].

Density: by weighing and hydrostatic weighing after application of paraffin (AFTES 1992).

Thickness:

- Tested by drilling holes. The placing may be specified using a template, according to Swedish standard (see Fig. 6).

Alternatively, the Norwegian Concrete Association draft (1992) states that thickness can be tested:

- By sticking a pricker through the fresh shotcrete; or
- By applying distance pins in the first shotcrete layer.

Table 55. Recommendations regarding beam dimensions for test beams.

Recommendations of Beam Dimensions	Reference Source
• 100 x 100 x 350 mm (thick sections) Equal to the actual thickness used (thin sections)	ASTM C1018, 1989 Norwegian Concrete Association 1992
• 75 x 125 x min. 550 mm	EFNARC 1992
• 75 x 125 x 600 mm	EFNARC 1992

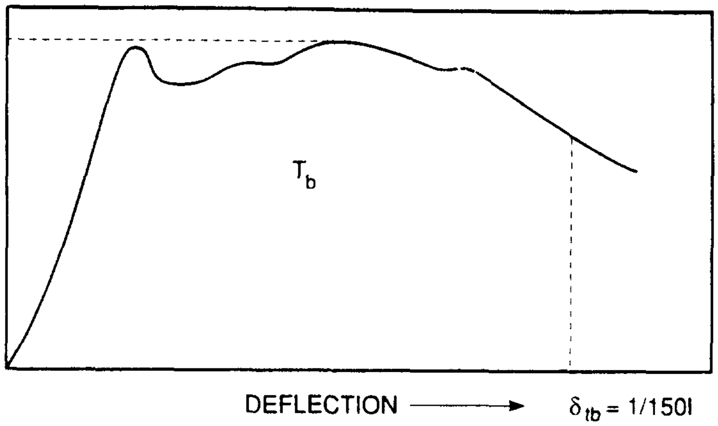
Bond:

- Preferably performed in a laboratory on cores ϕ80 mm (AFTES 1992).
- Measured on a random 1-m² surface area of the tunnel lining. Six cores are tested, at the earliest, after 10 days. The cores are wrapped in plastic sheeting before being taken to a laboratory. The mean centric tensile strengths are measured at age 14 days (Maidl 1992).
- Measurement of bond may be stopped if the bond strength > 1.5 MPa (DIN 18551, 1992).
- Controlled by knocking. If there are non-bonded areas, the reason shall be investigated and the need of additional support evaluated (Norwegian Concrete Association 1992).

Watertightness shall be tested on cores (ϕ150 mm and h = 120 mm) from shotcrete panels, according to DIN 1048 (1989). □

References

ACI 506-66. 1983. Recommended Practice for Shotcreting. American Concrete Institute.



$$f_u = P_u \cdot \frac{l}{b \cdot h^2} \qquad f_e = \frac{T_b}{\delta_{tb}} \cdot \frac{l}{b \cdot h^2}$$

Figure 5. Definition of equivalent flexural strength, according to JCI (Vandewalle 1991).

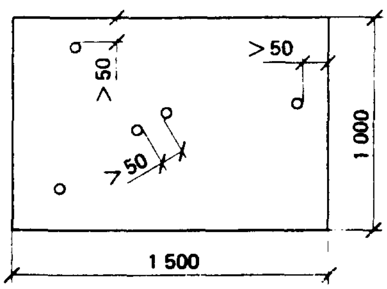


Figure 6. Template used when testing thickness of shotcrete lining, according to Swedish standard (Swedish Standardisation Commission 1987).

AFTES (Association Française des Travaux en Souterrain). 1992. "Recommendations on Sprayed Shotcrete: Technology and Practice." Report of AFTES Working Group No. 6. Paris: AFTES.

ASTM C 1018-89. 1989. "Standard Test Method for Flexural Toughness and First Crack Strength of Fiber Reinforced Concrete. ASTM.

ASTM C 1116-89. 1989. "Standard Specification for Fiber-Reinforced Concrete and Shotcrete."

Austrian Concrete Society. 1990. Guideline on shotcrete, Part 1: Application. Austrian Concrete Society.

CBI (Cement och Betong-Institutet [Swedish Cement and Concrete Research Institute]). 1990. Toughness of fibre reinforced shotcrete—Recommended test method. Draft 901031. Stockholm: CBI [Swedish Cement and Concrete Research Institute].

DIN 18551- (German Construction Standard). 1992. "Shotcrete, production and quality control." March 1992.

EFNARC (European Federation of National Associations of Special Repair Contractors and Material Suppliers). 1992. "Draft Specification for Sprayed Concrete". September 1992 and April 1993.

International Tunnelling Association. 1991. *Shotcrete in Tunnelling: Status Report 1991, International Tunnelling Association*. 1991. BeFo report 521:1/91. Stockholm: BeFo.

Japan Tunnelling Association. 1991. Report of JTA Working Group on Shotcrete: "Specifications and Guidelines for shotcrete for tunneling in Japan." Tokyo: Japan Tunnelling Association.

JCI (Johannesburg Consolidated Investment Company Ltd.). 1991. General specification No. GS 042 for Steelcreting. Johannesburg: JCI.

Kasperkiewicz, J. and Skarendahl, Å. 1990. Toughness estimation in FRC composites. CBI Report 4:90. Stockholm: CBI [Swedish Cement and Concrete Research Institute].

Maidl, B. *Spritzbeton* (draft). 1992. Bochum, Germany.

Morgan, D. R. 1991. Steel fibre shotcrete for support of underground openings in Canada. Concrete International, November 1991.

Norwegian Concrete Association. 1992. "Shotcrete for rock support." Draft report.

Pöllä, J. 1991. Guidelines for Shotcreting and Current Development in the Wet-mix technique in Finland. *Shotcrete in Tunnelling: Status report 1991, International Tunnelling Association.* BeFo report 521:1/91, 63–87.

SANCOT (South African National Council on Tunnelling). 1991. Report of SANCOT Working Group on Shotcrete: "Shotcrete specification on Inanda-Wiggins Aqueduct, South Africa." Correspondence August 1991.

Skurdal, S. 1989. "Evaluation of test methods for fibre reinforced concrete". Technical Report, Olav Olsen A/S. Lysaker, Norway.

Specification for Lesotho Highlands Project—Dry Mix Concrete. 1991.

Sprayed Concrete Association (U.K.). 1990. *Shotcrete Guidelines and Specifications*. (Reprinted September 1990; originally published October 1986.) U.K.: Jaggerprint Ltd.

Stille, H. and Franzén, T. 1990. Design of shotcrete support from the rock mechanical viewpoint. *Proc., 5th Conference on Shotcrete for Underground Support, Uppsala, Sweden, June 1990,* 1–9. New York: U.S. Engineering Foundation.

Stockholm City Streets and Traffic Administration. 1990. Tender document for underground project "Skarpnäck." Stockholm: Stockholm City Streets and Traffic Administration.

Swedish National Rescue Services Board. Tender document. Unpublished.

Swedish Railroad Department. 1991a. Tender document on railway tunnel project "Grödingebanan-Södertälje Syd-Gerstaberg". Stockholm: Swedish Railroad Dept.

Swedish Railroad Department. 1991b. Tender document on railway tunnel project "Hallandsåsen". Stockholm: Swedish Railroad Dept.

Swedish Standardisation Commission. 1987. Testing of Concrete with Swedish Standard. Stockholm: Swedish Standardisation Commission.

Tiefbau-Berufsgenossenschaft. 1985. Unfallverhütungsvorscrift. Bauarbeiten. April 1985.

Tiefbau-Berufsgenossenschaft. 1988. Unfallverhütungsvorscrift. Gesundheitsgefährlicher mineralischer Staub. Okt. 1988. (in German)

Torsteinsen, P. and Kompen, R. 1986. High-strength fiber-reinforced shotcrete: new types of fibers and test results. *Proc. of 24th Rock Mechanics Day, Oslo, Norway, 1986.*

Vandewall, M. 1991. *Tunneling the World.* Zwevegem, Belgium: N.V. Bekaert S.A.

Wood, D. F. 1992. Specification and application of fiber reinforced shotcrete. In *Proc. of International Symposium on Rock Support, Sudbury, Ontario, Canada, June 1992*, 149–156. Rotterdam: A. A. Balkema.