Fracture Mechanics of Concrete Structures,
Proceedings FRAMCOS-2, edited by Folker H. Wittmann,
AEDIFICATIO Publishers, D-79104 Freiburg (1995)

MODE I FRACTURE BEHAVIOUR OF RECYCLED CONCRETE

S. Ishiguro and S.E. Stanzl-Tschegg ,
University of Agriculture, Vienna, Austria
E.K. Tschegg ,
Technical University of Vienna
R. Travnicek ,
BPV, Lanzendorf, Austria

Abstract

The load-displacement curves of concrete, which had been produced from natural (NC) or with recycled concrete aggregate (RC), were determined with cubic specimens and a wedge splitting procedure allowing stable crack growth. From the load-displacement curves, fracture mechanical data and the softening diagram were derived.

The specific fracture energy of RC is 71.5 N/m, which is only 60 % of that of NC. The maximum load of RC in the load-displacement diagram is only 70 % of NC. The observed differences of the fracture behaviour between RC and NC and fractographic results are analyzed and discussed.

1 Introduction

Natural aggregates will become short for the production of concrete in many urban areas in near future. At the same time, large amounts of demolished concrete will result from deteriorated and obsolete structures which have to be skipped. Therefore it is reasonable to use recycled concrete aggregates for the production of new concrete, if this can indeed substitute natural aggregates.

Extensive studies have been performed on this subject. An excellent review on the state of knowledge is given in the Report of RILEM technical Committee 37 "Demolition and reuse of concrete" edited by Hansen 1992. Many interesting aspects of the concrete recycling technique and technology are extensively discussed there and in the references. The mechanical properties of recycled aggregate concrete and especially the influence of recycled concrete aggregates on compressive strength, modulus of elasticity, stress-strain relationship, creep, tensile, flexural, shear and fatigue strength of new concrete are treated. The fracture behaviour, however, is not discussed there. The purpose of this investigation therefore is to report on this topic. The fracture properties of concrete, which had been produced from recycled and natural aggregates, are characterized with the aid of a wedge splitting technique, and the results are compared and analyzed.

2 Experiments

Load-displacement curves have been determined during stable crack growth until final fracturing. Cubic specimens with natural and recycled concrete aggregate were tested in a simple wedge-splitting procedure according to the patented method of Tschegg (Tschegg 1986). Testing method and measuring procedure are described shortly; for more details see Tschegg 1990, Tschegg 1991.

2.1 Testing method

The principle of the testing method is shown schematically in Fig. 1. Cubic or cylindrical specimens are placed on a narrow linear support in a compression testing machine. A wedge splitting facility (consisting of wedge and load transmission pieces, Tschegg 1990) is placed into the rectangular groove of the specimen with a starter notch at the bottom of this groove. Wedge, starter notch and linear support area are in the same vertical plane. The load is transmitted directly from the testing machine to the specimen, without any detour. Therefore this wedge splitting facility is very stiff and guarantees stable crack propagation even in brittle materials (Tschegg 1991).

The wedge transmits a force F_M from the testing machine to the specimen. The slender wedge exerts a large horizontal force component F_H and a small vertical component F_V to the specimen. The horizontal component splits the specimen similar as in a bending test. F_M is determined with a load cell in the testing machine. Knowing the wedge angle, the force F_H in horizontal direction may be determined. Wedge angle and thus the vertical force are small enough to not influence the results. Friction between wedge and load transmission pieces is minimized by use of roll bodies (needle bearings according to Tschegg 1990, see Fig. 1) and thus may be neglected (mean error approximately 1 %) (Tschegg 1991).

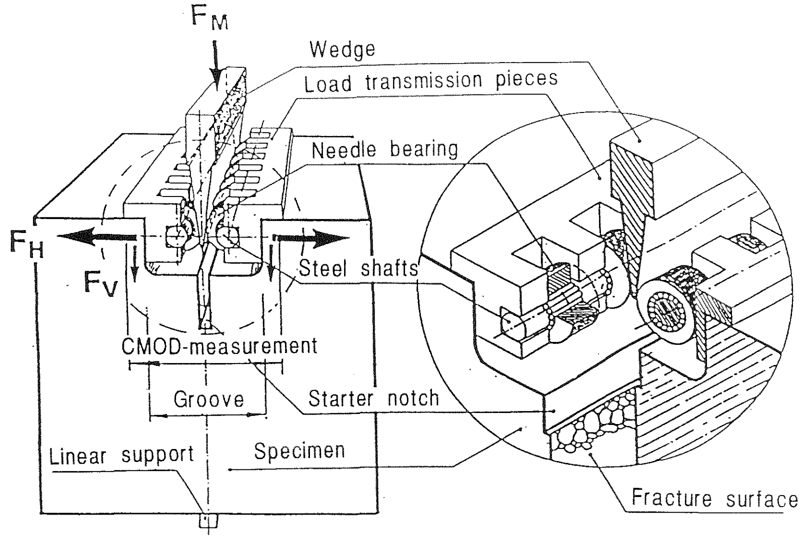


Fig.1 Principle of the testing method according to Tschegg (Tschegg 1986)

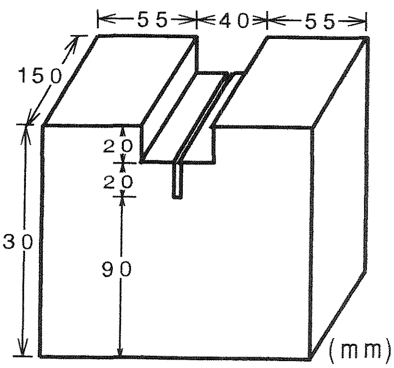


Fig.2 Size and shape of specimen

The load displacement δ (or "CMOD", crack mouth opening displacement) is measured on both ends of the groove on the specimen surface with two electronic displacement gauges. The two measurements of δ serve to obtain mean values of δ on one hand and to be able to detect whether the crack front has propagated parallel to the starter notch in the direction of the linear support area on the other hand. If the resulting values differ by more than 10 %, these measurements are not evaluated any more.

Force F_M and displacements δ1 and δ2 are recorded by an electronic data logger; from this, the load-displacement curve (F_H-δ curve) is obtained. This load-displacement curve characterizes the fracture behaviour of the tested material and yields basic information on appropriate fracture parameters. The area under the F_H-δ curve corresponds to the fracture energy W, which is needed to separate the specimen. The specific fracture energy G_F characterizes

Table 1 Concrete properties

	N-Concrete	R-Concrete
Cement PZ 275 (kg/m^3)	380	380
Water (kg/m^3)	190	190
Type of aggregate	natural	recycled
Fine sand (0-1mm) (kg/m^3)	410(22 %)	476(28 %)
Coarse sand (1-4mm) "	555(30 %)	374(22 %)
Coarse gravel (4-8mm) "	370(20 %)	425(25 %)
Coarse gravel (8-12mm) "	518(28 %)	425(25 %)
From aggregates sucked water	0 % [1)]	3 % [1)]
Superplasticizer (kg/m^3)	0.95	7.6
Water-cement ratio (w/c)	0.50	0.50
Compressive strength (N/mm^2)	46.1	35.0

[1)] mass percent related to aggregate

the crack growth resistance and is obtained as the ratio of fracture energy W and fracture area (its normal projection). The maximum load in the load-displacement diagram is termed F_{Hmax} and may be transformed into a usual notch tensile strength. For more details on evaluation and handling of the wedge splitting test see (Tschegg 1991).

2.2 Specimen, material and experimental details

Specimen shape and dimensions are shown in Fig. 2. The rectangular groove is formed during the cast procedure already, whereas the starter notch is introduced into the root of the groove with a stone saw with a kerf of 3.5 mm shortly before testing.

Two concrete sorts have been studied:

1. Concrete with natural aggregates (termed NC in the following). Composition, grain distribution of the addition and compressive strength are listed in Table 1.
2. Concrete with recycled concrete aggregate (termed RC in the following): The RC aggregates come from a demolished steel-concrete hall. The old-concrete quality was B160 (compressive strength 16 N/mm^2) up to B400 (40 N/mm^2). The composition of the RC concrete is summarized in Table 1. 3 wt. % water were added to the recycled aggregates. This water has not been considered for calculating the w/c values.

After casting and additional 48 hours, the specimens were removed from the

Table 2 Experimental results of maximum load and specific fracture energy

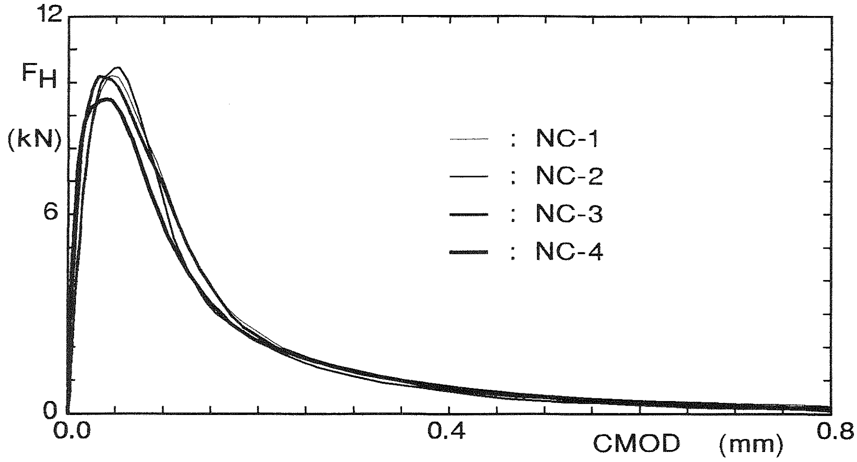
Specification	Ligament-length [mm]	Specimen-width [mm]	F_{Hmax} [N]	G_F [N/m]
NC-1	90	151	10195	128.3
NC-2	91	149	10455	113.1
NC-3	94	151	10170	119.5
NC-4	93	151	9486	111.1
Mean value			10076	118.0
Coefficient of variation			3.6 %	5.7 %
RC-1	89	151	6999	72.7
RC-2	90	152	6954	71.5
RC-3	89	151	7288	72.3
RC-4	90	152	7179	69.6
Mean value			7105	71.5
Coefficient of variation			1.9 %	2.0 %

molds and stored in water 28 days until testing.

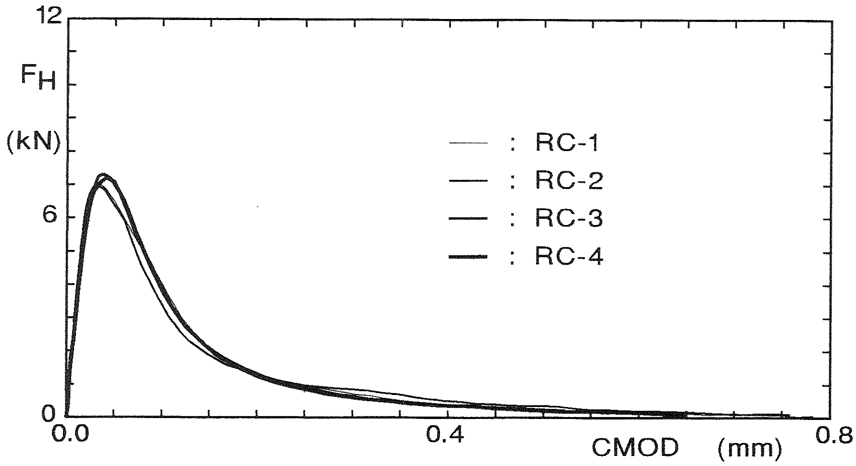
Tests were performed with a mechanical compression testing machine with a load capacity of 10 tons. The splitting-equipment is very stiff, so that unstable crack growth was not observed in any test. The cross-head velocity was 1 mm/min in all tests (as recommended for concrete fracture tests) (RILEM Tech. Comm. 50-FMC, 1985). Testing temperatures were 20 °C. Four identical specimens of each material were tested in order to obtain enough data for statistical evaluation.

3 Results and analysis

The load-displacement curves of all NC and RC specimens are plotted in Figs. 3a and 3b. The ligament lengths and widths as well as the F_{Hmax}- and G_F-values are summarized in Table 2. Fig. 3 shows that scattering of the data is



a) Concrete with natural aggregate



b) Concrete with aggregate from recycled concrete

Fig. 3 Load(F_H)-displacement(δ,CMOD) curves

small especially in the softening regime of NC and even smaller for RC; the coefficient of variation of the G_F values of RC is 2 % and 5.7 % for NC.

Comparison of the mechanical properties of NC and RC yields following values:

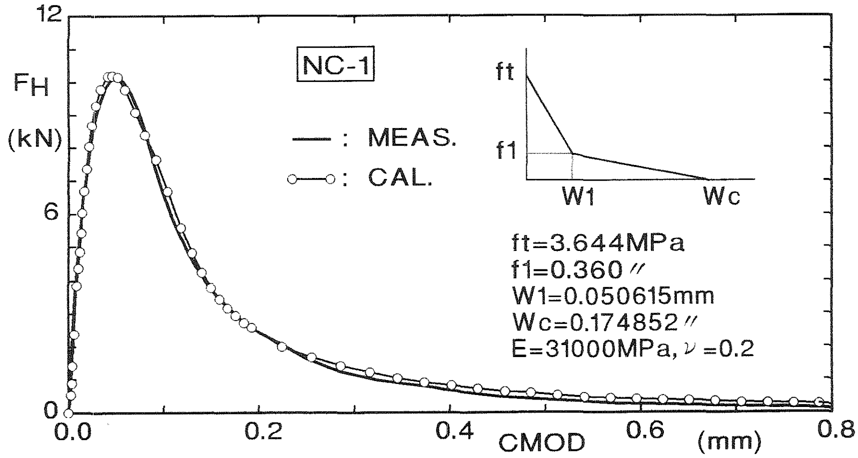
Compressive strength RC / compressive strength NC = 0.76

F_{Hmax} RC / F_{Hmax} NC = 0.7

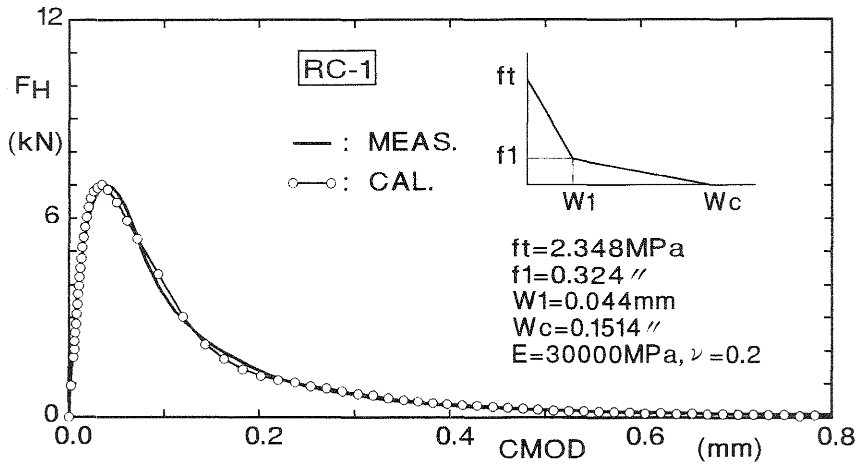
G_F RC / G_F NC = 0.6

These results show that the G_F values of RC are lowest in comparison with the other mechanical properties, that have been determined in this study. G_F of RC is only 60 % of the crack growth resistance in NC. This means that G_F, among the three other parameters, reacts most sensitively to changes of the aggregates.

Reasons for the low G_F values probably are:



a) Concrete with natural aggregate



b) Concrete with aggregate from recycled concrete

Fig. 4 Measured and calculated load-displacement curves, as well as parameters for bilinear softening behaviour

(a) The crack may choose a flat path through the material and needs not bypass the numerous hard and stiff natural aggregates. This result is proved by fractographic observations, which show that the fracture surfaces of RC specimens are flatter and less tortured than those of NC specimens. In addition, less grain boundary fractures along aggregates may be observed on RC fracture surfaces. The energy consumption owing to "grain bridging" behind the crack tip obviously is reduced as well as the energy needed to create new fracture surface, so that the resulting fracture energy is reduced.
(b) Aggregates in RC concrete with B160 to B400 quality do not lead to as high fracture resistances as for example limestone aggregates. Therefore the fracture process zone in front of the crack tip is smaller, which in addition leads to less energy consumption during crack propagation.

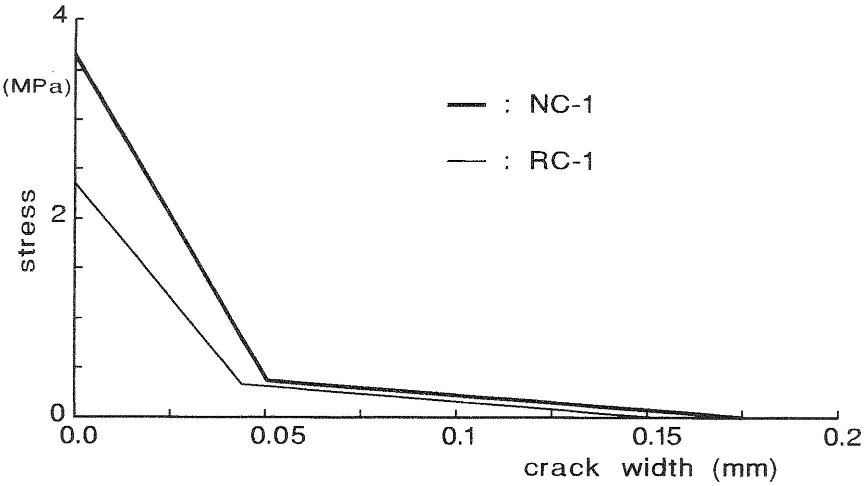


Fig. 5 Bilinear softening curves of concrete with natural (NC) and aggregate from recycled concrete (RC)

The mechanisms as discussed in (a) and (b) seem appropriate to explain the 40 % lower fracture energies of RC in comparison with NC concrete.

5 to 40 % lower values of compressive strength and tensile as well as flexural strength (their nominal values are in some respect proportional to F_{Hmax}) of RC in comparison with NC concrete are reported in the literature generally (Hansen 1992). Compressive strength and flexural tensile strength of similar material as investigated in this study have been determined in Lukas 1993. The ratios of the compressive strengths of NC and RC, as well as of the flexural tensile strengths are in good agreement with the results of this study.

In order to characterize the fracture behaviour of concrete, not only the above mentioned parameters, but also the strain-softening behaviour has to be determined. This is obtained from a bilinear σ-δ diagram usually. It has been determined with the SOFTFIT program (Roelfstra 1988) from the experimentally measured load-displacement diagrams in this study. SOFTFIT is based on finite element methods and the fictitious crack model (Hillerborg et al. 1976). The characteristic values of the bilinear softening diagram are obtained with a best-fit procedure comparing calculated and measured load-displacement curve in this calculation program. Measured and calculated load-displacement curves are plotted in Figs. 4a and 4b for NC and RC concrete. The fitting procedure was finished when the ratio of $G_F$cal./$G_F$meas. was 0.98 - 1.02. Figs. 4a and 4b show that good agreement between measured and calculated load-displacement curves can be obtained. The resulting characteristics of the bilinear softening behaviour are important basic values for simulations of specimen geometry influences on G_F with FEM.

The Young´s modulus values of this study agree well with those reported in the literature (Hansen 1992, Lukas 1993) for similar concrete. They are almost identical (approximately 30 000 MPa) for NC, whereas values of 26 000 MPa are reported for RC (Lukas 1993) and values between 60 and 90 % of NC (Hansen 1992). Large amounts of mortar in recycled concrete were considered to be responsible for the reported lower Young´s moduli (Hansen 1992).

In this study, the Young´s moduli of RC, as calculated with a best fit procedure, are only slightly lower than the values for NC. Contrary to this, the G_F and F_{Hmax} values of RC are 40 % and 30 %, respectively, lower than for NC.

The diagram in Fig. 5 shows the bilinear values of NC and RC. The values for NC agree well with the literature values (Roelfstra 1988) for similar NC. The different fracture processes in front and behind the fictitious crack tip and their portion within the whole fracture energy will be analyzed in another study, in a similar way as reported (Tschegg et al. 1995) for concrete with different grain size.

4 Summary

Following mechanical properties of concrete with natural (NC) and with recycled (RC) aggregate have been measured:

1. Compressive strength RC / compressive strength NC = 0.76
   F_{Hmax} RC / F_{Hmax} NC = 0.7
   G_F RC / G_F NC = 0.6
   Less crack deflections than in natural aggregate probably are responsible for the low fracture values of RC. Flatter fracture surfaces of RC than of NC corroborate this explanation.

2. The bilinear softening diagrams agree well with results in the literature for NC and serve as an important base for further FEM calculations of RC fracture.

3. The splitting method using cubic and cylindrical specimens according to Tschegg (1986) is appropriate to characterize RC concrete. The equipment provides especially stiff testing conditions and thus guarantees stable crack propagation.

5 Acknowledgments

The authors thank Mr. O. Zelzer for experimental assistance. This project was financed by the ''Fonds zur Förderung der wissenschaftlichen Forschung'' (Austrian Science Foundation) under the project number P 10377-ÖPH.

6 References

Hansen, T.C.(1992) Recycling of demolished concrete and masonry. Report of Technical Committee 37-DRC, E&FN Spon, Chapman & Hall, London.

Hillerborg, A., Modeer, M. and Peterson, P.E. (1976) Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. **Cement and Concrete Research,** 6, 773-782.

Lukas, W.(1993) Auswirkungen auf technologische Kenngrößen von Beton bei Verwendung von Recycling-Material. **Zement und Beton,** 3, 33-95.

RILEM Draft Recommendation (50-FMC,1985): Determination of the fracture energy of mortar and concrete by means of three-point bending tests on notched beams. **Materials and Structures,** Vol. 18, 287-290.

Roelfstra, P.E.(1988) Numerical concrete, Thèse No. 788, EPF Lausanne, Switzerland.

Tschegg, E.K.(1986) Testing method and appropriate shape for tests to measure fracture values (in German). Patent AT-390328.

Tschegg, E.K.(1990) Load transmission equipment for fracture tests (in German). Patent AT-396 997.

Tschegg, E.K.(1991) New equipments for fracture tests on concrete. **Material Testing** (Materialprüfung), Vol. 33, 338-343.

Tschegg, E.K., Elser, M. and Kreuzer, H.(1995) Mode I fracture behaviour of concrete under biaxial loading. **J. of Materials Science**, 30, 235-242.