# Grouts for Pre-stressed Structures and Ground Anchors: A Critique of European Standards and Guidelines

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## 1. Introduction

Portland cement grout is used in post-tensioned and retaining structures to provide a bond between the tendon/anchor and the surrounding concrete/ground and to ensure durable structures. An optimum grout combines desirable fresh and hardened properties with good corrosion protection. The space between the steel and surrounding material (duct, rock, etc.) should be fully filled with grout, creating physical barriers and ensuring corrosion protection for the tendons and ground anchors. Grout for bonded post-tensioning is a combination of Portland cement and water, along with different admixtures needed to obtain the required properties. Important properties are rheology, stability of the suspension with respect to bleeding and settlement, setting times, expansion, mechanical strength, bond strength and permeability.

The currently applicable as well as the provisional European Standards EN 445 [1] and 447 [2] "Grout for pre-stressing tendons" as well as the *fib*-guideline "Grouting of tendons in pre-stressed concrete" [3] provide general guidance and define test procedures for quality control of grouts, but there is no guidance for grout formulation. Therefore investigations have been carried out in a direct cooperation between the authors on the influence of different admixtures such as a plasticizer, an expanding and gas entraining agent, etc., on physical and mechanical grout properties with the overall goal to develop rules for grout formulation [4] . These investigations are part of the European COST Materials Action 534 "New Materials and Systems for Pre-stressed Concrete Structures", which is running from 2003 to 2007.

In this paper, the requirements and test methods as specified in the standards and the guideline as well as our own investigations and test results are described. Each section contains some comments with regard to the advantages and/or disadvantages of requirements and the prescribed test methods.

## 2. Materials and test program

The grouts tested were cement/water-suspensions prepared without or with the addition of admixtures such as a super plasticizer or commercially available products sold for grout preparation which contain all necessary ingredients (IM). In total, seven super plasticizers (SP) based on polycarboxylate (SP 1, 2, 4, 5, 6 and 7) or melaminesulfonate (SP 3), four expanding agents (Exp), one retarder (Re) and three types of IM were used. The active ingredient(s) of Exp, Re and IM were unknown except for Exp 2 which is the only product which is not sold as a grout admixture. It is pure azodicarboxamide ($C_2H_4N_4O_2$). The w/c-ratio was 0.40 in most cases and the admixtures were formally considered to be aggregates. Cements from Austria, Croatia and the UK were used (CEM I; CEM II-AS, CEM II B-S and CEM II F-S). In addition, one commercially available grout, ready for mixing with water, was included in the tests. The investigations reported here included the following tests:

- Rheological parameters
- Volume change
- Bleeding
- Setting times

## 3. Rheological parameters

### 3.1 Prescribed test methods

Three methods are prescribed in the regulations for measuring the fluidity of the grout, namely the cone test, the immersion test and the grout spread method. The most common one is the cone test according to which the time required by 1 litre of grout to pass through the orifice of a cone with a diameter of 10 mm is measured. It is prescribed in the EN 447:1996, which is still in force, that the efflux time must be equal to or less than 25 seconds within 30 minutes after mixing and that it must be at least 10 seconds at the duct outlet time. The latter is to be seen in connection with the fact that the grout needs certain stiffness in order to be able to expel water and air from the duct. The *fib*-guideline and the prEN 447 contain practically the same requirement up to 30 minutes after mixing with the additional requirement that the measurement time must not deviate by more than 20% within 30 minutes after mixing or at the time specified by the manufacturer, but there is no requirement given for the duct outlet time. The latter is a disadvantage because it is important to know whether the grout has the necessary flow behaviour until the duct is fully filled.

The immersion test, which is contained only in the EN 445:1996, is based on measuring the time which a plunger needs to drop through a defined amount of grout in a tube. The grout spread method is contained only in the prEN 445. The grout is filled into a cylinder made of plastic or steel with a diameter of 39 mm and a height of 60 mm. It is placed on a flat glass plate. After filling, the mould is lifted and the spread diameter is measured 30 seconds after lifting. The spread diameter must be at least 140 mm for a period of 30 minutes after mixing.

## 3.2 Cone test

As the immersion test is rarely used and because the grout spread method is not yet in force, only the cone test was included in the investigations. Table 1 show results obtained from cement pastes with a w/c-ratio of 0.40. The results are part of a series of tests performed on 40 different grout mixtures [5].

Table 1: Results of fluidity test

| ADMIXTURE (%, w/w cement) | FLUIDITY (s) |
|---|---|
| - | 170/420 |
| 0,20 % SP 1 | 24/24 |
| 0,35 % SP 2 | 16,5/20 |
| 0,5 % IM 1 | 19,5/26 |
| 1 % IM 1 + 2 % Re 1 | 20,3/21 |
| 0,50 % SP-3 + 5 % silica fume | 34/44 |
| 0,20 % SP 1 + 0,75 % Exp 1 | 15/22 |
| 0,20 % SP-1 + 1,2 % Exp 1 | 16,5/16 |
| 0,20 % SP-1 + 0,50 % Exp 4 | 43,5/53,9 |

It can be seen from the results that the sample prepared without the addition of an admixture clearly failed to meet the requirement. This was also the case at the highest w/c-ratio allowed by the standards of 0.44 (fluidity values: 34s/40s) and shows that the use of a plasticizer is necessary for grout preparation. As can be seen further, the fluidity was influenced differently when (i) different super plasticizers and (ii) a second admixture were added. The latter shows that one admixture can influence the effect of another admixture and makes clear that the effect of admixtures must be tested before their use.

## 3.3 Coaxial Rheometer

One point of criticism of the prescribed test methods is that all are single-point methods whereas rheology is a complex property which cannot be described adequately by single-point methods [ 6]. Therefore, rheology tests using a scientific instrument were included (coaxial rheometer; Paar Physica MCR 300). Such instruments are available with a cylinder as rotating body only. However, when a suspension like a cement paste is tested, there is a risk of sedimentation and of water film formation on the surface of the cylinder and, consequently , of underestimating the shear stress. Therefore, an impeller was used to avoid such separation effects, as suggested by Banfill et al [7, 8]. Figure 1 shows the test program used. Each test was started exactly 5 minutes after the addition of the cement to water. At the beginning, there was a pre-shear period of 5 minutes at a shear rate of 250/s. This is useful in the case of cement in order to break down the existing internal structure formed by agglomerates, etc. Then the measurement started, beginning at a shear rate of practically zero. In the first stage, the shear rate was increased in 10 steps, each having a measurement time of 45 seconds, up to a shear rate of 10/s (R-1; R: ramp) and then, in a second ramp, in 9 steps of 45 seconds each from 20/s to 200/s (R 2) and after this in the same way back to zero (Ramps 3 and 4). Therefore, one cycle (indicated by steps in Figure 1) was completed after 23 minutes. Six equal steps were measured within one test, thus the whole test was completed after 138 minutes.

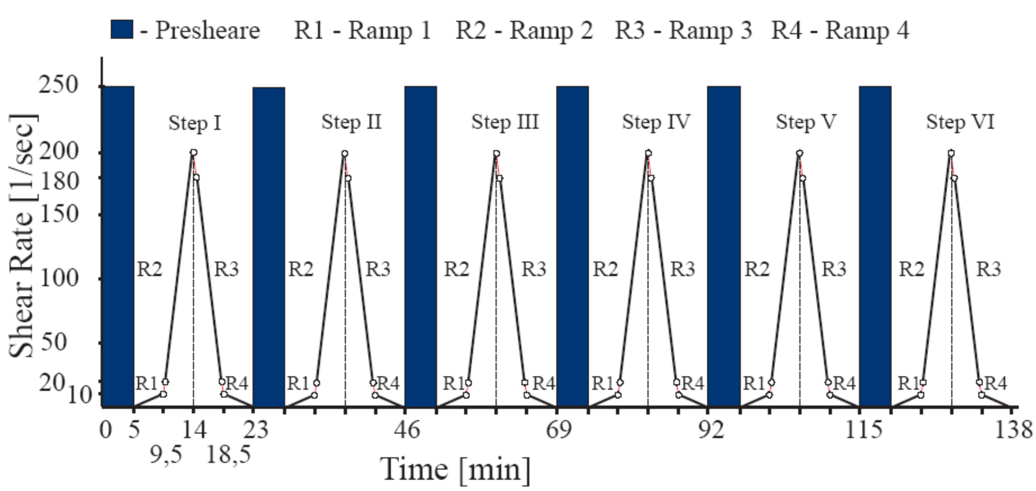


Figure 1: Test program

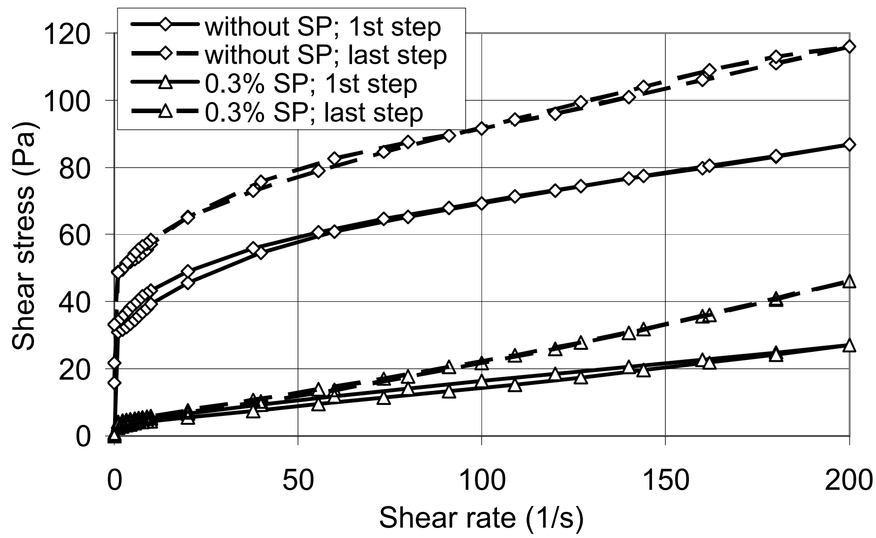


Figure 2: Flow curves of cement pastes prepared without and with the addition of SP 1

Figures 2 and 3 show selected results of the rheology tests with the shear stress versus the shear rate. To make it easier to compare the results, only the curves of the first and of the last of the 6 measurement steps are shown. The increase of the shear stress from the 1st step to the last one indicates that a structure was formed in the cement paste with time. As can be seen from comparison of the curves in Figure 2, the addition of 0.3% of the super plasticizer SP -1 (polycarboxylate based) caused a remarkable decrease of the shear stress values, which were very low even at the end of the test.

Figure 3 shows that the two commercially available products for grout preparation, IM 2 and IM 3 behaved rather differently. The rheological behaviour of the sample IM 2 was equally good as that of SP 1, whereas IM 3 showed hardly any difference from that of the paste prepared without any admixture. The latter interaction shows that tests before use are necessary even in case of products sold for grout preparation.

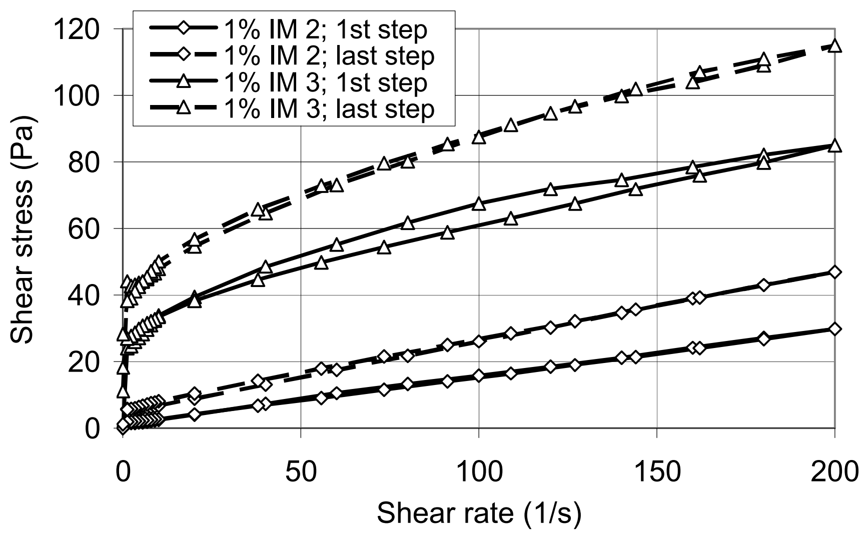


Figure 3: Flow curves of cement pastes prepared with different commercially available products for grout preparation

It should be noted that pre-shearing caused a breakdown of agglomerates so that the curves start at a shear stress of practically zero. However, when the shear rates returned to about zero at the end of one step, the shear stress remained at values which can be seen on the ordinate. This means that the injection process of a grout showing a flow curves such as the ones "without SP" in Figure 2 or "IM 3" in Figure 3, should never be interrupted. Otherwise there is a risk that the yield stress makes it difficult or impossible to start the movement of the grout again. Such effects cannot be detected from the fluidity test according to EN 445:1996. This standard prescribes only 2 measurements, after mixing and 30 minutes later, during which the grout should be continuously agitated according to chapter 6 "Batching and mixing" [1]. This example clearly indicates that the information content of a flow curve is much higher than that of the fluidity test.

## 4. Bleeding and volume change

### 4.1 Standard test methods

Volume change of hydrating cement is primarily happening due to two effects, shrinkage and sedimentation, which are usually combined in the practice. Expansion of the grout is desirable, and therefore the addition of expansive admixture is to be recommended.

The EN 445:1996 test procedure for volume change measurement prescribes either the cylinder or the can method. In the case of the cylinder method, a glass cylinder with a diameter of either 25 mm or 50 mm is needed into which the grout is poured up to a height of 50 mm or 200 mm, respectively. In case of the can method, three metallic cans are used with a diameter of 100 mm and a height of 120 mm. The grout is filled to a height of 100 mm. Then a plate with 6 holes is put onto each can and the distance between the plate and the grout surface is measured with a sliding calliper at 6 different places each. Then the cans are closed with a metal plate to avoid evaporation of water. Bleeding is determined by measuring the volume (height) of the water layer above the grout after 3 hours standing undisturbed and must be equal to or lower than 2 % of the initial volume. The results obtained that way seem to be good enough to allow a comparison of different grouts, but they do not represent the true conditions inside the duct because no strands are present, which have a strong influence. The volume change is measured within 24 hours, meaning that the height of grout in the cylinder or cans is measured immediately and 24 hours later. The limits are: 1% for shrinkage, 5% for expansion.

As the above tests represent the true conditions inside the duct inadequately, the *fib*-guideline prescribes other test methods, which were taken over in the prEN 447:2004, namely the inclined-tube test (for bleeding) or the Wick-induced test (bleeding and volume change). This is why the threshold value for bleeding of 0.3 % of the initial volume is much lower here than in EN 447:1996. For the inclined-tube test, a transparent tube of 5 m in length and a diameter of approximately 80 mm, into which 12 strands are installed, are prescribed. It must be fixed on their supports at an inclination of 30° and will be filled from the bottom by applying a pressure (after filling the pressure must be maintained). For the Wick-induced test, a transparent tube of 1 m in length and a diameter of 60-80 mm, used in a vertical position and containing a 7-wire strand, is necessary. As before, bleeding is measured after 3 hours standing also here. For the determination of volume change, the height of the grout used for the Wick-induced bleeding test must be recorded at 15-minute intervals for the first hour and subsequently at 30-minute intervals until there is no further change in three consecutive readings. This seems to be a progress compared to the EN 445:1996 because information is obtained on how fast and for how long the volume changes. However, these tests are rather difficult to carry out and seem to be suitable at the construction site but not in normal laboratories. Due to these difficulties, bleeding and volume change were tested in the laboratories according to the glass cylinder and the can method only. Some results are shown in Table 2.

Table 2: Results of bleeding tests

| Binder (w/b-ratio: 0.40) | Admixture code | Admixture quantity (% w/w cement) | Bleeding (%) | Volume change (%) |
|---|---|---|---|---|
| CEM I | --- | zero | 1.0 | -5.3 |
| | SP 1 | 0.2 | n.d. | -3.5 |
| | SP 2 | 0.35 | n.d. | -5.0 |
| | IM 2 | 1.0 | n.d. | 0.9 |
| CEM II B-S 32,5R | --- | zero | 1.3 | n.d. |
| | SP 1 | 0,3 | 1.0 | n.d. |
| | SP 2 | 0,3 | 0.3 | n.d. |
| | SP 4 | 0,6 | 0.3 | n.d. |
| | SP 5 | 0,6 | 0.7 | n.d. |
| | SP 6 | 1,0 | 0.7 | n.d. |
| | SP 7 | 0,6 | 1.7 | n.d. |
| | IM 1 | 0.5 | n.d. | -1.1 |
| Grout *) | -- | zero | 1.3 | n.d. |

*) commercially available product; n.d.: not detected

The results show that all samples met the requirement on bleeding of EN 447:1996 and that the admixture can influence the bleeding behaviour. It should be mentioned that the results of bleeding tests, although showing the same trends, did not always correspond very well between the partners. The reasons are not clear yet but may possibly be explained by different mixing techniques and/or by different materials having the same name, e.g. an admixture with the same name made by the same producer in different countries might behave a bit differently. The requirements on volume change were clearly failed in the sample made of CEM I without an admixture. The addition of a super plasticizer reduced volume change, but the requirements were not met. Even in the case of the addition of the recommended quantity (0.5%) of IM 1 (CEM II), the requirement was not met. This shows that the addition of a super plasticizer is not enough and that a stabilising component is necessary.

## 4.2 Newly developed method

It is important to know for how long and how fast the volume is changing in order to obtain information on the volume change of the grout after injection. As the Wick-induced test seemed to be undesirable for laboratory conditions and because the volume change of grout over time

is not determined with the method according to EN 445:1996, a new and more sensitive method was developed:
A glass vessel as shown in Figure 4 was used. It consisted of an Erlenmeyer flask with a neck on its side and a 10 ml pipe on its top with graduations of 0.02 ml per division mark. It was placed on a magnetic stirrer and the paste was stirred during filling. A tube was attached to the neck and a funnel on the free end of the tube. The cement paste was filled in until it reached the lower end of the scaling of the pipe, for which about 150 ml of cement paste was necessary. Then the tube was closed with a clamp and the funnel was removed. Immediately after filling, the position of the paste on the scale was noted down. The volume changes were recorded every 10 minutes up to a total of 150 minutes.

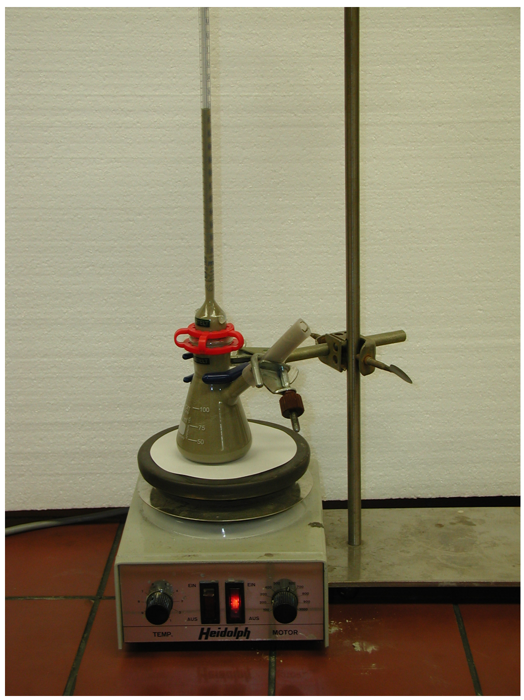


Figure 4: Measurement of volume change of a fresh cement paste

As the ultimate goal of the project is to define rules for grout preparation and because the ingredients of the commercially available products are kept secret by the producers, it was intended to find an agent causing an expansion of the fresh cement paste by gas development. It turned out that Azo-Dicarboxamide ($C_2H_4N_4O_2$) was suitable. This compound is scarcely soluble in neutral water but easily soluble in an alkaline aqueous solution. It decomposes slowly, forming ammonium gas ($NH_3$) and therefore causing expansion.

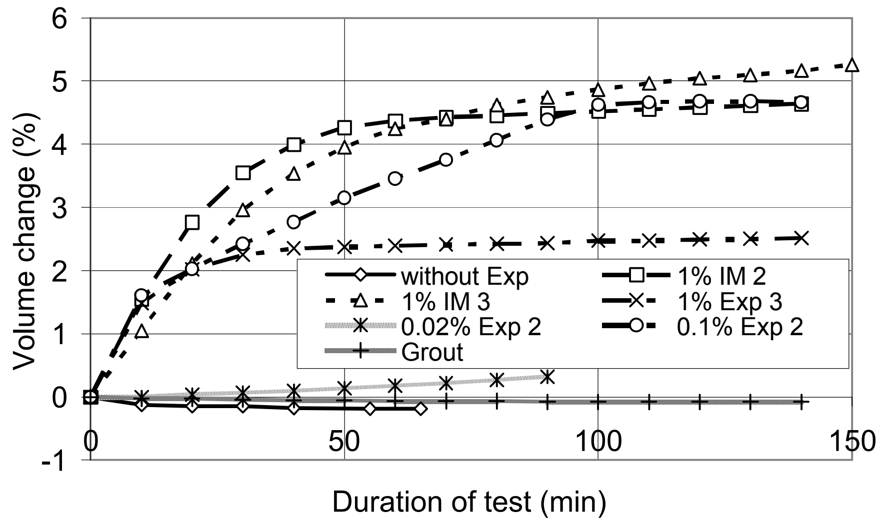


Figure 5: Volume change of cement pastes (w/c- ratio: 0.40) prepared without and with the addition of expanding agents

Figure 5 shows the results obtained at room temperature. As expected, the volume of the paste prepared without the addition of an additive decreased somewhat due to chemical shrinkage (volume difference between free and chemically bound water). The volume of the pastes containing 1%, w/w cement, of the commercially available products IM 2 or IM 3 (1% is the quantity recommended by the producers) showed the greatest expansion within 60 minutes. Expansion was more or less complete in case of IM 2 after this time, but increased slowly in case of IM 3 until the end of the measurement. The expansion agent Exp 3 showed a volume increase of only about 2.5 % and its expansion was already completed after about 30 minutes. Several quantities of Azo-Dicarboxamide (Exp 2) were tested and the results of two of them are shown in Figure 5. The addition of 0.1% by mass of cement showed a total expansion comparable to that of the products IM 2 and IM 3, but the rate of expansion was lower. The tests had been carried out at room temperature (between about 20°C and 25°C) and further tests showed that temperature has a strong influence on expansion. At 10°C, expansion took place more slowly and was not always completed after 1 hour. It was surprising to see that the commercially available grout showed practically neither expansion nor contraction, which shows that expansion is not always considered to be necessary by the producers.

The results show that different products behave rather differently which is demonstrated by the total percentage of expansion and by the time during which expansion occurs. However, no respective information is contained in the product descriptions of the producers. Since it is important to know for how long and how much grout will expand under practical conditions, it seems to be necessary to test them before usage.

## 5. Setting times

The test was carried out according to EN 196-3:2005 [9]. The water demand was determined with the admixture-free paste of each cement and remained constant regardless of the influence of the admixture. The results of the immersion test obtained with CEM I 42,5R (w/c-ratio: 0.40) according to the above standard are given in Table 3.

Table 3: Setting time

| Admixture code | Admixture content (% w/w cement) | Results of immersion test (mm) | Setting time (h:min) initial | Setting time (h:min) final |
|---|---|---|---|---|
| --- | zero | 6 | 2:40 | 3:00 |
| SP 1 | 0.5 | 0 | 6:05 | 6:35 |
| SP 2 | 0.5 | 0 | 5:35 | 6:00 |
| SP 4 | 1.0 | 0 | 5:45 | 6:10 |
| SP 5 | 0.3 | 0 | 5:05 | 5:40 |
| SP 7 | 1.0 | 0 | 6:35 | 7:05 |
| IM 2 | 1.0 | 0 | 6:45 | 7:20 |
| IM 3 | 1.0 | 4 | 4:00 | 4:50 |

As it can be seen from Table 3, all pastes containing an admixture met the requirement for setting according to prEN 447 (initial: >3 hours; final: <24 hours) and *fib*-guideline (initial: >3 hours; final: not specified). The setting times obtained from pastes containing commercially available products for grout preparation (IM 2 and IM 3) or one of the tested super plasticizers were much longer than that of the paste containing no admixture. This shows that the addition of a retarder as an extra additive is not necessary for grout preparation.

## 6. Discussion and conclusions

Apart from the fact that the European standards and fib-guideline contain requirements but do not provide any guidance how the requirements can be met, there are also some other points of criticism. The main points are (i) that some of the test methods prescribed in the prEN 445:2004 and the fib-guideline:2002, such as the inclined-tube test or the Wick-induced test are not suitable for a normal laboratory and that no alternative test methods are specified, (ii) that the requirements seem not always to be good enough, (iii) that cross connections between the requirements are partly missing and (iv) that the prescribed test methods do not always fully deliver the necessary information.

It has been shown that, e. g. the rheological properties of grouts are rather complex and cannot be sufficiently described by single-point measurements as prescribed by EN 445 and the *fib*-guideline. However, as it is necessary to prescribe test methods which can be carried out relatively easily without scientific equipment, it will not always be possible to avoid such imperfections. On the other hand, within the first trial of a newly developed product containing all necessary ingredients for grout preparation it seems to be justified to request more efforts for testing. What appears to be more serious is the fact that the rationale underlying of some of the requirements is not enlightening, e. g. that no expansion of grout is required. Expansion of the fresh grout is considered to be important not only by the authors but obviously by some companies manufacturing products for grout preparation as well. The latter can be concluded from the fact that the investigated products IM 2 and IM 3 contained an expanding component. Unfortunately, the test method according the EN 445: 1996 which is still in force does not include the rate of expansion, and the method prescribed in the prEN 450 is too complicated for a normal laboratory. The test method developed by the authors showed that expansion was completed in most cases after about 1 hour, at least at room temperature. However, after that time the grout is not necessarily fully filled into the duct. As expansion makes sense only when the grout already is in the duct, the standards should contain a requirement for the time of expansion, which should be linked with that of the beginning of setting, etc.

## 7. References


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