DETERMINATION OF THE TENSILE STRENGTH OF CONCRETE

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ABSTRACT

A uniaxial tensile test method is presented. Uniaxial methods provide a direct measurement of the tensile strength. Nevertheless, they are not commonly used. Instead, the simple tensile splitting method is chosen. In this paper, the two different tensile tests are evaluated and compared on the basis of results with high strength concrete. It is shown that reliable and valid uniaxial tensile strengths are efficiently obtained with the proposed test method.

Key words: Concrete, tension, strength, uniaxial

1 INTRODUCTION

The compressive strength has been, and still is, the main parameter for characterizing concrete quality. Traditionally, the compressive load bearing capacity of concrete is used in design, and hence, the simple compression test is an adequate quality measure. Although the tensile properties of concrete play an important role in several design situations, the tensile strength is seldom measured. A direct uniaxial tensile test is difficult to perform. Therefore, indirect measures like tensile splitting or flexural strengths, are often used. When needed in design, the tensile strength is usually derived from the compressive strength through empirical based expressions.

In the last two decades, it has been a rapid development within concrete technology with design of high performance concretes. This calls for a broader set of mechanical properties to be determined in order to provide a satisfactory characterization of the concrete properties. Use of admixtures, additives, and aggregate materials with a wide range of properties, makes it difficult to establish mathematical relations of general validity between compressive strength and other properties. Thus, the need for reliable methods for determination of properties like tensile strength, modulus of elasticity and fracture energy have continuously increased.

In the present paper, a reliable and efficient method for determination of the uniaxial tensile strength is presented. The method that is based on a proposal by Petersson /1/, is compared with and evaluated against the more frequently used tensile splitting test method. Application of the uniaxial test method is demonstrated through test results obtained on high strength concrete within several research projects.

2 UNIAXIAL OR TENSILE SPLITTING STRENGTH

The tensile strength of concrete may be determined either directly in a uniaxial tensile test or indirectly in a tensile splitting test. When conducting uniaxial tensile tests, the main problem is to obtain a uniform stress distribution without introducing stress concentrations. Necked specimens with a narrow mid-section have been used to minimize stress concentrations. Such specimens have however not found common use, due to the inconvenient shape and the risk of eccentricities.

In the most frequently applied uniaxial tensile test method, steel plates are glued to the end surfaces of prismatic or cylindrical specimens (e g, RILEM CPC 7). In such tests, the adhesive and the concrete will normally exhibit different lateral strains due to differences in E-modulus and Poisson's ratio. Consequently, shear stresses are introduced in the contact zone and failure is likely to occur near the specimen ends. According to Petersson /1/, this makes it necessary to use necked specimens even in this case. To avoid necked specimens Petersson used a method with specially designed grips, as shown in Fig 1. This method with some improvements is described in Section 3.

Indirect tensile test methods like the tensile splitting test also called the "Brazilian test", have been widely used. This is due to their simplicity and the difficulties experienced with uniaxial tensile test methods. In the splitting test, the specimen, a cylinder or a cube, is loaded along two opposite generatrices/sides as shown in Fig 2. According to linear elastic theory a stress-field with tensile stresses normal to the loading plane, is then established.

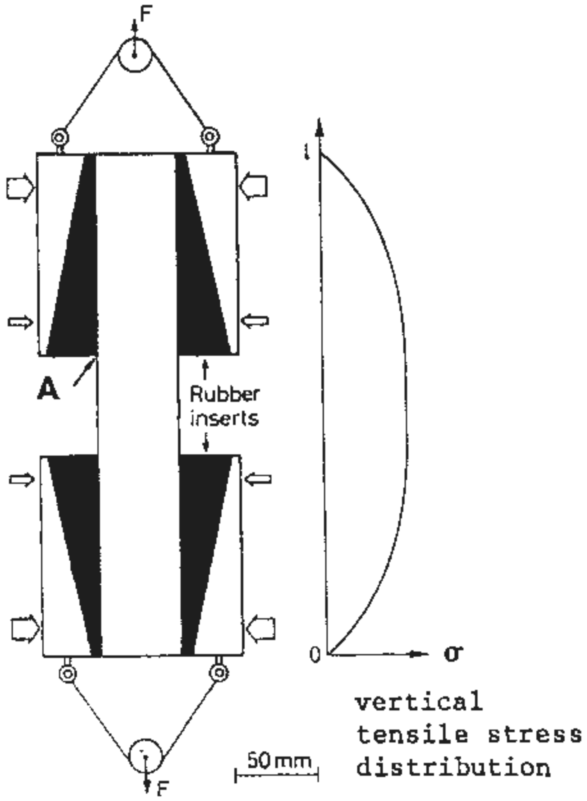

Fig 1 Direct uniaxial tensile test for concrete prisms, according to Petersson /1/

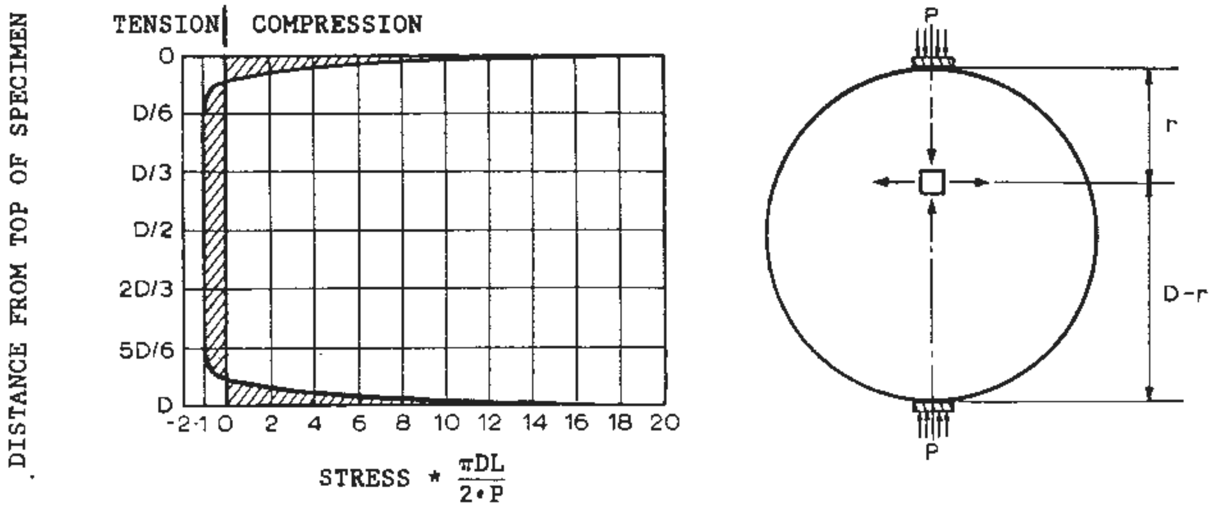

Fig 2 The splitting test method with horizontal stress distribution according to the theory of elasticity /2/

The tensile splitting strength at failure, f_{sp}, is found as:

$$f_{sp} = \frac{2P}{\pi \cdot l \cdot D}$$

where P is the maximum load, l is the length of the line in contact of the specimen (in mm) and D is the cross-sectional dimension of the specimen (in mm).

There have been several investigations comparing the strengths obtained in uniaxial tension and tensile splitting. Any unique relation has however not been found. The more common tensile splitting strength (f_{sp}) is usually considered larger than the uniaxial tensile strength (f_t), e.g. /2-5/. In other investigations /6,7/, the tensile splitting strengths have in some cases been found lower than the uniaxial tensile strength. This scatter in observations is shown in Fig 3.

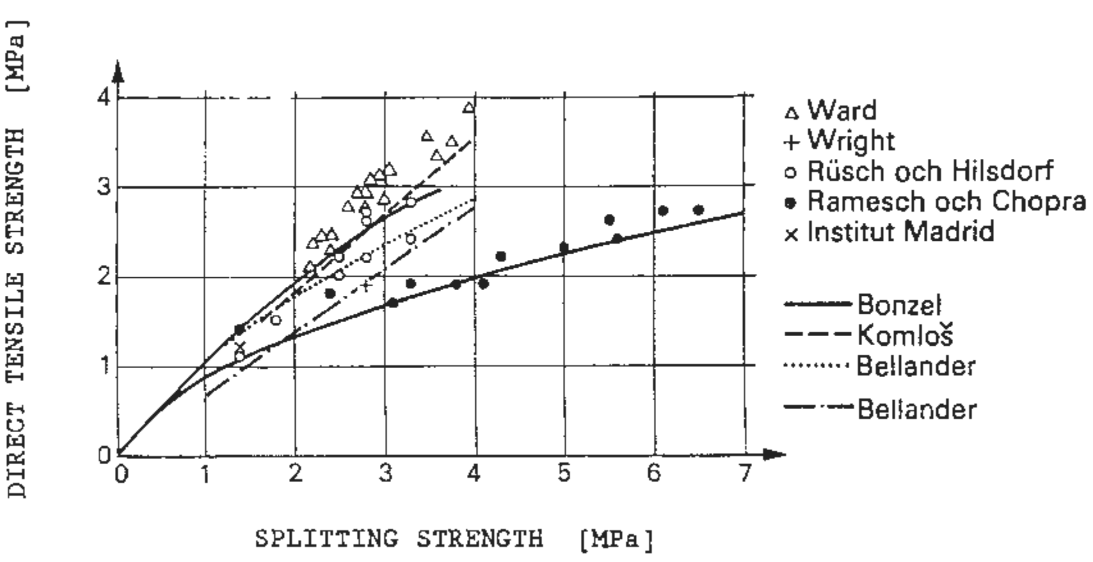

Fig 3 Various relations between the uniaxial tensile strength and tensile splitting /8/

It seems like the relations depend on the concrete grade, or more likely the concrete ductility. Kaplan /9/, who found an average f_t/f_{sp}-ratio of 0.89, stated that: "The difference between the ultimate stresses in these two tests tends to disappear at higher strength levels." In /9/, the highest uniaxial tensile strength was 3.85 MPa.

In an evaluation of the two test methods, Wright /2/ points out three important aspects that should be considered when comparing them:

1) The tensile splitting strength is calculated from the failure load assuming that concrete obeys Hooke's law. It is well known, however, that Hooke's law does not hold good for concrete. In fact will a stress-strain relation like in concrete tend to smooth out high stresses, and thus, the tensile splitting strength overestimates the true tensile strength. (This has been shown in numerical analysis by Modéer /10/).

2) The volume in which failure can be initiated is significantly larger in the uniaxial tensile specimens. Thus, the possibility of combining a high stress with a weak zone increases. In the uniaxial tensile test, an eccentric load would also tend to reduce the measured strength.

3) In the uniaxial tensile test, tensile stresses are present in one direction only. In the tensile splitting test, the portion subjected to high tensile stress is also subjected to a compressive stress perpendicular to the tensile stress. As the strains produced by the two stresses are additive, the actual strain will be considerably greater than that due to the tensile stress alone. As a consequence, failure occurs at a lower stress than in the uniaxial tensile test.

Based on theoretical considerations, Fagerlund and Larsson /11/ assumed that the stress at failure in a tensile splitting test would be 90% of the true tensile strength due to the two-dimensional stress field alone. Fagerlund and Larsson also argued that the lack of consistency in the relation between the uniaxial tensile and the tensile splitting strengths might be due to differences in curing conditions. The uniaxial tensile specimens are more sensitive to drying causing surface shrinkage stresses because the applied stress is uniformly distributed over the cross-section. Shrinkage stresses or cracks will therefore cause failure at an average stress below the true tensile strength. The effect of drying is less significant in the tensile splitting since failure is initiated inside the specimen.

This makes three reasons why the uniaxial tensile test would be expected to give lower results than the tensile splitting test, and one reason why the splitting test would give lower results than the uniaxial tensile test.

As far as high strength concretes are concerned, the first aspect by Wright is probably less significant as the ability to smooth out high stresses decreases with increasing brittleness. It is therefore likely that the difference between f_t and f_{sp} is reduced for HSC. The impact of the third aspect by Wright is obviously dependent on the stiffness of the aggregates. In concretes made of an aggregate type with relatively low stiffness, close to the stiffness of the mortar, the tensile strain contribution caused by compressive stresses in the perpendicular direction, will be small. Increased difference in stiffness between aggregates and mortar, as in low strength concrete and

HSC made of stiff aggregate types, will on the other hand result in a higher strain contribution from the compressive stresses.

For laboratory test specimens stored in water until testing, the effect of drying can be neglected. Self desiccation that is observed for HSC specimens, may however cause initial stresses and microcracks. This may give lower and specimen size dependent tensile strengths.

It has been argued that the ratio of the splitting strength to the uniaxial tensile strength depends on the specimen size and the concrete ductility. This has been shown in numerical simulations by Modéer /10/, Fig 4, where the ductility is expressed in terms of the characteristic length, l_{ch}. The characteristic length is derived from the modulus of elasticity, the fracture energy and the uniaxial tensile strength, according to the expression shown in Fig 4. The results in Fig 4 imply that small size specimen and/or a ductile material (large l_{ch}) give a significant increase in tensile splitting strength compared with uniaxial tensile strength.

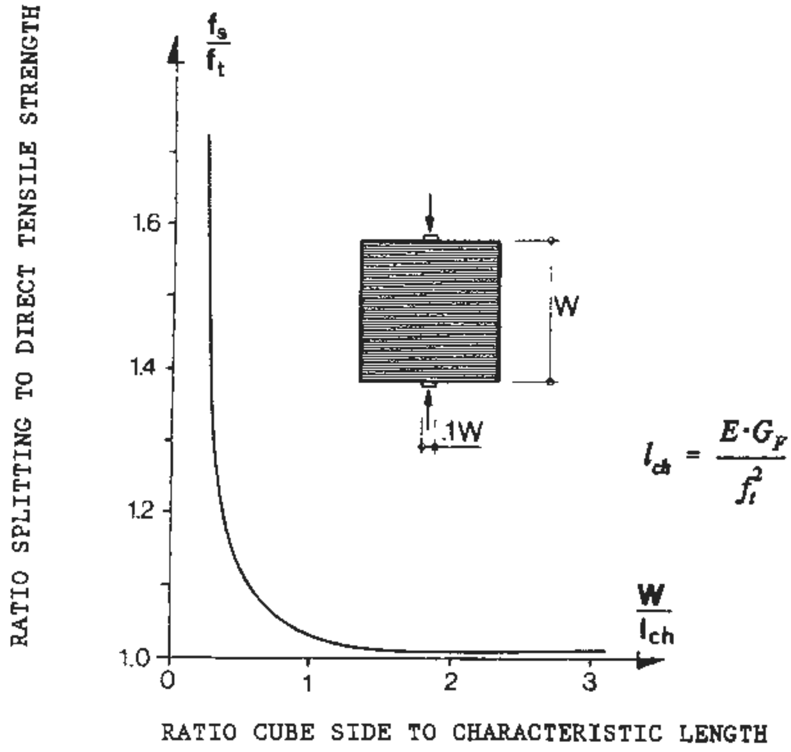

Fig 4 Relation splitting to uniaxial tensile strength versus cube side over characteristic length based on calculations with finite elements and fracture mechanics /10/

3 UNIAXIAL TENSILE TEST METHOD

3.1 Petersson's grips

Petersson's grips were designed to ensure a uniform stress distribution in prismatic bodies. The grips, shown in Fig 1, transfer stress through friction and consist of wedge-shaped rubber inserts glued to steel plates. Clamping forces are applied at two levels on each grip, with a higher force near the end of the specimen. Most of the clamping force is, thereby, applied near the specimen ends where the tensile forces are low. Hence, only a small lateral compressive force acts in the critical section with high tensile stresses, close to the free unclamped part of the specimen. This ensures a smooth transition to a uniform stress field as shown schematically in Fig 1. Experimental results by Petersson /1/, show that failure usually occurs in the unclamped part of the specimen, confirming that a uniform stress field most likely is achieved.

To verify the assumptions by Petersson, a numerical simulation of the tensile test method was carried out /12/. A linear elastic FEM program with six noded triangular elements was used to model steel, rubber and concrete. The influence of the following parameters on the tensile stress distribution was investigated in the numerical simulation:

- the size of the clamping forces and their mutual relation
- the stiffness of the rubber inserts
- the shape of the rubber inserts

Different combinations of the two clamping forces were examined. The smoothest stress distribution was obtained, when the clamping force near the end of the specimen equalled approximately twice the lower clamping force. An optimum stress distribution was obtained, when the total clamping force was only large enough to avoid sliding between concrete and rubber.

Simulations with different stiffness of rubber, ranging from 1-10 MPa, revealed no influence on the stress distribution. The shape of the inserts had, on the other hand, a significant influence. A wedge shape with an angel of 15° to the concrete surface was compared with no wedge shape, i.e., uniform thick rubber. The tensile stress distribution in the most critical cross-section, i.e., the transition between clamped and unclamped specimen, was evaluated.

In the case with no wedge shape, the tensile stresses at the surface rise 9% above the average stress in the simulation. When the inserts are given a 15° slope, the surface stress rise is reduced to 3% only. In actual tests with grips without wedge shaped rubber inserts, the tensile strength will accordingly be underestimated. The wedge shape reduces the risk of underestimation, but the stress rise is not eliminated. A certain stress rise must however be anticipated, at least in the numerical simulation. Whether such a small stress rise is significant or not can only be determined through experiments.

Grips with rubber inserts of uniform thickness had been used in previous tests of tensile strength. According to the simulations, this would increase the risk of failure at the end of the grips. The localization of the fracture surface in some previously tested prisms, which were still available, was therefore examined to verify this prediction. The prisms had been tested at ages ranging from one to six months. Of a total of 70 beams, 34 had been cured in water until testing, while the remaining 36 beams had been cured in air at 20°C and 50% RH from age one day. As shown in Fig 5, 72% of the water cured specimens had failed in the transition zone between clamped and unclamped concrete, while only 35% of the dried specimens had failed in this zone.

These results imply that the stress increase caused by uniform thick rubber inserts, was for the majority of the water cured prisms, large enough to initiate cracks and cause failure in the transition zone. In the dried specimens, the more evenly distribution of the failure zone indicates that failure is not determined by the rubber inserts. Probably was the more evenly distribution of the fracture surfaee for dried specimens due to shrinkage cracks. The randomly distributed cracks induced by shrinkage, caused stress concentrations that most likely equalled or exceeded the stress rise due to flat inserts. Thus, these findings support the analytical solution, i.e., flat inserts give rise to a significant stress concentration. The stress concentration is large enough to influence the failure in wet prisms, but not large enough to exceed the stress concentration due to shrinkage cracks in dried prisms.

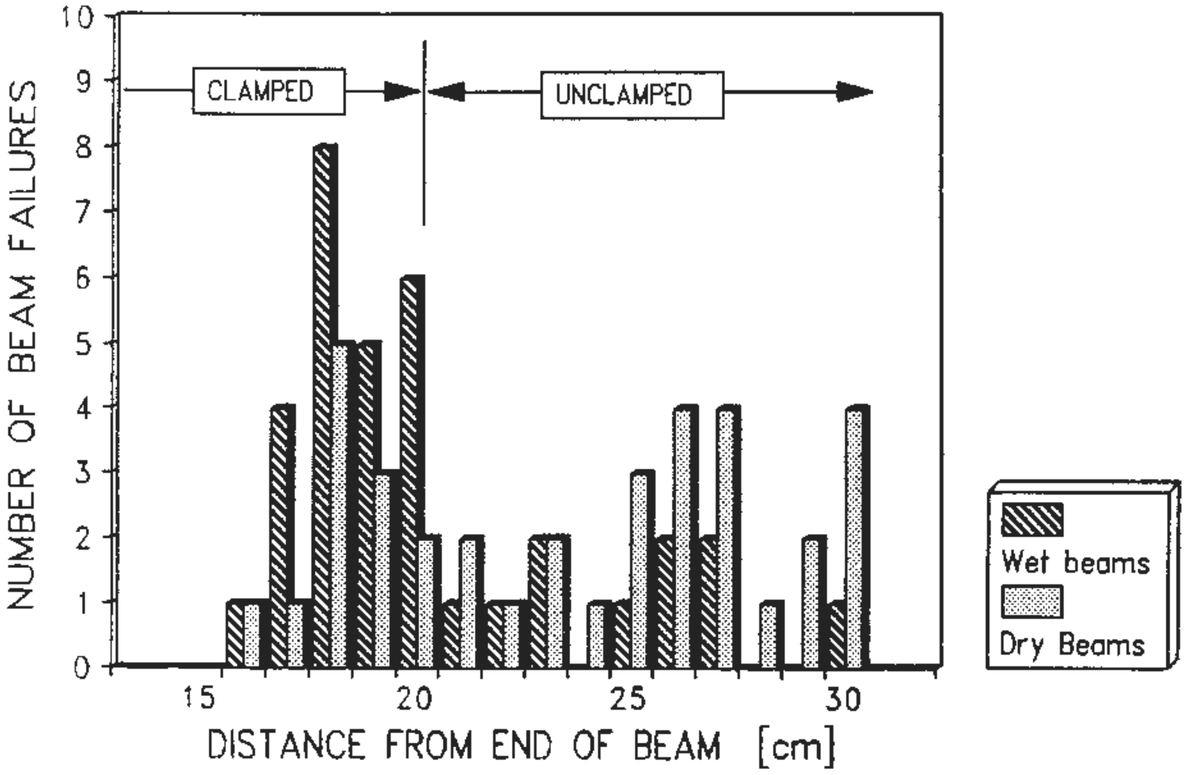

Fig 5 Localization of the failure zone in tensiled prisms

3.2 Modified grips

The clamping arrangement used for the grips shown in Fig 1, does not satisfy the requirements for a controlled and reproducible test. Since, the clamping forces are applied through bolts tightened with a torque wrench, only the moment and not the actual force is known. Due to the visco-elastic deformation of the rubber inserts, adjustment of the four bolts on each grip in mutual balance is then complicated and time consuming. In addition, the considerable shear deformations of the relatively soft rubber inserts during testing, reduce the clamping force. This makes it necessary to apply a high clamping force to ensure sufficient friction throughout the test until failure. Application of a large clamping force involves the risk of concrete failure due to biaxial loading in the clamped part of the specimen and should therefore be avoided.

To achieve better control on the clamping force, the grips were modified. As shown in Fig 6, clamping is supplied by two hydraulic jacks on each grip. Besides a significantly simpler mounting, the jacks provide constant forces and controlled clamping throughout the test. Any reduction in the clamping force due to shear deformation of rubber is immediately compensated. The ratio of clamping force in the hydraulic jacks can be adjusted through separate control of the hydraulic pressures.

Gluing of cut rubber to the steel grips did not provide sufficient bond. The rubber inserts were therefore instead vulcanized directly to the steel plates that had been machined with an inclined groove to the steel surface (Fig 6). This gave an excellent bond and a strong wear resistance. Other important features of the grips are the three ball bearings at the end of each grip. Together with spacers, they reduce eccentricities to a minimum.

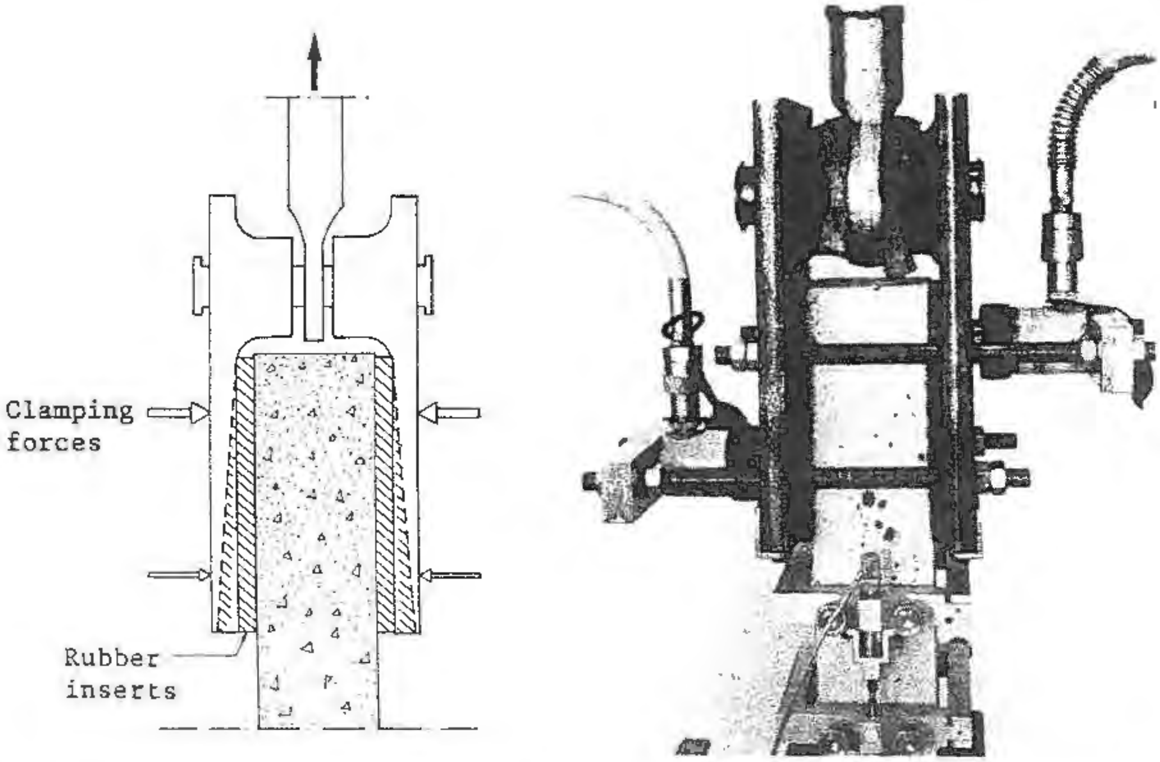

Fig 6 Modified grips with hydraulic jacks, where also one of the two transducers for displacement recording is seen

3.3 Evaluation of the modified grips

There is no universally accepted method for determination of the concrete tensile strength. The validity of a test method can therefore not be compared with an exact solution. Consequently, indirect measures on the validity are needed. In the evaluation of the uniaxial tension test method with modified grips, it was considered important that failure occurred along the unclamped part of the specimen. Then, it could be assumed that a uniform tensile stress distribution without significant stress concentrations, had been established.

The localization of the failure zone was investigated in two test series. In the first series, water cured prisms of dimension 100·100· 600 mm were tested at ages 45 and 90 days. At the age of 45 days only seven out of 18 prisms, i.e., 39%, failed in the unclamped part, while eight failed in the transition zone at the end of the grips and three within the grips. Too high clamping forces were considered the reason for the high percentage of failure at the end of and within the grips. In the test at 90 days, the clamping forces were therefore reduced by 35%. Now 13 out of 18 prisms, i.e., 72%, failed in the unclamped part, while the rest failed at the end of the grips.

In the second series, a total of 84 prisms was tested /13/. Seven different mixes of both normal density (ND) and lightweight aggregate (LWA) concrete were used, confer Table 1. The 100·100· 600 mm large prisms were cured in water and tested at ages one, three, seven and 28 days. For ND-concrete 41 out of 48 prisms, i.e., 85%, and for LWA-concrete 22 out of 36, i.e., 61%, failed in the unclamped part.

Table 1 Constituents (kg/m^3) and properties of concretes in the second series for evaluation of tensile test methods and the influence of admixtures on the strength development /13/

Constituents	ND-O	ND-A	ND-AE1	ND-AE2	LWA-O	LWA-A	LWA-AE
Cement	400	397	367	419	425	426	416
Silica fume	32	32	29	31	25	22	22
Sand 0-5 mm	836	833	769	798	645	647	632
Gravel 8-16 mm	1024	1018	940	1044	-	-	-
Liapor 4-16 mm	-	-	-	-	646	648	632
Water	147	137	135	140	167	158	164
Plasticizer	13.2	13.1	12.1	13.8	11.7	15.3	10.0
Admixture	-	Acceler	Air E	Air E	-	Acceler	Air E
w/(c+silica)	0.34	0.34	0.34	0.31	0.37	0.37	0.37
Air content	1.0	1.2	9.0	2.1	1.9	1.3	4.3
Density	2550	2530	2360	2570	1917	1900	1930
f_{c28} [MPa] (1)	101.2	99.5	78.5	101.3	85.5	84.8	89.8
f_{t28} [MPa] (1)	5.8	5.0	5.2	5.8	4.9	4.9	4.8
f_{sp28} [MPa] (1)	5.4	5.1	4.5	5.7	4.5	4.6	4.6

(1) f_{c28} - 100 mm cube strength (28 days), f_{t28} - uniaxial tensile strength, f_{sp28} - tensile splitting strength strength values are the mean value of three samples from each test type

In the second test series, the uniaxial tensile strength was compared with the tensile splitting strength. From each mix, the splitting strength was determined on three cylinders (ø150 mm/300 mm), at ages one, three, seven and 28 days.

The results from ND concrete given in Fig 7, show that the tensile splitting strength and the uniaxial tensile strength are almost identical. For the ND-A and the ND-AE2 specimens there are no significant differences. For the ND-0 specimens the largest difference occur at age 28 days where f_t is 1.07 times f_{sp}. For the ND-AE1 concrete, f_t increases more with age than f_{sp}, and at 28 days f_t equals 1.16 times f_{sp}. It is also worth noting that the extremely high air content in the ND-AE1 concrete caused no significant reduction in the uniaxial tensile strength as compared with the other concrete mixes. This may be related to the differences in the stress distribution and in failure mechanisms. In uniaxial tension, the weakest part, i e, the interface zones between coarse aggregate particles and cement paste, most likely determine the strength. In tensile splitting, cracks will develop both in the interface zones and the mortar phase before failure. Reduction in the tensile splitting strength may be caused by air voids in the mortar due the air-entraining agencies.

For LWA concrete, the results in Fig 8 show larger variations at early ages compared with ND concrete. At early ages the tensile splitting exceeds the uniaxial tensile strength, while at the age of 28 days the uniaxial tensile strength is the largest one. For the LWA-0 mix the splitting strength is considerable already after three days. In fact, it is almost constant from three days (4.6 MPa) to 28 days (4.5 MPa). There is no obvious reason for this behaviour, but also the uniaxial tensile strength is relatively high at age three days for LWA-0.

Bearing in mind the numerical results by Modéer given in Fig 4, the small difference between the two different tensile strength measures is reasonable. According to Modéer there ought to be no difference for a ratio W/l_{ch} exceeding one. In the present test, the characteristic length was estimated to be about 150 and 100 mm for ND and LWA concrete respectively, i.e., the ratio W/l_{ch} is close to one.

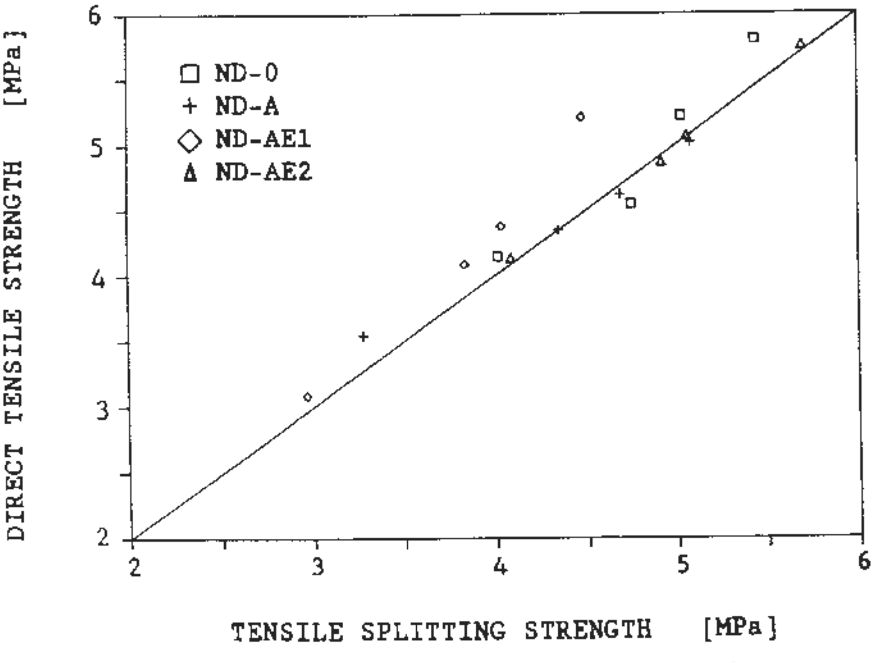

Fig 7 Uniaxial tensile versus tensile splitting strength at ages one, three, seven and 28 days for the ND concretes in Table 1 /12/

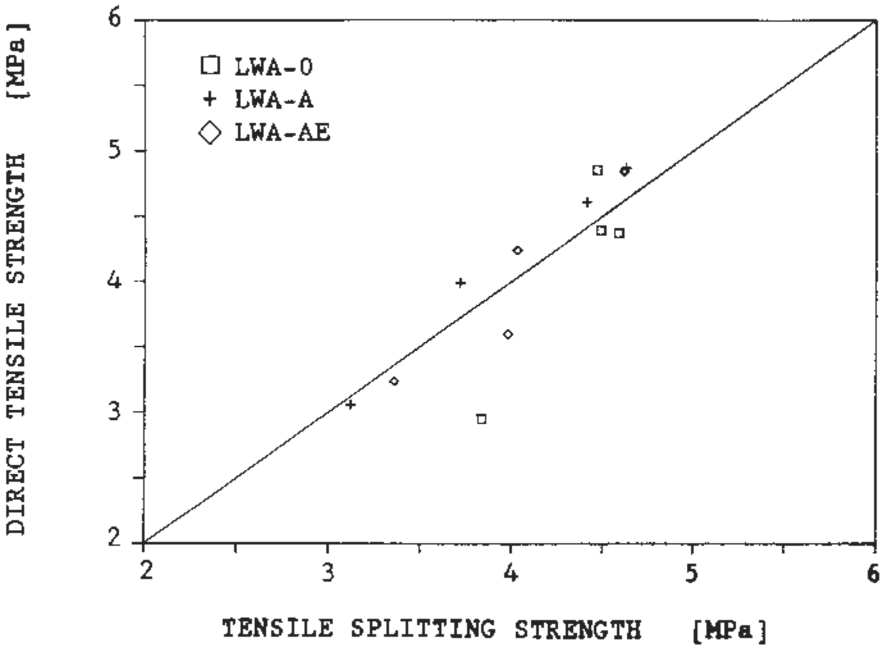

Fig 8 Uniaxial tensile versus tensile splitting strength at ages one, three, seven and 28 days for the LWA concretes in Table 1 /12/

4 APPLICATION TO HIGH STRENGTH CONCRETE

In several research projects on high strength concrete, both the uniaxial and tensile splitting strengths have been determined. In all these projects, the modified grips were used to determine the uniaxial tensile strength.

The small differences between the uniaxial tensile and tensile splitting strengths observed in the evaluation test were confirmed in an investigation /14/ with four mixes made with different aggregate types according to Table 2. As can be seen from the results in Table 3, the uniaxial tensile strengths at age 60 days are from 2 to 6% higher than the splitting strengths.

The four mixes in Table 2 differed not only with respect to the aggregate type, as the content of silica, superplasticizer and filler, and the water-binder ratio were also varied. These variations resulted from the aim of producing concretes with different brittleness but almost the same compressive strength.

Table 2 Constituents (kg/m^3) of the concrete mixes used to investigate the influence of aggregate type /14/

Constituents	LWA Concrete	Granite concrete	Basalt concrete	Qartzdiorite concrete
Cement	494	391	487	399
Silica fume	55	43	-	44
Water	148	156	165	173
Sand 0-5 mm	630	918	702 (1)	535 (2)
Liapor 8 (4-16 mm)	600	-	-	-
Granite (8-16 mm)	-	918	-	-
Basalt (4-16 mm)	-	-	1109	-
Quartzite (4-16 mm)	-	-	-	1247
Superplasticizer	18.7	4.9	12.5	6.8
Filler	19.5	-	37.0	10.0
w/(c+s)	0.27	0.36	0.34	0.39

(1) crushed basalt

(2) crushed quartzite

Table 3 Mechanical properties of the concretes in Table 2, mean values of three samples except for the uniaxial tensile strength results which are the average of six prisms /14/

Property	Age at test [days]	LWA Concrete [MPa]	Granite concrete [MPa]	Basalt concrete [MPa]	Qartzdiorite concrete [MPa]
Compressive cube strength (100 mm cubes)	28	93.8	104.1	105.1	106.7
	60	97.4	111.9	109.2	113.7
Tensile splitting strength (150/300 mm cylinders)	28	4.6	5.1	5.9	5.8
	60	4.4	5.2	6.1	5.3
Uniaxial tensile strength (100·100· 600 mm)	60	4.5	5.3	6.4	5.6

Within the research programme "High Strength Concrete" both the tensile splitting and the uniaxial tensile strength have been determined within several subprojects. Some of these results are presented in Fig 9 /15/. For all concretes, a granite type aggregate is used, together with a 5% silica content and water/binder ratios in the range 0.27 to 0.5. As opposed to the results in Fig 3 and Table 3, it can be seen that the tensile splitting strength is with one exception higher (up to 25%) than the uniaxial tensile strength.

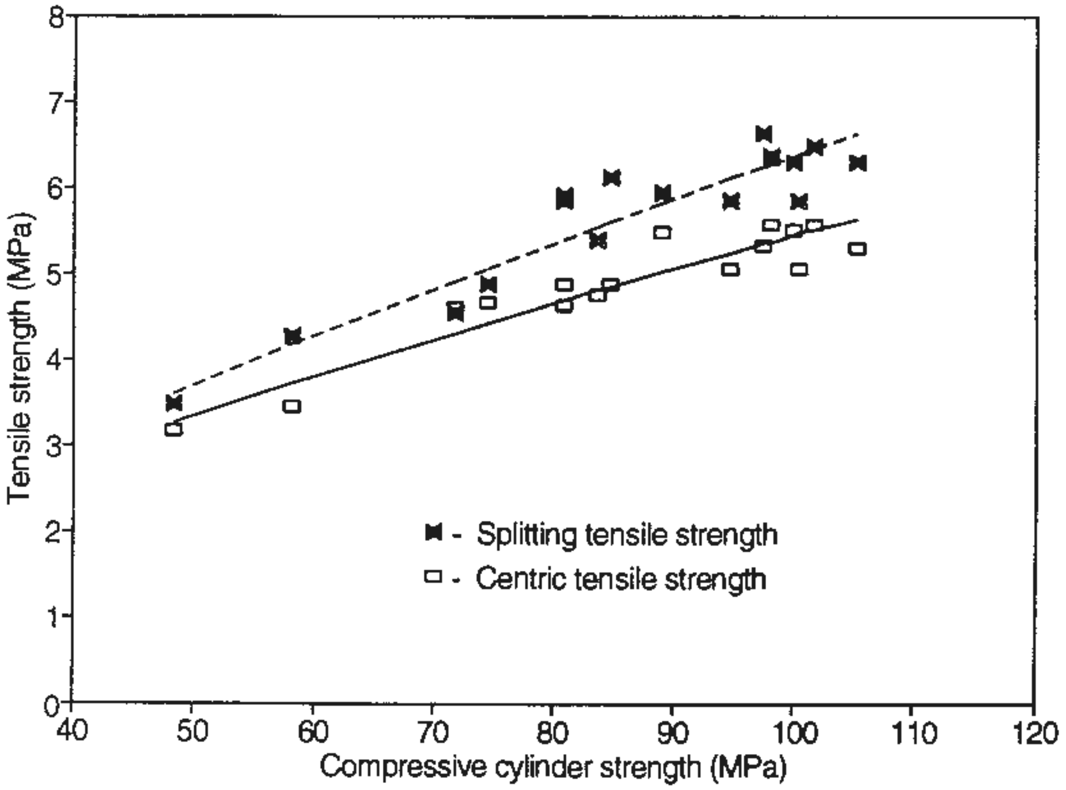

Fig 9 Tensile splitting and uniaxial tensile strength versus compressive cylinder strength, each point is an average of three samples from tests within the HSC research programme /15/

According to Fig 4, the strength level and the specimen size might influence the ratio of uniaxial to tensile splitting strength. To examine this influence, a test series was performed on concretes with compressive strengths in the range 70 to 130 MPa /16/, Table 4. Different specimens sizes were used for the tensile splitting tests only as the specimen size is difficult to alter in the uniaxial test rig. The results are presented in Table 5 and Figs 10-11. From these results, it is evident that the test method and specimen size have a strong impact on the measured tensile strength. It is a general trend that a higher splitting strength is obtained on cubes than on cylinders with the same cross-sectional dimension. It is also a clear tendency for the splitting strength to increase more with increased compressive strength compared with the uniaxial tensile strength.

Table 4 Concrete mixes used to investigate the influence of specimen size and type /16/

Constituents (kg/m^3)	Mix "70"	Mix "100"	Mix "130"
Cement (Norcem HS65)	377	420	496
Silica (dry)	11.7	36.6	55.1
Water	175	160	138
Sand 0-5 mm	926	859	793
Quartzdiorite 8-16 mm	926	969	1009
Superplasticizer (Mighty 150)	3	6	10
water/binder ratio	0.45	0.35	0.25

Table 5 Compressive strengths, uniaxial tensile strength and tensile splitting strengths for the concretes in Table 4, average values of three (compressive strengths) or six (tensile strengths) samples with coefficient of variation in brackets /16/

Concrete quality	Cube strength f_{c28} [MPa]	Cylinder strength f_{cc28} [MPa]	Uniaxial tensile strength f_{t28} [MPa]	Splitting strength Cubes [MPa]			Splitting strength Cylinders [MPa]	
				100 mm	150 mm	200 mm	ø100mm	ø145mm
"70"	74.6 (0.027)	62.3 (0.010)	5.6 (0.018)	5.1 (0.051)	4.4 (0.051)	4.5 (0.031)	4.8 (0.048)	3.9 (0.050)
"100"	95.1 (0.011)	84.9 (0.027)	6.0 (0.029)	6.4 (0.050)	6.2 (0.056)	5.5 (0.062)	5.3 (0.076)	5.3 (0.088)
"130"	126.9 (0.006)	114.8 (0.023)	6.2 (0.051)	7.9 (0.058)	7.1 (0.027)	7.4 (0.026)	7.3 (0.063)	6.7 (0.079)

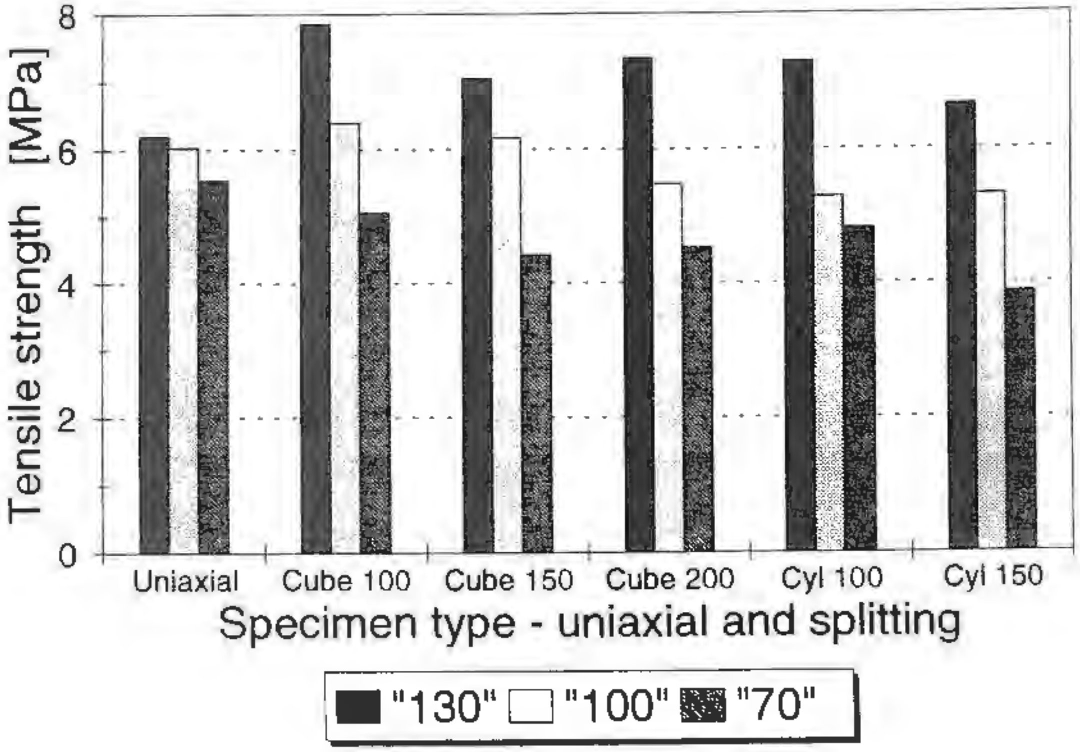

Fig 10 Uniaxial and tensile splitting strength from Table 5, for each specimen type values from all three mixes are grouped together

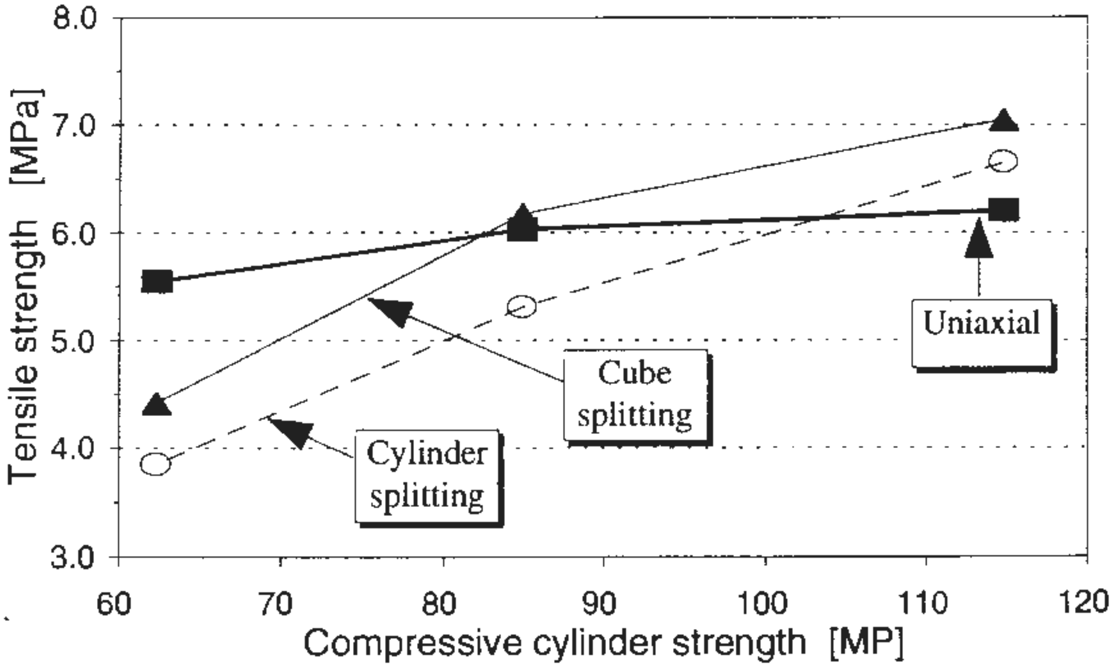

Fig 11 Tensile strength vs compressive cylinder strength, the curves represent: "Uniaxial" = uniaxial tensile strength, "Cube splitting" = splitting of 150 mm cubes, "Cylinder splitting" = splitting of ø150 mm cylinders

The significant difference between the uniaxial tensile strength and the cylinder splitting strength for the "70" and "100" concretes are in contrast to previous results shown in Fig 9. This may reflect differences in the properties of the coarse aggregate particles used, in particular the stiffness and surface texture (quartz-diorite is a relatively stiff rock type). Results from previous investigations on aggregate properties and concrete ductility /12,14/, indicate that the uniaxial tensile strength depends on the bond strength and fracture energy of the interface zone, while the tensile splitting strength also depends on the strength and fracture energy of the mortar. When the w/c-ratio is reduced below about 0.4, it appears to be no further increase in the bond strength, while the mortar strength increases. A more thorough discussion on the influence of aggregate properties on the tensile properties of high strength concrete may be found in /17/.

5 DISCUSSION

In the evaluation of the proposed tensile grips, failure in the unclamped part was regarded a necessary, but not sufficient condition for uniaxial failure. For most of the tested concretes, 70 to 85% of the prisms fail in the unclamped part. A lower percentage found in some cases seemed to result from inaccurate adjustment of the clamping forces.

Statistically, a certain amount of the prisms will fail at the end of the grips as discussed by Petersson /1/. Close to failure, the deformation of the rubber inserts is so extensive that there is no or negligible contact between rubber and concrete along the outer two centimetres of the inserts. Thus, even in this part of the prism, there is an almost uniform tensile stress. Two centimetres at the end of each grip represent a 20% increase of the unclamped length which initially is 20 cm. Given a random distribution of the failure zone along the unclamped part of the prism, failure should occur at the end of the grips in nearly 20% of the prisms. A percentage in the range 15 to 30% as found in most of the tests is therefore reasonable to expect. It does not necessarily reflect the presence of any significant stress-concentration. This was confirmed by the measured tensile strengths. Failure at the end of the grips caused no reduction in the recorded strength compared with the average value of the specimen that failed in the unclamped part.

Failure in the unclamped part is not a sufficient condition, because eccentricities may still be present. Eccentricities are minimized by use of three ball bearings in each pair of grips. The fact that the uniaxial tensile strength in most cases of the evaluation was found to equal or exceed the tensile splitting strength, indicates negligible eccentricities. Thus, the modified tensile grips can be considered to provide valid measurements of the true tensile strength.

6 CONCLUSIONS

The uniaxial tension test method is the only method for a direct determination of the tensile strength of concrete. Due to difficulties in performing the uniaxial tensile test it has not been commonly used. As demonstrated these difficulties are overcome with use of the grips presented in this paper. Reliable and valid test results are obtained in an efficient test where the time consume equals that for compressive cube tests. One major advantage with uniaxial tensile tests compared with indirect methods is the possibility for measuring the deformation in the loading direction. This allows determination of the ultimate strain and the E-modulus in tension.

Realizing that the equipment for uniaxial tensile tests requires a special test rig, its application will be limited to research institutes and universities. It is therefore still a need for an additional test method for quality control. The tensile splitting test, that is carried out in an ordinary compression test machine, has been widely used for low to medium strength concretes. Results from high strength concrete do not indicate that the difference between the uniaxial tensile strength and the tensile splitting strength is larger than for low to medium strength concretes. Hence, the tensile splitting method may also be used for high strength concrete at least up to a cylinder compressive strength of 100-110 MPa. It should, however, be stressed that this yields tensile splitting strength obtained on ø150· 300 mm cylinders, as cube specimens may overestimate the tensile strength. However, for concretes that differ from those usually tested with respect to aggregate type and size, silica content etc, it is advised to determine the uniaxial tensile tests for comparison and control.

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