STRENGTH OF CERAMIC TILES

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1. INTRODUCTION

Characterisation of the mechanical behaviour of ceramic tiles is an important issue considering the resistance to damage against various types of loading as induced during normal use. As an example, the resistance against impact loading is a critical parameter for many applications. To be able to take into account the brittle behaviour of these materials in a tool for analysis of strength of these components, some aspects of the mechanical behaviour of both floor and wall tiles have been examined. In particular the results of conventional bend and fracture toughness tests are compared with results from contact load tests to assess their relation. Also the influence of processing history has been analysed in order to see whether this yields differences in mechanical properties that can be determined from mechanical tests.

2. MATERIALS AND METHODS

The ceramic tiles used are from different producers. The floor tiles labelled F1-3 are a class B1 tile. These tiles are normally pressed at a pressure of 400 bar. To analyse the influence of this pressure also tiles were produced at pressures of 200 and 300 bar which are labelled F1-1 and F1-2, respectively. These tiles were pressed with a size of about 300*300 mm. The tiles labelled F2-1 and F2-2 were also class B1 floor tiles. F2-1 tiles were pressed with a size of 200*200 mm, whereas F2-2 tiles were pressed with a size of 400*400 mm. The tiles labelled W1-1 and W1-2 are wall tiles. W1-1 tiles had a size of 200*250 mm, whereas W1-2 tiles had a size of 250*330 mm.

From these tiles suitable samples for mechanical testing were produced by sawing and grinding. The glaze layer of the tiles was not removed. The surface roughness of the ground surfaces was typically 1 mm as determined by contacting profilometry.

The strength of the materials was determined by 3-point (3PB), 4-point (4PB) and ball-on-ring (BOR) bend tests[1]. The fracture toughness was determined by means of a single edge notched beam (SENB) test[2]. In the 3PB, 4PB and SENB tests the specimens had typical dimensions length*width*heigth 50*15*7 mm. The 3PB test was carried out with a support span of 40 mm. The 4PB test had a support span of 40 mm and a loading span of 20 mm. The SENB tests was carried out in 3-point bending with a support span of 40 mm. The notch in the SENB samples had a width of about 120 mm and a depth of 1.5 mm.

The BOR tests were carried out on disks with a diameter of 100 mm and a thickness of about 7 mm. The support radius was 78 mm and the hardened steel loading ball had a diameter of 15 mm.

The contact load tests or ball-on-plane (BOP) tests were carried out to analyse the influence of support conditions on the fracture behaviour. This test was carried out by loading a disk-shaped sample (diameter 100 mm and thickness about 7 mm) using a steel ball with a diameter of 15 mm. The sample was placed on a hardened steel support with a varying number of sheets of plain copier paper between sample and support. By varying the number of sheets of paper the stiffness of the supporting layer can be varied. For a stiff support bending of the sample will be suppressed and fracture due to contact stresses near the loading ball on the upper surface of the sample can be expected (as in case of impact loading on a stiff support[5]). For a soft support the bending stresses can become significant, causing fracture to originate on the lower surface of the sample (as in case of impact loading on a soft support). In the tests carried out the number of sheets of paper was set to 1, 10 and 100.

All tests were carried out on a universal testing machine at room temperature and ambient humidity (about 50% RH). The crosshead speed was about 1 mm/min in all tests. To get a proper description of the statistical distribution of the strength values normally about 30 samples were tested in a test. The fracture toughness was determined from at least 8 samples.

3. RESULTS OF STRENGTH AND FRACTURE TOUGHNESS TESTS

3.1. STRENGTH TESTS

The measured fracture forces in the strength tests were translated to maximum tensile stresses S_f at the surface in tension using standard formulae[3]. The stress data were subsequently analysed using Weibull statistics[4], resulting in the Weibull modulus m and the average fracture stress $\overline{S}_f$ according to the expression

$$P_f = 1 - \exp[-(\frac{1}{m}!)^m (\frac{S_f}{\overline{S}_f})^m]$$

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[1]. L. Dortmans, G. de With and A. Reymer, *Size effect for the strength of ceramic tiles*. Proceedings Qualicer 1996, 563-569.

[2]. J. Srawley, *Wide range stress intensity factors expressions for ASTM E399 standard fracture toughness specimens*, Int. J. Fracture Mechanics, 12 (1976), 475-476.

[3]. H. Scholten, L. Dortmans, G. de With, B. de Smet and P. Bach, *Weakest-link failure predictions for ceramics II: design and analysis of uniaxial and biaxial bend tests*, J. Eur. Cer. Soc., 10(1992), 33-40.

[4]. W. Weibull, *A statistical theory for the strength of materials*, Ingeniors Vetenskaps Akadamien Handlingar, no. 151, 1939.

[5]. D. Sherman and D. Brandon, *The ballistic failure mechanisms and sequence in semi-infinite supported alumina tiles*, J. Mater. Res., 12(1997), 1335-1343.

for the failure probability P_f at a fracture stress S_f with $(1/m)!$ as the gamma function. Figure 1 gives a typical result (Weibull plot) for the 3PB test on floor tile F2-1 and wall tile W1-1. The average fracture stresses $\overline{S}_f$ for the various tests carried out are given in Table 1.

The Weibull modulus was fairly consistent for all tests and amounted about 20-25 for the floor tiles and about 15-20 for the wall tiles.

3.2. FRACTURE TOUGHNESS TESTS

The measured fracture forces in the SENB tests were translated to fracture toughness value K_{Ic} using standard formulae[2]. The scatter in the values thus determined for 8 to 10 samples was typically about 5%. The average values are given in Table 1.

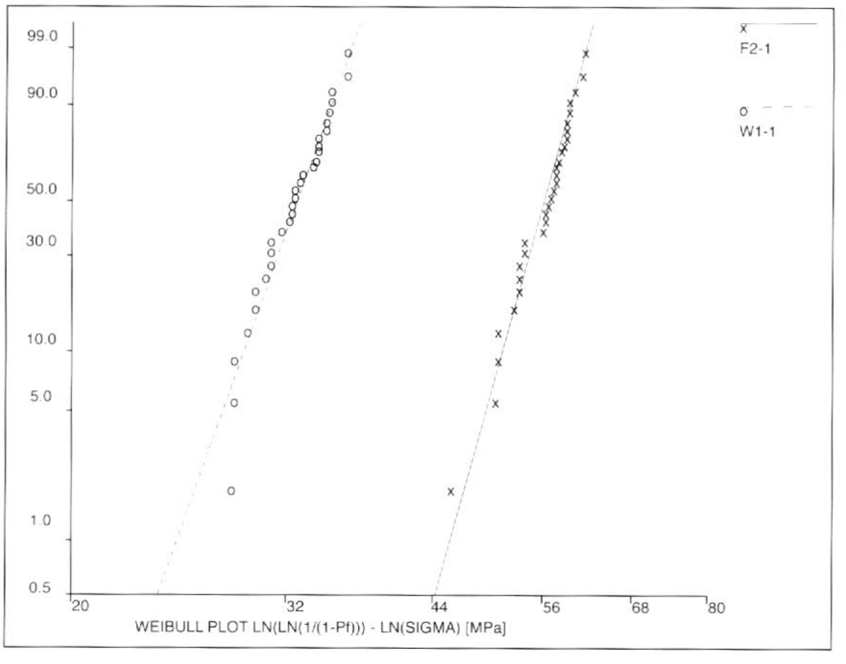

Figure 1. Weibull plot for 3PB tests on floor tile F2-1 and wall tile W1-1.

material	$\overline{S}_f$ 3PB	$\overline{S}_f$ 4PB	$\overline{S}_f$ BOR	K_{Ic}	a
F1-1	58	52	62	1.25	370
F1-2	65	59	70	1.32	320
F1-3	64	62	69	1.55	400
F2-1	56	49	100	1.26	420
F2-2	59	51	60	1.25	380
W1-1	32	30	36	0.83	480
W1-2	30	26	34	0.75	520

Table 1. Average fracture stress [MPa], fracture toughness [$MPam^{0.5}$] and calculated defect size a [μm] for various materials and tests.

[2]. J. SRAWLEY, *Wide range stress intensity factors expressions for ASTM E399 standard fracture toughness specimens*, Int. J. Fracture Mechanics, 12 (1976), 475-476.

3.3. DISCUSSION OF STRENGTH AND FRACTURE TOUGHNESS TESTS

The 3P and 4PB strength values for the floor tiles as normally produced (F1-3, F2-1 and F2-2) are comparable, although the strength of tiles F2 is somewhat lower than that of tiles F1-3. The BOR strength value for floor tile F2-1 is remarkably high if compared to F1-3 and F2-2, for which no obvious explanation could be found as fracture in all cases originated from the surface loaded in tension.

From the results for the floor tiles F1-1, F1-2 and F1-3 it is obvious that an increase in pressure during pressing leads to an increase in strength, although the difference between F1-2 and F1-3 is not large indicating that not much difference is obtained by increasing the pressure from 300 to 400 bar. The strength of the wall tiles is about half that of the floor tiles.

The fracture toughness values for the floor tiles F1-1, F1-2 and F1-3 show a marked increase with increasing pressure. Also there is a difference in fracture toughness between F1-3 and F2-1/2. To analyse this difference in more detail, use is made of the Griffith relation between strength, fracture toughness and defect size

$$K_{Ic} = YS_f \sqrt{a}$$

with Y as a defect shape parameter and a as the typical defect size. Assuming the defect is semi-elliptical in shape Y amounts 1.26. Then the above relation, the 4PB strength data and the fracture toughness values in Table 1 result in the values for the average defect size a as given in Table 1.

The defect size for the floor tiles F1-3, F2-1 and F2-2 is quite comparable (about 400 micrometer). This shows that the difference in strength as shown in Table 1 between these tiles can largely be explained by a difference in fracture toughness. For the wall tiles the defect size is comparable to that of the floor tiles. Therefore their relatively low strength can be explained by the lower fracture toughness.

The Weibull moduli for the different materials are relatively high, indicating a narrow defect size distribution. The defects from which fracture originates in these materials have in some cases been identified by optical microscopy and appear to be large pores or quartz particles. The size of these defects corresponds well to the size as calculated above. However, further fractographical analyses are required to substantiate this.

4. CONTACT LOAD TESTS

4.1. WALL TILES

The results for the contact load tests carried out on the wall tiles are given in Table 2 as the average fracture force $\overline{F}_f$ and the Weibull modulus m according to the Weibull expression

$$P_f = 1 - \exp[-(\frac{1}{m}!)^m (\frac{F_f}{\overline{F}_f})^m]$$

The thickness for the W1-1 samples was 7 mm and for the W1-2 samples 8 mm.

material	number of sheets	$\overline{F}_f$	m
W1-1	1	2200	3
	10	890	17
	100	900	15
W1-2	1	3800	8
	10	1240	21
	100	1200	16

Table 2. *Average fracture force [N] and Weibull modulus m for contact load tests on wall tiles.*

4.2. FLOOR TILES

The results for the contact load tests carried out on the floor tiles are given in Table 3 as average fracture forces and Weibull moduli. The thickness for the F1-1, F1-2, F1-3, F2-1 and F2-2 samples was 5, 5, 8, 6 and 8 mm, respectively.

4.3. DISCUSSION OF CONTACT LOAD TESTS

The results for the contact load tests on the wall tiles can be understood taking into account the fracture patterns. In case of 1 sheet of paper between sample and support fracture is due to high contact stresses on the upper surface of the sample. This results in the formation of cone cracks accompanied by plastic deformation beneath the indenting ball. For 10 and 100 sheets of paper fracture is from the lower surface of the sample which is subjected to tensile stresses as in the strength tests discussed in section 3. In these cases the average fracture force and the Weibull moduli are comparable to that obtained for the ball-on-ring test. For W1-1 the average fracture force in the BOR test was 800 N and for W1-2 1000 N. Also the Weibull moduli for 10 and 100 sheets of paper agree fairly well with that for the BOR (and 3PB and 4PB) test. The difference in fracture force for 10 and 100 sheets can be explained by the difference in thickness t. The bending stress at the lower surface will be proportional to F/t^2. From Table 2 the ratio F/t^2 for W1-1 and W1-2 with 100 sheets is about equal (18.4 versus 18.7 MPa) which is in agreement with the results of the bend tests as these resulted in about the same strength for these materials (Table 1). The much higher fracture force and much lower value for the Weibull modulus in case of 1 sheet of paper must be explained by considering the tensile stresses developed near the loading ball. This is not without problems given the influence of the support conditions, glaze layer, friction, plastic deformations etc. and needs further analysis.

For the floor tiles similar results are obtained as for the wall tiles. For 1 sheet of paper (stiff support) high fracture forces and a large scatter are obtained, with fracture originating at the upper surface near the loading ball. For 10 and 100 sheets of paper the results agree fairly well and the scatter reduces to the values found in the bend strength tests (with a typical Weibull modulus of 20 to 25). The ratio F/t^2 for the F1-1, F1-2, F1-3, F2-1 and F2-2 samples with 100 sheets of paper is 29.2, 33.2, 35.6, 29.2 and 33.3 respectively. These data are in agreement with the strength data given in Table 1 and about twice that of the ratio F/t^2 for the wall tiles as could be expected from the strength values given in Table 1.

material	number of sheets	$\overline{F}_f$	m
F1-1	1	1356	1.4
	10	750	25
	100	730	24
F1-2	1	1850	3
	10	892	12
	100	830	28
F1-3	1	5390	6
	10	2569	10
	100	2278	18
F2-1	1	860	11
	10	950	17
	100	1050	26
F2-2	1	1830	16
	10	1980	20
	100	2130	24

Table 3. *Average fracture force [N] and Weibull modulus m for contact load tests on floor tiles.*

5. CONCLUSIONS

Strength and fracture toughness tests have been carried out on ceramic floor and wall tiles. Differences in mechanical properties in these brittle materials due to differences in processing history can be determined as was shown by an analysis of the influence of the pressure applied during pressing of floor tiles. Clearly an increase in pressure leads to stronger materials. This can largely be explained by an increase in fracture toughness as the average size of the strength limiting defects is more or less constant. Similarly the difference in strength between floor tiles and wall tiles can largely be explained by the difference in fracture toughness.

It was shown that the behaviour under contact loading strongly depends on support conditions. For a soft support fracture due to bending stresses becomes the dominant failure mechanism. In this case strength data obtained by bend tests are useful. However, in case of a stiff support other aspects must be considered. High tensile stresses in the vicinity of the contacting medium can cause failure. In further research the relation between the critical load in these conditions and relevant material properties must be established.