ELSEVIER

Cement & Concrete Composites 25 (2003) 379–385

Cement & Concrete Composites

www.elsevier.com/locate/cemconcomp

Horizontal shear transfer across a roughened surface

Mitchell Gohnert *

Department of Civil Engineering, School of Civil and Environmental Engineering, University of the Witwatersrand, Private Bag 3, P.O. Wits, Johannesburg 2050, South Africa

Received 23 October 2001; accepted 16 July 2002

Abstract

A total of 90 concrete composite members were tested to determine the horizontal shear strength along the interface of a roughened surface. The "push-off" method of testing was implemented to determine the capacity. It was ascertained that the roughness of the surface had a profound effect on the shear capacity and is a far better indicator of strength than the compressive strength of the concrete. Design curves are provided based on the surface roughness and the compressive strength of the in situ concrete. In addition, six beams were bent in flexure until horizontal shear failure occurred. The results of these tests are compared with specifications of various codes.

Keywords: Horizontal shear; Shear; Composites; Precast concrete; Design

1. Introduction

In South Africa, a large portion of the domestic and light industrial floor slab market comprises of a slab system referred to as rib and block floor slabs. The floor system is a concrete composite with non-structural hollow blocks used to create voids. The end product is a one-way spanning trough slab. A typical cross-section is illustrated in Fig. 1. The interface between the precast rib and in situ concrete transfer the horizontal shear by a roughened surface or by shear steel. The shear steel is typically in the form of a loop which projects across the shear interface. However, in many of the rib and block floor systems, shear steel is generally only used when the horizontal shear is excessive. In the majority of designs, the horizontal shear is transferred by roughening the surface which is considered to be the most economical solution.

Codes of practice, such as ACI 318 [1], BS 8110 [2], Eurocode 2 (draft) [3], and SABS 0100 [4], specify the horizontal shear strength which is based on two fundamental parameters—the surface quality or profile (i.e., roughness or if free of laitance) and the quantity of shear steel. A comparison of the codes cited above is given in Table 1 which indicates a lack of congruency. ACI 318 specifies two categories of roughness, but no concrete compressive strength is specified for the given capacities (the horizontal shear capacity is assumed to be the same regardless of the concrete compressive strength). On the other hand, BS 8110, Eurocode 2 and SABS 0100 express the shear capacity as a function of the compressive strength. Another significant difference is the categorizing of degrees of roughness. BS 8110 merely states the type of instrument used to create the roughness whereas the Eurocode assigns measurable properties (i.e., 3 mm for rough surfaces and 5 mm or greater for indented surfaces). As one compares these codes several questions arise:

- Is the horizontal shear capacity related to the compressive strength of the concrete? The ACI 318 approach infers that it is not by omitting strength, even a minimum concrete compressive strength.
- Can the degree of roughness be specified by merely stating the instrument used to create the roughness (i.e., brushed or raked) or is it necessary to specify an actual measurement of roughness?
- A lack of agreement between the codes has led to the question, what is the horizontal shear capacity for a given concrete strength or surface condition?

* Tel.: +27-11-717-7125/716-2459; fax: +27-11-339-1762.

E-mail addresses: gohnert@civil.wits.ac.za, gohnert@civin.civil.wits.ac.za (M. Gohnert).

0958-9465/03/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S0958-9465(02)00050-1

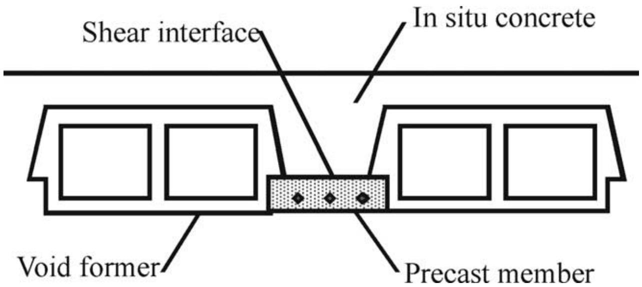

Fig. 1. Typical cross-section of a rib and block floor system.

Table 1
Comparison of horizontal shear strengths of various codes

Code	Roughness	Concrete strength[a] (MPa)	
		25	30
ACI 318 95	Clean, free of laitance and intentionally roughened	0.55[b]	0.55[b]
	Clean, free of laitance and intentionally roughened to a full amplitude of 1/4 in. (6.4 mm)	1.79[b]	1.79[b]
Eurocode 2 (draft)	Very smooth interfaces	0.08	0.09
	Smooth interfaces (slip-formed or extruded)	0.22	0.27
	Rough interfaces (3 mm roughness)	0.41	0.51
	Indented interfaces (5 mm roughness)	0.45	0.54
BS 8110 & SABS 0100	As-cast or as-extruded	0.40	0.55
	Brushed, screeded or rough-tamped	0.60	0.65

[a] Cube strength.
[b] The horizontal shear capacity is only a function of the roughness.

To answer the above questions, a total of 90 horizontal shear tests were performed. The majority of these tests constituted a study of shear transfer by varying the degree of roughness and the concrete compressive strength. Similar studies have been done by Bass et al. [5], Ali and White [6] and others [7].

2. Description of test rig, test specimens and concrete mix

2.1. Test rig

A composite member is designed to act monolithically. Nevertheless, as the member is bent in flexure, the precast member and in situ concrete tend to slide relative to each other as illustrated in Fig. 2. The horizontal shear between the two materials is resisted by the shear capacity of the interface. It is common to model the horizontal shear by the "push-off" test method [8,9]. A schematic figure of the test rig is given in Fig. 3. As illustrated, the precast member is braced and the in situ concrete is pushed by a ramping load until shear failure occurs. A roller support is placed on top of the specimen to prevent instabilities inherent in the test. Since the interface lacks reinforcement, failure is dramatic and well defined.

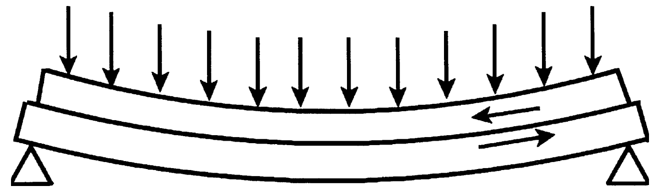

Fig. 2. Horizontal shear along the interface of a composite member bent in flexure.

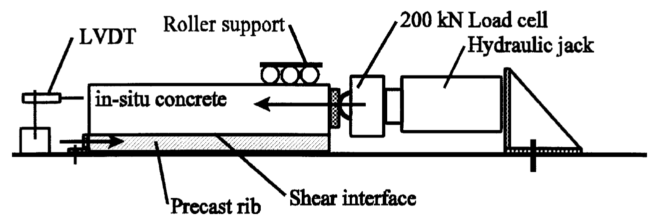

Fig. 3. Schematic of the push-off test rig.

2.2. Test specimens

The precast members (ribs) were obtained from five manufacturers located throughout South Africa. The number and variety of test specimens are intended to give diversity to the possible configurations of surface conditions and therefore give credence to the experimental program. The basic dimensions of the test specimens are given in Fig. 4 and details are listed in Table 2. The overall depth and length of each specimen was kept constant at 210 and 750 mm, respectively. The width and depth of the precast members varied depending upon the supplier (115–250 mm).

It is customary in South Africa to provide wire loops which are placed perpendicular to the interface and spaced at about 1000 mm centers. The loops are nonstructural; the purpose is to assist in transportation and placement of the precast members. The wires are typically 4 mm in diameter, made of mild steel and

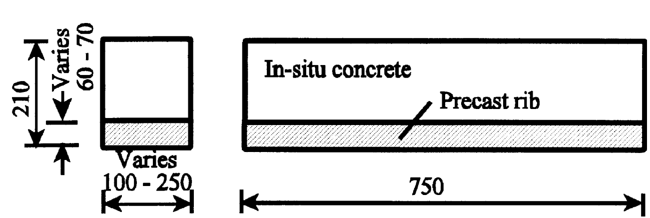

Fig. 4. Basic dimensions of the composite members.

Table 2
Contact dimensions, surface roughness, steel, concrete strengths and failure load

Test specimen	Contact width (mm)	Contact length (mm)	Depth of in situ concrete (mm)	Concrete cube strength (MPa)	Interface steel loops (%)	Roughness R_z (mm)	Failure load (kN)
A-1	151	753	149	In situ:	0.06	0.94	119
A-2	150	754	149	22.8			78
A-3	151	752	152				117
A-4	150	751	150	Precast:			141
A-5	150	751	149	41.7			89
A-6	153	755	148				100
B-1	152	751	150	In situ:	0.00	0.94	72
B-2	152	750	150	22.8			123
B-3	152	750	148				103
B-4	155	752	151	Precast:			148
B-5	151	753	150	41.7			127
B-6	153	750	150				127
C-1	150	752	154	In situ:	0.06	4.02	108
C-2	151	755	159	25.5			155
C-3	150	750	155				158
C-4	152	750	146	Precast:			220
C-5	149	749	148	41.7			146
C-6	150	748	151				219
D-1	155	751	149	In situ:	0.06	0.94	144
D-2	156	750	149	31.4			149
D-3	155	751	150				109
D-4	156	753	150	Precast:			135
D-5	155	749	151	41.7			129
D-6	156	753	151				148
E-1	151	752	154	In situ:	0.06	4.02	171
E-2	149	754	156	29.2			176
E-3	150	748	156				190
E-4	150	751	155	Precast:			135
E-5	149	752	154	41.7			194
E-6	149	751	156				193
F-1	150	753	148	In situ:	0.07	3.82	172
F-2	150	753	151	23.9			167
F-3	154	752	147				125
F-4	153	754	150	Precast:			173
F-5	150	750	147	31.5			148
F-6	151	750	150				177
G-1	151	752	145	In situ:	0.07	3.82	173
G-2	155	754	151	30.5			174
G-3	150	756	147				171
G-4	151	752	150	Precast:			175
G-5	155	753	145	31.5			175
G-6	150	753	146				177
H-1	160	751	151	In situ:	0.02	3.09	172
H-2	162	753	151	26.4			153
H-3	160	753	150				144
H-4	165	752	150	Precast:			145
H-5	162	750	148	56.2			147
H-6	162	752	150				174
I-1	115	752	152	In situ:	0.02	3.46	160
I-2	118	751	151	25.3			139
I-3	115	754	152				130
I-4	115	754	152	Precast:			174
I-5	114	755	151	56.2			176
I-6	115	755	155				136
J-1	162	753	148	In situ:	0.02	3.09	172
J-2	162	754	149	30.1			155

(*continued on next page*)

Table 2 (*continued*)

Test specimen	Contact width (mm)	Contact length (mm)	Depth of in situ concrete (mm)	Concrete cube strength (MPa)	Interface steel loops (%)	Roughness R_z (mm)	Failure load (kN)
J-3	165	754	151				169
J-4	164	752	149	Precast:			154
J-5	163	752	149	56.2			139
J-6	163	752	151				153
K-1	119	750	149	In situ:	0.02	4.22	174
K-2	121	751	147	29.9			168
K-3	118	749	150				173
K-4	115	750	152	Precast:			177
K-5	120	755	151	56.2			135
K-6	124	753	147				165
L-1	153	754	152	In situ:	0.02	3.41	181
L-2	154	752	151	24.4			181
L-3	152	750	153				189
L-4	150	754	150	Precast:			185
L-5	150	752	154	33.9			189
L-6	151	754	155				188
M-1	150	755	150	In situ:	0.02	3.41	179
M-2	154	752	150	29.6			164
M-3	155	754	151				201
M-4	160	755	149	Precast:			179
M-5	152	753	152	33.9			178
M-6	154	751	150				154
N-1	248	749	153	In situ:	0.10	0.89	175
N-2	251	751	151	24.7			140
N-3	252	751	154				179
N-4	254	750	151	Precast:			175
N-5	250	751	153	45.4			179
N-6	250	750	152				167
O-1	252	750	144	In situ:	0.10	0.89	149
O-2	182	753	162	28.3			70
O-3	175	752	155				120
O-4	178	754	153	Precast:			120
O-5	178	754	140	45.4			125
O-6	253	751	142				177

embedded ≈100 mm into the precast member. The majority of the specimens have one loop across the interface. Although the experimental program is a study of horizontal shear resisted entirely by surface roughness, the wire loops were left in place for safety reasons and to protect the testing equipment. The total steel across any interface did not exceed 0.07% and the embedment of the steel was insufficient to contribute to the shear resistance. This was confirmed by a comparison of 12 tests (not recorded here) to determine the effect of the wire loops. The tests indicated that the loops made no contribution to the resistance of shear.

The roughened surface, of each specimen, was formed by means of a stiff wire brush or a rake. The pressure applied by each of these instruments varied from one manufacturer to another; thus, different roughness amplitudes are recorded. In all of the specimens, the wavelength (spacing of the surface undulations) width did not exceed 20 mm and the direction of lay is perpendicular to the direction of the shearing force as well as the length of the specimen.

The roughness values listed in Table 2 are based on procedures suggested by BS 1134 [10]. Although this code appears to be focused on materials in which the surface undulations are significantly smaller than those of roughened concrete, the procedures are relevant to any textured surface. Theodossius et al. [11] adapted BS 1134 to determine the roughness of concrete subjected to frictional forces. The only deviation from the original code is the sampling length. Theodossius profiled the surface based on a sampling length of 200 mm. The roughness of the tests presented here are similarly based on a sampling length of 200 mm. However, the number of readings increases from a code recommendation of 10 to a maximum of 30 (depending on the irregularity of the surface and spacing of the peaks). A graphical representation of the measurements is given in Fig. 5. A micrometer was the instrument used to make these

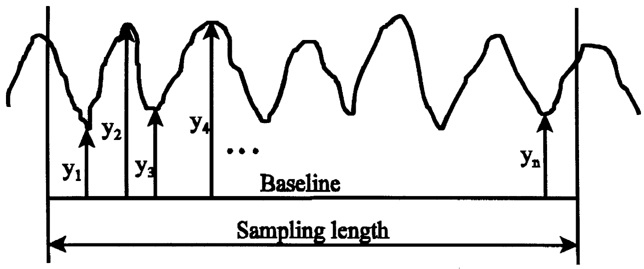

Fig. 5. Graphical representation of roughness measurements.

measurements. The roughness (R_z) is calculated as the difference between the average height of the peaks and the average height of the valleys from an arbitrary baseline.

The concrete strengths listed in Table 2 are cube compressive strengths (i.e., measurements on 100 mm × 100 mm × 100 mm cubes). The mix design of the in situ concrete is given below. The masses are dry weights in kilograms per cubic metre of concrete. The mix is for a concrete strength of 40 MPa at 28 days; however, the samples were tested at an earlier date when the concrete reached the test strength of ≈25 or 30 MPa (measured on cubes).

Cement OPC 42.5	375 kg
Filler sand (FM = 1.64)	125 kg
Crusher sand (FM = 2.98)	765 kg
Stone (16–22 mm, average = 19 mm)	900 kg
Admixture	1310 ml
Water	208 l

(FM = fineness modulus)

3. Test results

The failure load of each of the tests are included in Table 2. The horizontal shear stress is determined by dividing the failure load by the contact area. It is traditional to express the horizontal shear capacity in terms of the concrete compressive strength. Fig. 6 illustrates the relationship between these two parameters. The regression curve is given in Eq. (1).

$$v_h = 0.0286 f_{cu} + 0.5701 \tag{1}$$

where v_h is the shear capacity determined from a regression analysis and f_{cu} is the concrete compressive strength of the in situ concrete, both in MPa. The regression curve was dropped to the 95% one-sided confidence interval according to the statistical procedures outlined in BS 2846 [12] to obtain the design curve given in Eq. (2).

$$v_{hd} = (0.0286 f_{cu} - 0.0544)/\gamma_m \tag{2}$$

where v_{hd} is the design horizontal shear capacity in MPa and γ_m is a material or safety factor applied according to

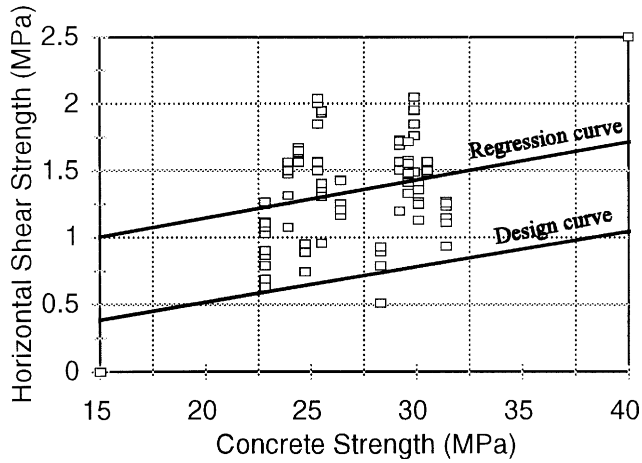

Fig. 6. Horizontal shear strength versus concrete strength.

the relevant code (e.g., BS 8110 and SABS 0100 specify a material factor of 1.4 for shear). The design curve in Fig. 6 is illustrated with a material factor equal to one.

The scatter of data (Fig. 6) is so broad that any trend or correlation is hardly distinguishable. In fact, it is evident that an attempt to establish a correlation between the horizontal shear and the concrete compressive strength is questionable. If all of the specimens tested were from a single manufacturer or if a similar surface profile was used the correlation would be significantly better, but the results would be limited in application. Testing a wide range of surface profiles is seen as essential to obtain horizontal shear strengths that are relevant to industry and a host of possible surface textures. It is therefore apparent that other parameters, which influence the horizontal shear, should be considered.

In Fig. 7, the horizontal shear strength is expressed in terms of the surface roughness. By inspection, the scatter is far more compact indicating a somewhat better correlation with surface roughness than with the

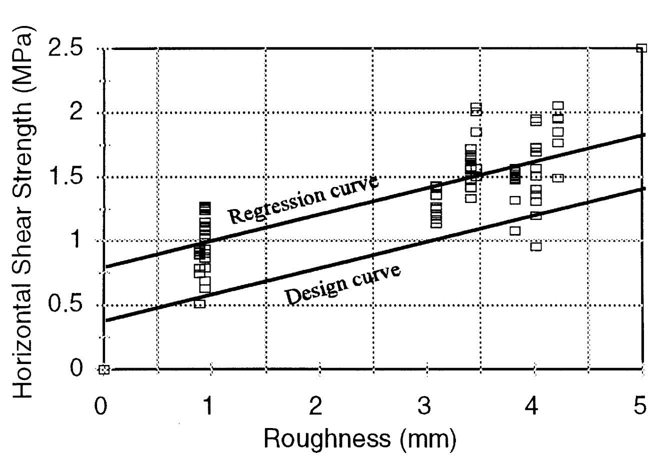

Fig. 7. Horizontal shear strength versus roughness.

compressive strength of the concrete. The regression curve is given in Eq. (3).

$$v_{\mathrm{h}} = 0.2090R_z + 0.7719 \tag{3}$$

where R_z is the surface roughness in mm.

Similarly, the regression curve is dropped to the 95% one-sided confidence interval. The design equation is given in Eq. (4).

$$v_{\mathrm{hd}} = (0.2090R_z + 0.3762)/\gamma_{\mathrm{m}} \tag{4}$$

Upon close inspection of Eqs. (3) and (4), for every millimeter change in roughness, the shear capacity changes by 0.2 MPa. The change in shear capacity is significant and therefore underscores the necessity to specify the degree of roughness. Merely stating the instrument (e.g., brush or rake) by which the undulations are formed is not sufficient. The roughness of a brushed or raked surface can vary significantly according to the amount of pressure applied to the instrument. In a few of the specimens tested the surface was brushed, but the roughness did not exceed 1 mm. In these cases, although compliant with BS 8110 and SABS 0100, the actual shear capacity fell below the recommended shear strength for a brushed surface. To avoid this problem, a measurement of roughness should be specified.

4. Test results compared with code specified shear strengths

An attempt is made to compare the test results with various codes of practice. This comparison is given in Table 3. In constructing this table, the difficulty lies in determining the degree of roughness for various specifications. For example, the ACI merely states that the surface is clean, free of laitance and intentionally roughened—no actual measurements of surface roughness is stated. Similar problems exist with Eurocode 2, BS 8110 and SABS 0100. Several assumptions were therefore required.

The comparison indicates that Eurocode 2 is significantly more conservative than the other codes. The ACI specification is the only code that allows a higher value than those determined from experimentation for very rough surfaces. However, when comparing the experimental design curve with the various design codes, it should be noted that the design curve was not reduced by any safety or material factors that are commonly applied in many codes of practice; this will effectively reduce the design values determined in Eq. (4).

Table 3
Test results compared with various codes of practice (minimum concrete strength 25 MPa)

Code	As cast, slip formed or extruded (assume a maximum of 1 mm roughness)	Intentionally roughened by a brush or rake (assume a maximum of 3 mm roughness)	Rough surface (assume a maximum of 5 mm roughness)
ACI 318	–	0.55	1.79
Eurocode 2	0.22	0.41	0.45
BS 8110 & SABS 0100	0.40	0.60	–
Design Eq. (4)	0.59	1.00	1.42

5. Comparison of test data with test beams bent in flexure

Six additional beams were tested in flexure. These beams were loaded gradually until horizontal shear failure occurred. The results are compared with the horizontal shear strengths determined from the push-off tests. The basic configuration of the test beams is given in Fig. 8. The average contact width, the span of the beam and the average surface roughness of the interface measured 100, 950 and 0.94 mm respectively. The contact interface was reduced by 50 mm by wedge-shaped formers. Four equally spaced point loads were applied to each beam to simulate a uniformly distributed load. The concrete compressive strengths and failure loads are given in Table 4.

Elastic equations are used to estimate the horizontal shear stress at failure. Elastic equations are by no means an exact representation but are the simplest and the most practical method for estimating the horizontal shear [13]. Eurocode 2 gives the following equation to determine the horizontal shear stress:

$$v_{\mathrm{Edi}} = \frac{V_{\mathrm{Edi}}S}{b_{\mathrm{i}}I} < \frac{V_{\mathrm{Edi}}}{b_{\mathrm{i}}d} \tag{5}$$

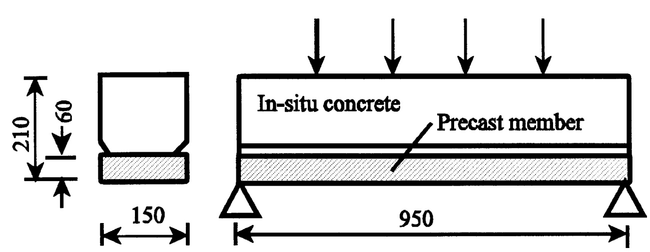

Fig. 8. Test beams bent in flexure.

Table 4
Concrete strengths and failure loads of beams bent in flexure

Beam	Concrete cube strength (MPa)	Failure load (kN)
P-1	In situ: 31.0	110
P-2	Precast: 42.7	94
P-3	In situ: 16.6	60
P-4	Precast: 42.7	45
P-5	In situ: 20.8	75
P-6	Precast: 42.7	94

Table 5
Theoretical predictions of horizontal shear compared with experimentation

Beam	Eurocode 2 $\frac{V_{\mathrm{Edi}}S}{b_i I}$ uncracked I (Mpa)	Eurocode 2 $\frac{V_{\mathrm{Edi}}S}{b_i I}$ uncracked I (Mpa)	BS8110 & SABS 0100 $\frac{2f_y A_s}{bl\gamma_m}$ (Mpa)	Eurocode 2 & ACI 318 $\frac{V_{\mathrm{Edi}}}{b_i d}$ uncracked I (Mpa)	Experimentation Eq. (3) (MPa)
P-1	3.33	3.17	5.48	2.96	0.97
P-2	2.84	2.71	5.48	2.53	0.97
P-3	1.84	1.67	2.35	1.59	0.97
P-4	1.40	1.33	6.26	1.23	0.97
P-5	2.29	2.09	2.35	1.99	0.97
P-6	2.87	2.62	2.35	2.49	0.97

where V_{Edi} is the vertical shear force, S is the first moment of area, b_i is the contact width, I is the moment of inertia and d is the effective depth. As indicated by Eq. (5), the limiting stress is the average vertical stress over the cross-section of the member; the ACI specification corresponds with this expression.

BS 8110 and SABS 0100 endorse an equation based on ultimate limit state theory:

$$v_h = \frac{2f_y A_s}{bl\gamma_m} \tag{6}$$

where v_h is the horizontal shear stress, f_y is the yield stress of the steel, A_s is area of reinforcing or prestressing steel, b is the width of the contact area, l is the span length and γ_m is a material factor.

Eqs. (5) and (6) are given in Table 5 along with the experimental predictions. The intension of this table is to examine how close the experimental values (determined from push-off test) represent actual shear failures in beams bent in flexure. In every case, the prediction is conservative.

6. Conclusions

As illustrated in Fig. 6, the scatter of data is broad and a poor correlation exists between the horizontal shear strength and the compressive strength of the concrete. It is therefore not advisable to specify the horizontal shear strength as a function of the concrete compressive strength. However, the regression analysis does indicate an upward trend in capacity as the concrete strength is increased. Although the influence of the concrete strength may be less pronounced (compared to other factors), the compressive strength does influence the shear strength and therefore at least a minimum compressive strength should be specified.

Specifying a roughness by merely stating the instrument used to create the undulations is not sufficient; an actual measurement of roughness should be specified. A brush or rake can produce a vast range of roughness values depending on the stiffness of the instrument, the amount of pressure applied and the viscosity or age of the mix. Fig. 7 clearly indicates a significant increase in the shear capacity as the roughness increases.

Design equations are provided In most cases, the experimental equation (Eq. (4)) give a higher shear strength than the codes cited—Greater economy in design can therefore be achieved. However, no safety or material factors were applied to Eq. (4). In many codes of practice, the application of safety and material factors are common. Given the degree of scatter (see Fig. 7), a safety or material factor would be justified.

Acknowledgement

The author would like to acknowledge the Concrete Manufacturers' Association of South Africa for its support and financial assistance during this research.

References

[1] ACI 318-95. Building code requirements for reinforced concrete. Detroit, MI: American Concrete Institute; 1995.
[2] BS 8110-1:1997. Structural use of concrete. London: British Standards Institute; 1995.
[3] Eurocode 2: prEN 1992-1:2001 (1st draft). Design of concrete structures. Brussels: European Committee for Standardization.
[4] SABS 0100-1: 1992. The structural use of concrete. Pretoria: The Council of the South African Bureau of Standards; 1992.
[5] Bass RA, Carrasquillo L, Jirsa JO. Shear transfer across new and existing concrete interfaces. ACI Struct J 1989;86(4):383–93.
[6] Ali MA, White RN. Enhanced contact model for shear of normal and high strength concrete. ACI Stuct J 1999;96(3):348–60.
[7] Federation Internationale de la Precontrainte. Shear at the interface of precast and in situ concrete. Technical Report. 1978.
[8] Choi D-U, Jirsa JO, Fowler DW. Shear transfer across interface between new and existing concretes using power-driven nails. ACI Struct J 1999;96(2):183–92.
[9] Lam D, Elliott KS, Nethercot DA. Push-off tests on shear studs with hollow-cored floor slabs. Struct Eng 1998;76(9):167–74.
[10] BS 1134: Part 1: 1988, Assessment of surface texture. London: British Standards Institute; 1988.
[11] Theodossius P, Tossios T, Vintzeleou EN. Concrete-to-concrete friction. J Struct Eng 1987;113(4):832–49.
[12] BS 2846:Part 3:1975, Guide to statistical interpretation of data. London: British Standards Institute; 1975.
[13] Loov R, Patnaik A. Horizontal shear strength of composite beams with a rough interface. PCI J 1994;39(1):48–67.