TESTS ON LOAD CARRYING CAPACITY OF CONCRETE FLAGS

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ABSTRACT

Contrary to concrete blocks pavements, there is a lack of design guidelines for pavements of precast concrete flags. Despite the similarities between these two pavement types, the recommendations for concrete block pavements cannot be used for concrete flag pavements without alterations. The slenderness ratio (the ratio between length and thickness) is considerably higher for flags than pavers. The "stout" pavers rarely crack whereas the flags crack when they are subjected to heavy loads. The concrete block pavement is designed as a pavement system in which blocks and joint sand are interacting structurally as a whole forming a fictitious layer distributing the load to the underlying layers. There is no need for a design of the paver per se. However, the flag pavement design has to consist of two parts: (i) design of the pavement system and (ii) design of the concrete flag. This paper deals with the latter design.

Factors that may effect the load carrying capacity of the concrete flag and hence the design are (a) flag thickness, (b) slenderness ratio, and (c) flexural strength. A test series was carried out to study how these factors affect the load carrying capacity. Totally, 33 specimens of eleven different flag types were tested. Test variables were flag thickness, flag size, and strength class. During testing, the flag specimen was supported on bedding sand on a compacted unbound subbase and loaded to failure by a centrically point load. The test results contained a considerable scatter, but indicated that increased flag thickness increase the cracking load and that reduced slenderness ratio and increased flexural strength also may enhance the cracking load.

More tests are needed to reduce the scatter. Furthermore, surveys on loaded concrete flag pavements are needed to supplement the load tests in the laboratory. How much do the joint sand and surrounding neighbour flags contribute to the load carrying capacity of a single flag? The final goal is to synthesize test results and experiences into a design handbook.

1. INTRODUCTION

In Sweden (Swedish Concrete Block Paving Association, 1999 and 2002) and many other countries, there are design recommendations for concrete block pavements (see, e.g., Shackel, 1990). The design recommendations are usually semi-empirical, i.e., the thickness of the each layer in the pavement system is determined by combining strain computations and experience from successful case stories. Since the experience show that failures rarely occur in the pavers, the computations are limited to make clear that the compressive vertical strain of the uppermost layer of the subgrade and the tensile horizontal strain at the bottom layer of an untreated roadbase, if any, are less than strain values based on empirical failure criteria considering fatigue.

In the second edition of the Swedish design guide for pavers and flags (Swedish Concrete Block Paving Association, 2002), there is a design table for pavements systems consisting of a flag layer, bedding sand, untreated roadbase, and a subbase. The Swedish design guide defines a paver through

the following geometrical conditions: thickness = 60 to 120 mm, length < 280 mm, and area < 0.05 m^2. All other kinds of rectangular units are defined as flags. According to this design guide, the thickness of the pavement system containing flags is slightly larger than the thickness of a similar system with pavers instead of flags. This table is based on experience and limited to very small traffic volumes (< ½ million 100 kN standard axles).

A concrete flag pavement system cannot be designed in the same manner as the concrete block pavement system, since the possible failures of the first system include crushed corners and through cracks dividing the flag into two ore more parts. Such failures are very rare on concrete block pavements. The design of the concrete flag system needs to consist of two parts: (i) design of the flag per se and (ii) design of the entire multi-layer pavement system. The latter design may be similar to the design of the concrete block pavement system, but the effective stiffness of the flag layer has to be determined first. This paper deals with the design of the flag per se. As a part of this design, flags of various size, thickness, and strength have been loaded to failure in the laboratory. The results will be summarized and analysed in the following chapters.

2. KEY FACTORS

Figure 1 describes schematically how a precast concrete flag is loaded by a wheel load *F*. In Table 1, a list of parameters that may have influence of the cracking risk of the flag are given.

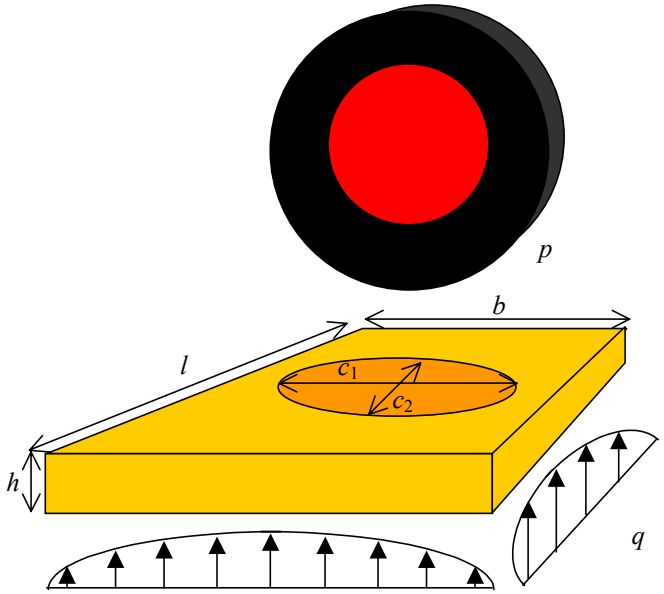


Figure 1. A concrete flag is loaded by a wheel load. The flag has the length l, width b, and thickness h. The wheel load F is assumed to be distributed on an elliptical loading surface with the extent of c_1 and c_2 in two perpendicular directions. The contact pressure is p. The reaction pressure from the bedding sand underneath the flag is q.

The following parameters are considered to be the paramount ones:

- Flag thickness *h*
- Flag length *l*
- Flag width *b*
- Flexural strength of the flag f_{cfl}
- Magnitude of the wheel load *F*
- Tyre pressure *p*
- Length of loading surface c_1
- Width of loading surface c_2

- The distribution of the contact pressure p within the loading surface
- The distribution of the reaction pressure q

Table 1. Parameters that may influence the cracking risk of the concrete flag. From Silfwerbrand (2002).

Flag parameters	*Loading parameters*	*Parameters of the bedding sand and underlying layers*	*Other parameters*
Flag length l	Magnitude of the wheel load F	The distribution of the reaction pressure q	Laying pattern
Flag width b	Twin load arrangement, if any	Thickness of the bedding sand	Type of edge restraint
Flag thickness h	Tyre pressure p	Thickness variation of the bedding sand	Edge restraint anchorage
Flag shape (if other than rectangular)	Length of loading surface c_1	Grading of the bedding sand	Joint width
Height tolerance	Width of loading surface c_2	Mineralogy of the bedding sand	Joint width variation
Area tolerances	The distribution of the contact pressure within the loading surface	Type of bedding sand (natural or crushed)	Degree of joint filling
Height distribution within the flag	Dynamical additions	Compacting of the bedding sand	Grading of joint sand
Flexural strength f_{cfl}	Horizontal contributions due to acceleration, breaking, or turning of the vehicle	Type of roadbase	Mineralogy of joint sand
Compressive strength f_{cc}		Thickness of the roadbase	Type of joint sand (natural or crushed)
Fracture energy G_F		Type of subbase	
Modulus of elasticity E_c		Thickness of the subbase	
		Subgrade material	

3. LABORATORY TESTS OF PRECAST CONCRETE FLAGS

3.1 Aim and limitations

The tests aimed at testing the load carrying capacity of some frequently used Swedish precast concrete flags loaded and supported in such a way that the structural behaviour of traffic loading is reflected as well as possible without making the interpretation of the test results too difficult. The test results were anticipated to provide support for improved design guidelines for concrete flag pavements.

Unfortunately, the extent of the test series was limited. Certainly, 33 flags were tested, but it had been desirable if the test series had covered a larger variation concerning flag size. Now, all flag types except two were 350×350 mm. The test series contained three flags of each type. Since the spread of the test results was large, it had been better to test, e.g., six flags of each type. However, the budget was limited. Consequently, you have to consider the rather limited statistical base before drawing any final conclusions.

3.2 Test flags

The test series consisted of 33 precast concrete flags with quantified dimensions and strength classes according to the three participating manufacturer's normal assortment.

The following variables were included in the tests:

- Flag length
- Flag thickness
- Strength class of the flag
- Manufacturer

Only square flags were included in the test series. In all, 33 flags of eleven types were tested. Nine types had the side length of 350 mm, two types had a 500 mm flag length. The flag thickness varied from 30 to 80 mm. The nominal flexural strength was usually 7 MPa, but in two cases 9 MPa. Information on the manufacturer has not been considered to have any importance for the international reader. Interested ones may read the test report (Silfwerbrand, 2002).

3.3 Test setup

The test setup consisted of a box, a test specimen, and a load unit (Figure 2). The box was filled with compacted macadam supporting 30 mm of bedding sand. The macadam had a maximum aggregate size of 32 mm. The test flag rested on the bedding sand. On top of the flag, an 8 mm thick neoprene plate and a 40-50 mm thick circular steel plate, both with the diameter c = 252 mm, were placed. The load was applied centrically on top of the steel plate.

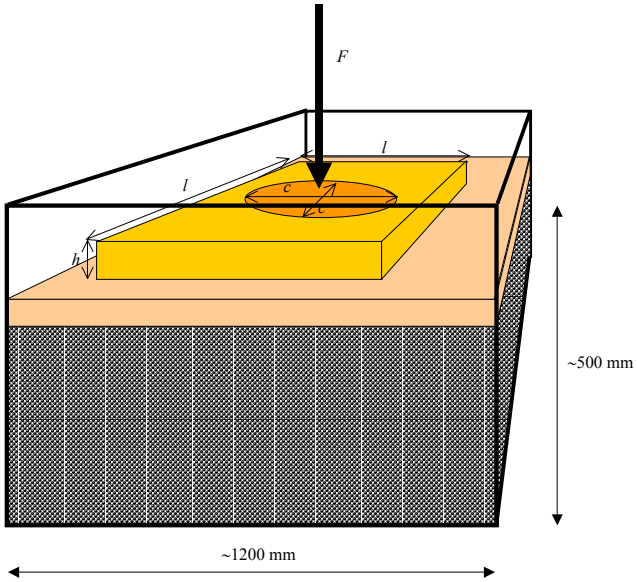


Figure 2. Test setup. The width is 1200 mm and the height is 500 mm.

3.4 Loading

The load was applied from the load unit centrically to the steel plate. The concrete flag was continuously loaded until failure. The vertical displacement of the load unit and the load were recorded. The loading velocity was approximately 20 kN/minute.

During the tests, it was observed that it was somewhat difficult to define a final failure load. At a certain load level, the flag cracked, but still it was possible to increase the load. However, the displacement increased faster per unit load. As the cracked increased in width, this displacement increase accelerated.

Since also a severely cracked flag in co-operation with bedding sand and underlying subbase is able to carry load, the loading was stopped when the load-displacement curve was approximately horizontal or if the load substantially had exceeded the cracking load. An example of a typical load-displacement curve is given in Figure 3.

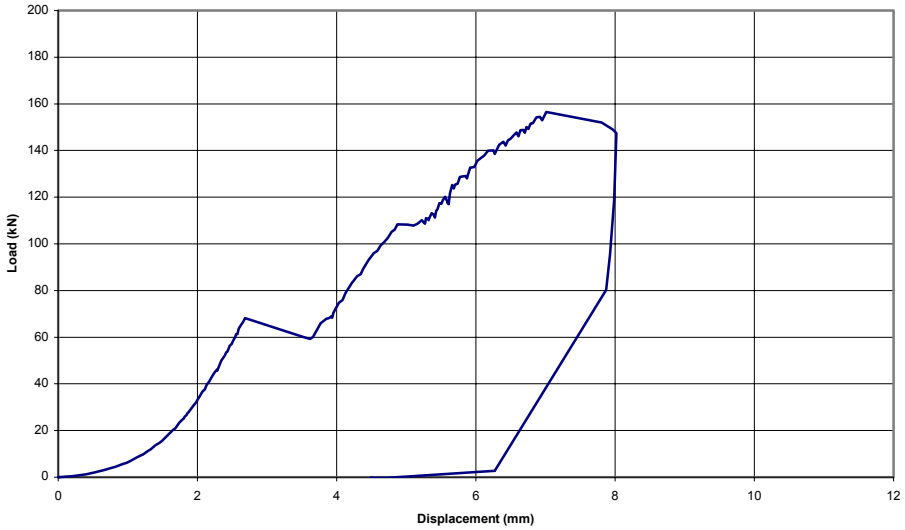


Figure 3. Load-displacement curve for slab No. Q1. The vertical axis shows loads between 0 and 200 kN. The horizontal axis shows displacements between 0 and 12 mm. By using the diagram, the cracking load was determined to 68 kN.

Usually, the flag cracked along two perpendicular lines crossing the flag center dividing the flag into four parts of similar size (Figure 4). The crack pattern is similar to those found on precast concrete flags on overloaded streets and squares.

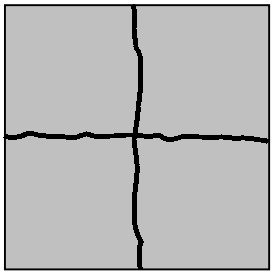


Figure 4. Principle sketch showing a typical flag after failure.

3.5 Reference tests

The failure load of all flag types except P and Q were tested by the manufacturers according to Swedish Standard SS 22 72 09. The failure loads have been converted to a flexural strength that is given in Table 2. For P and Q, the manufacturer's tabled values had to be used instead.

As indicated in Table 2, the various flags were tested at different ages. This was not desired, but was not possible to avoid. However, most of the flags were tested at ages between 28 and 32 days.

3.6 Test results

The results from the laboratory tests are summarised in Table 2.

Table 2. Test results.

Flag type	*Flexural strength (MPa)* *Mean value*	*Dimensions (mm)* *Nominal*	*Age at testing (days)*	*Flag No.*	*Thickness (mm)*	*Crack load (kN)* *First observed*	*Determined from diagram*	*Mean value**
A	9.1	350×350	37	A1	29.3	Not recorded	40	38
				A2	30.7	Not recorded	55	
				A3	29.6	55	20	
C	8.9	350×350	24	C1	49.6	55	26	34
				C2	48.5	55	43	
				C3	50.1	30	32	
E	6.7	350×350	20	E1	50.5	22	23	24
				E2	50.5	25	25	
				E3	50.6	23	23	
J	6.9	350×350	52	J1	49.8	45	35	43
				J2	50.5	35	35	
				J3	50.4	42	60	
K	7.0	350×350	30	K1	58.9	75	53	47
				K2	58.7	40	43	
				K3	58.5	43	45	
L	7.2	350×350	49	L1	69.9	85	75	64
				L2	69.4	33	34	
				L3	69.9	83	82	
N	8.0	350×350	Unknown	N1	51.1	57	57	45
				N2	49.5	35	37	
				N3	51.0	42	42	
O	6.8	350×350	277	O1	80.1	83	82	86
				O2	80.0	72	74	
				O3	80.3	104	103	
P	6	500×500	Unknown	P1	55.0	46	47	40
				P2	54.9	38	37	
				P3	54.8	35	35	
Q	6	500×500	Unknown	Q1	79.6	68	68	66
				Q2	79.7	64	63	
				Q3	80.5	68	68	
R	5.5	350×350	34	R1	69.4	48	48	58
				R2	68.7	74	73	
				R3	70.2	53	53	

Note. * Mean value is based on values determined from diagrams.

4. EVALUATION OF THE TEST RESULTS

4.1 Introduction

This Chapter contains the evaluation of the test results summarized in previous Chapter. It ought to be repeated that the number of tests was fairly small, why the conclusions must be regarded as preliminary. Figure 5 shows all crack loads.

4.2 Scatter in the test results

The scatter in the test results was large. Within one single flag type, the crack load often varied considerably. The scatter may be defined by the following relationship:

$$\text{scatter} = \frac{\text{max value} - \text{min value}}{\text{mean value}} \cdot 100 \qquad (1)$$

where, the max value is the largest crack value for one flag type, min value is the smallest and mean value is the average of the crack loads for this flag type.

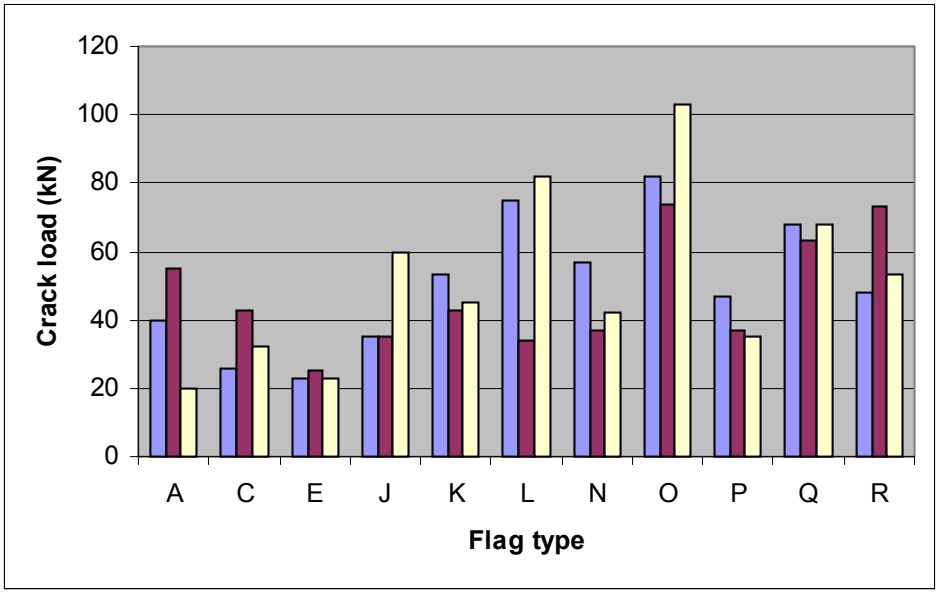


Figure 5. Crack loads for all tested flags. The results are given in the order of testing.

For the eleven flag types tested, the scatter varied between 8 and 91 percent. The average scatter was 42 percent. Flag types A and L had the largest scatter, E and Q the smallest. What can the cause of this large scatter be?

Some possible explanations are the following:

- A natural strength variation between the individual flags.
- A natural thickness variations between the individual flags.
- Eccentric loading.
- Uneven support.
- Continuous stiffening of the support since the same test setup was used.
- Difficulties in determining the crack load from the load-displacement diagram.
- The arbitrary location of the origin of the first crack.

The complete test report (Silfwerbrand, 2002) discusses all the causes. Here, there is only space for the main conclusion. It states that the causes Nos. 3, 6, and 7 are likely to be predominant.

4.3 Analysis of the results

Figure 6 shows the relationship between flag thickness and crack load for all flags tested. It means that no distinction is made between different sizes, strength classes, or manufacturers. The trend is obvious: thicker flags have higher crack loads. This conclusion will be more evident if only flags of one size and one strength class are compared (Figure 7).

By keeping the thickness constant, it can be shown that the crack load decreases slightly for increasing flag length (Silfwerbrand, 2002). More interesting might be to draw a graph with the flag thickness to flag length ratio versus crack length (Figure 8). It is obvious that the crack load increases with increasing value of this ratio.

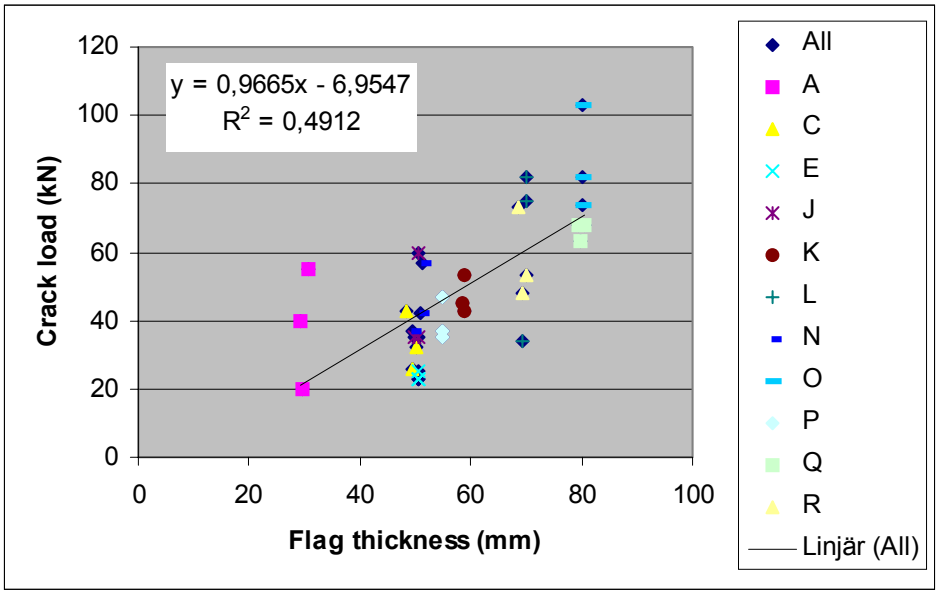


Figure 6. Relationship between thickness and crack load for all flags in the test series.

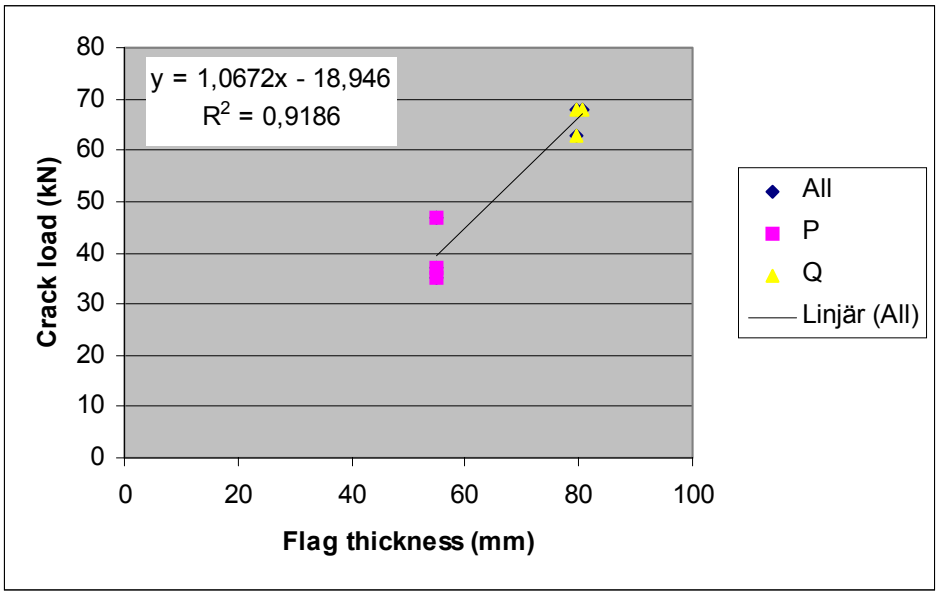


Figure 7. Relationship between thickness and crack load for all flags with dimensions 500×500 mm.

In Figure 9, it is shown that there is a weak relationship between increasing flexural strength and crack load.

By combining the most important factors that may influence the crack load, the following key factor may be defined:

$$k = f_{cfl} \cdot h^2 \cdot \frac{h}{l} \cdot \frac{c}{l} \qquad (2)$$

where, f_{cfl} = flexural strength of concrete flag, h = flag thickness, l = flag length, and c = diameter of loading surface.

If f_{cfl} is given in MPa and h, l and c in mm, the key factor k is obtained in N. Figure 10 shows the relationship between this key factor and the crack load for the eleven flag types tested. It can be seen that the relationship is linear with a correlation coefficient $r^2 = 0.76$. It may be argued that the test data do not support the inclusion of the flexural strength in this key factor (poor correlation between flexural strength and crack load, see Figure 9), but if the key factor should be used for a general design of flags made of concrete with a wider strength spectrum, a strength dependency cannot be neglected. The author is convinced that tests on very low strength concrete flags had resulted in low crack loads. In the test, however, the strength variation was limited to 3.5 MPa (from 5.5 to 9 MPa, see Table 2).

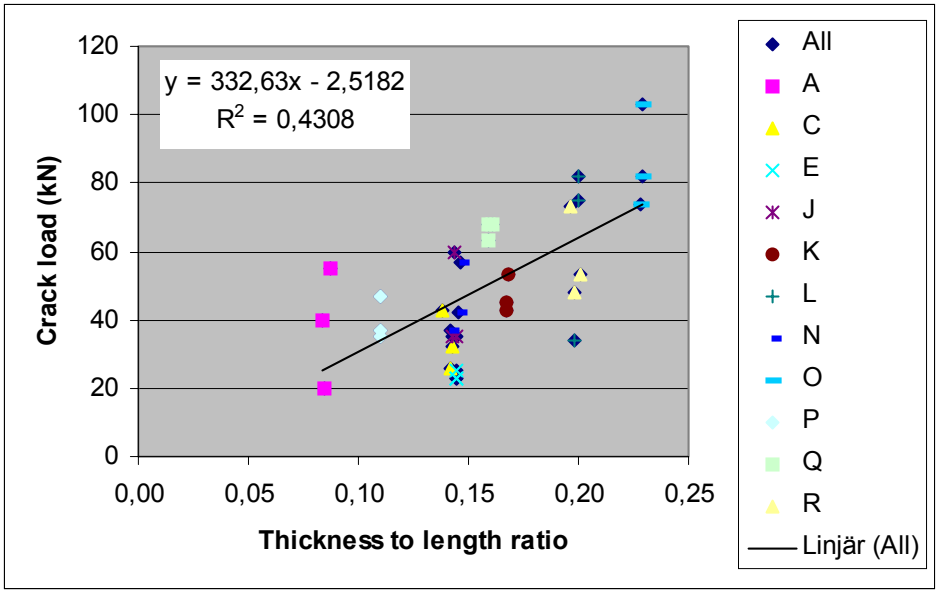


Figure 8. Relationship between flag thickness to flag length ratio and crack load for all flags in the test series.

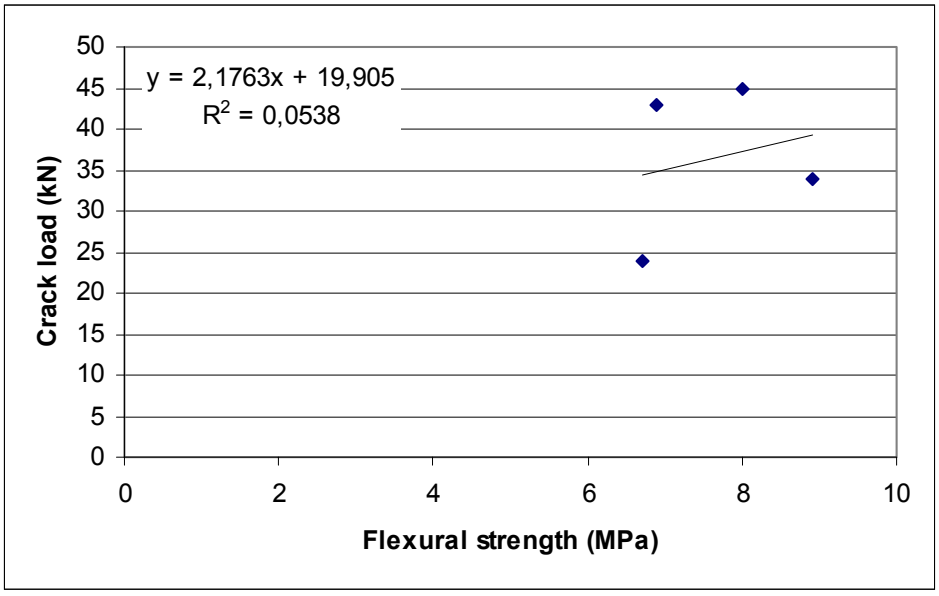


Figure 9. Relationship between flexural strength and crack load for flag types with the dimensions 350×350×50 mm. Each flag type is represented by the average of the crack loads for all three flags within this flag type.

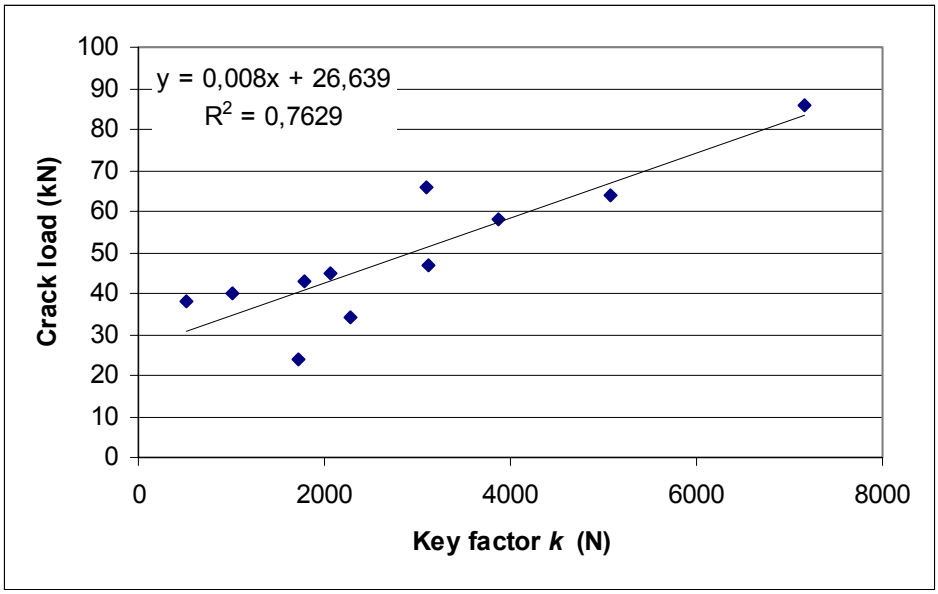


Figure 10. The relationship between the key factor *k* and the crack load for all flags in the test series. Each flag type is represented by the average of the crack loads for all three flags within this flag type.

5. CONCLUSIONS

In all, 33 flags of eleven different types were tested to failure. Two flag sizes, six flag thicknesses, and two strength classes were included in the investigation. The flags were placed on bedding sand in turn resting on compacted macadam.

Based on the test results, the following conclusions may be drawn:

- The scatter in the test results was large.
- Comparing different flag types, it is obvious that the flag thickness is the single variable that has the predominant influence on the crack load and, thus, the load carrying capacity. Increasing thickness leads to increased load carrying capacity.
- Also the flag length and the flexural strength seem to influence the load carrying capacity. Decreasing flag length and increasing flexural strength seem to enhance the load carrying capacity.
- A key factor combining the most important factors affecting the load carrying capacity is defined. The linear relationship between this key factor and the load carrying capacity is fairly strong. It may be used for design purposes, but more test results are needed to support this and the other conclusions.
- Further research is needed to develop design methods for the entire flag pavement system. The tests reported were limited to study the structural behaviour of the individual flag.

6. REFERENCES

Shackel, B, 1990. Design and Construction of Interlocking Concrete Block Pavements. Elsevier Applied Science Publishers Ltd, Barking, Essex, England, 229 pp.

Silfwerbrand, J, 2002. Precast Concrete Flag Pavements – Key Factors and Flag Tests. Royal Institute of Technology, Dept. of Structural Engineering, Chair of Structural Design and Bridges, (Report No. 66), Stockholm. 49 pp. (In Swedish).

Swedish Concrete Block Paving Association [Svensk Markbetong] and Swedish Association for Local Authorities [Svenska Kommunförbundet], 1999. Paving with Concrete Flags and Blocks, Guide for Design and Planning. Printed by Wallin and Dalholm, Lund, Sweden, 111 pp. (In Swedish).

Swedish Concrete Block Paving Association [Svensk Markbetong] and Swedish Association for Local Authorities [Svenska Kommunförbundet], 2002. Paving with Concrete Flags and Blocks, Guide for Design and Planning. 2nd Edition. Printed by Ljungbergs tryckeri, Klippan, Sweden, 127 pp. (In Swedish).

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Biography

Dr. Johan Silfwerbrand, born 1958, is since February 1st, 2002, president of the Swedish Cement and Concrete Research Institute (CBI) in Stockholm. He is also a part-time professor in Structural Design and Bridges at the Royal Institute of Technology (KTH) in Stockholm. Silfwerbrand obtained his M.Sc. and Ph.D. degrees at KTH in 1982 and 1987, respectively. Silfwerbrand is active in American Concrete Institute (ACI), International Federation for Structural Concrete (fib), and RILEM. Beside concrete block pavement, Silfwerbrand's research interests include concrete pavements, concrete repair, industrial floors, and steel fibre reinforced concrete structures.