PAVEMENTS OF ROLLER-COMPACTED CONCRETE - PHYSICAL PROPERTIES

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A project concerning pavements of roller-compacted concrete is in progress at the Swedish Cement and Concrete Research Institute (CBI). This project deals primarily with testing methods and physical properties in respect of roller-compacted concrete. This report contains an account of the results of tests carried out to determine physical properties in connection with placing 54 small test pavements, approx 3 m^2 each, which were cast in the field under controlled conditions. The composition and compaction of the concrete were varied in order to throw light on the effect these factors have on the physical properties.

The compressive strength and splitting strength of the pavements was tested on core samples after 28 and 200 days respectively. The results are related to the degree of compaction and composition of the concrete in the pavements.

Frost resistance and shrinkage were studied on extracted samples and are related to the concrete standards applicable in Sweden as well as conventional pavement concrete used as a reference.

Key words: Roller compacted concrete, compaction, strength, frost resistance, shrinkage.

INTRODUCTION

Over the past few years, roller-compacted concrete has undergone rapid development in respect of both materials and technique. In actual fact, the technique was widely used back in the 1930s when it was called the hand-tamping casting technique. It subsequently fell into oblivion, primarily due to the limitations of the compaction equipment.

Through the use of roller-compacted concrete for various types of pavements and the construction of dams, widely varying concrete qualities and techniques have to be used (1). It is therefore important to define precisely what is meant by roller-compacted concrete. The definition of roller-compacted pavement in Sweden is that after compaction of the concrete with a vibratory roller it shall have a strength corresponding to Swedish strength class K 40 (a mean standard cube strength of at least 40 MPa after 28 days). The directly exposed top surface shall be resistant to frost and abrasion.

The work described in this report is part of a major project concerning pavements of roller-compacted concrete. This project is in progress at the Swedish Cement and Concrete Research Institute (CBI) and its progress is described regularly in CBI reports, see (2), for example.

MATERIALS AND DESIGN

The results of this study embrace samples from 54 small test surfaces (approx 3 m^2 each). The following binders were used in the study, Table 1.

TABLE 1. Chemical composition and physical data in respect of the two Ordinary Portland Cements (OPC), the Condensed Silica Fume (CSF) and the Fly Ash (FA) used as binders in the experiments.

Oxide analysis (weight %)	OPC (Slite)	OPC (Anl)	CSF (Ljungav)	FA (Västerås)
CaO	63.4	63.9	0.4	7.9
SiO_2	19.6	21.7	84.0	45.1
Al_2O_3	4.1	3.7	1.0	23.5
Fe_2O_3	2.2	4.7	2.2	8.6
K_2O	1.1	0.6	1.0	2.0
MgO	3.0	0.7	-	4.0
SO_3	3.0	1.9	-	0.8
Physical data				
Blaine (m^2/kg)	381	343	809	568
BET surface (m^2/g)	-	-	21.8	-
Density (kg/m^3)	3140	3210	2360	2370

All roller-compacted concrete contained 12.6-15.0% binder by weight and 4.6-5.0% water by weight. The water content was chosen so that the concrete would be suitable for compacting by a vibratory roller. The aggregate curve was uniformly composed of three different fractions, gravel 0-2 mm, gravel 0-8 mm and crushed aggregate 8-16 mm. Conventional pavement concrete was placed and compacted with a vibrating beam as a reference. This concrete contained 0.055% air entrainment agent (brand name Barra Aer L) by weight, which gave 5.5% air. In other respects the concrete was of Swedish strength class K 40, slump 90 mm with a water-cement ratio of 0.45.

On mixing the concrete the aggregate was added first and then the binder and finally the water. Mixing was carried out in a paddle mixer filled to about three quarters of its normal weight capacity. Mixing time was 120 s after adding the water.

The roller-compacted concrete was placed with a bucket and the pavement was adjusted manually with a rake. The underlying surface was hard-packed base course gravel in an abandoned stone quarry. Rolling was carried out with a vibratory tandem roller, a Dynapac LP65H with a static load of 5 kN/m. The

number of passes was varied to obtain different degrees of compaction but two static roller passes were always made first. The pavement surfaces were cured with asphalt, BL 20 RAK, 0.6 kg/m^2. Curing was carried out not later than 50 minutes after the water had been added during mixing.
All pavements had a thickness of 100 mm (compacted height).

TEST RESULTS AND DISCUSSION

Strengths

Test cores with a diameter of 100 mm were drilled out approximately seven days before test compression. The test specimens were smoothed down and stored at 20^{o}C, 50% RH for at least 3 days before testing. The results of the compressive strength tests after 28 and 200 days respectively are shown in Fig 1.

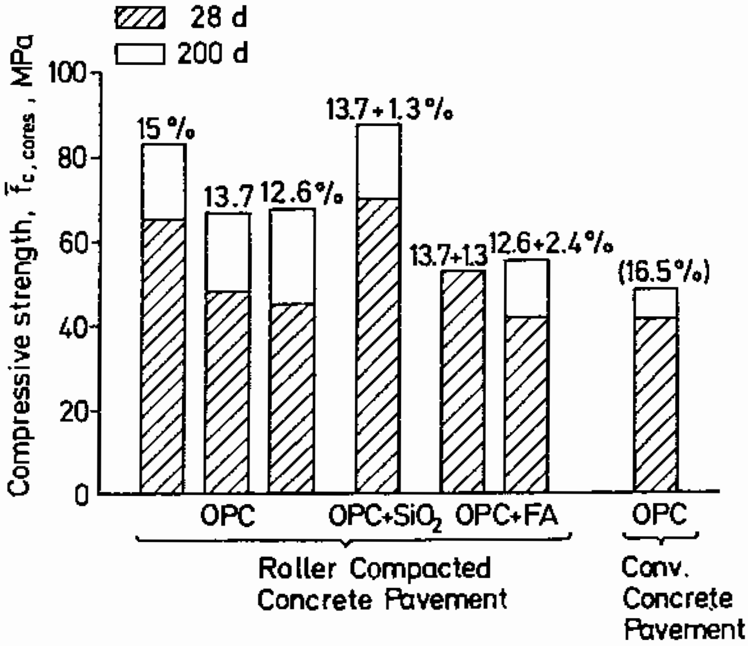

FIG 1. Compressive strength of core samples converted to apply to 150 mm cubes. In roller-compacted concrete, the water content varied between 4.6 and 5.0% by weight. Only samples with a compaction degree of 98-100% are shown. Total amount of binder 12.6-15.0% by weight.

The requirements of K 40 tested in a completed structure after 28 days in accordance with Swedish concrete standards are met for the conventional concrete pavement due to limited deviations in the results of the experiments. On the other hand, the requirements are not satisfied by roller-compacted concrete with only 12.6% OPC by weight or 12.6 + 2.4% OPC + FA by weight. Other tested binder combinations as shown in Fig 1 do satisfy the standards, on the other hand. The addition of fly ash has no positive effect on strength. On the other hand, the results show that SiO$_2$ makes an effective pozzolana and that it has a favourable effect on the properties.

Dispersion in strength within each test area is wide. This is analogous with previous experience indicating that roller-compacted concrete has a wider strength dispersion than conventional pavement concrete. This is explained primarily by the difficulty of obtaining the same degree of compaction over the entire pavement and the difficulty of mixing the dry roller compacted concrete homogeneously.

The average increase in strength of the roller-compacted concretes between 28 and 200 days is 38%. The corresponding increase in the strength of conventional pavement concrete is only half that, ie barely 20%. This difference is probably due to the low water content of roller-compacted concrete. A low water content leads to fast natural internal self-desiccation which in its turn counteracts hydration of the cement. This would give roller-compacted concrete a comparatively low rate of strength growth. External addition of moisture is decisive for a later strength increase. Since the test surfaces were situated outdoors, the external addition of water was assured by the Swedish autumn and winter.

The different effect of silica fume and fly ash on strength is probably also due to the rapid natural internal self-desiccation caused by the low water content of roller-compacted concrete. In their respective pozzolanic reactions with calcium hydroxide, fly ash and silica fume bind only an insignificant amount of water, apart from the water present in the calcium hydroxide that reacts, but their reactions require the presence of water. For the silica fume there was in the cases concerned here sufficient water for a pozzolanic reaction and the filler effect to result in high strength relative to Portland cement. Fly ash, on the other hand, is considerably less reactive and it is conceivable that the amount of water was therefore insufficient for its reaction.

A decisive factor bearing on compressive strength is the degree of compaction defined as below, equation 1. The relationship between compressive strength and degree of compaction will be evident from Fig 2 and Fig 3.

$$R_d = \frac{\gamma_{d,\mathrm{field}}}{\gamma_{d,\ \mathrm{mod\ proctor}}} \cdot 100\ \% \qquad (1)$$

where

R_d = degree of compaction (%)

$\gamma_{d,\ \mathrm{field}}$ = dry density measured in the field when the concrete was in a fresh state. If the dry density was obtained from core samples a correction has been made for water bound through cement hydration after the fresh state (kg/m^3)

$\gamma_{d,\mathrm{mod\ proct}}$ = dry density after heavy laboratory tamping in accordance with modified proctor (kg/m^3)

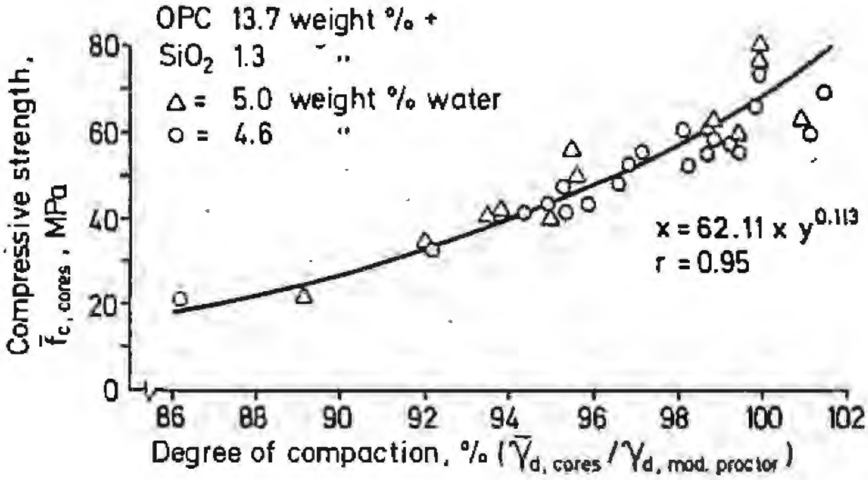

FIG 2. The relationship between degree of compaction and compressive strength for core samples with 4.6 and 5.0% water by weight. Compressive strength is converted so that it applies to 150 mm cubes. Sample age 28 days. The different degrees of compaction have been obtained by varying the number of roller passes.

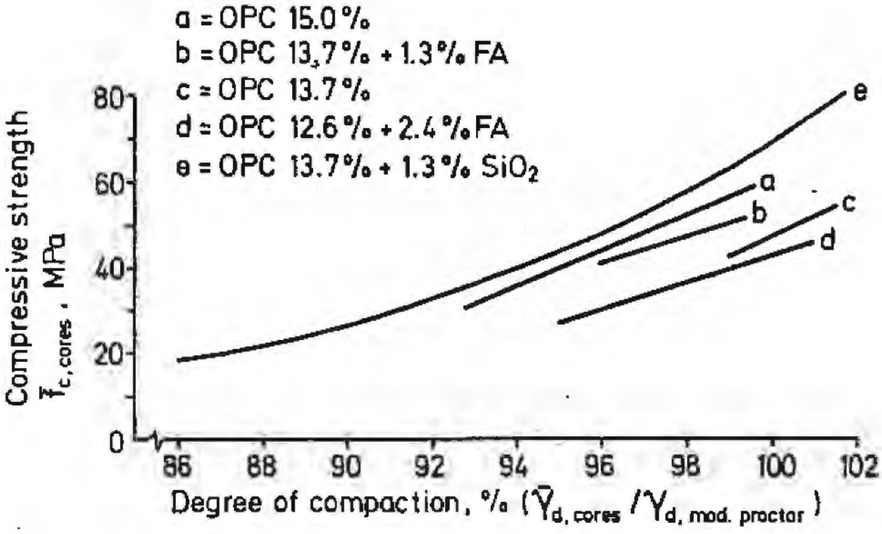

FIG 3. Relationship between degree of compaction and compressive strength for all core samples with 4.6 and 5.0% water by weight. Compressive strength is converted so that it applies to 150 mm cubes. Sample age 28 days.

A corresponding relationship was also obtained between splitting strength and degree of compaction, FIG 4.

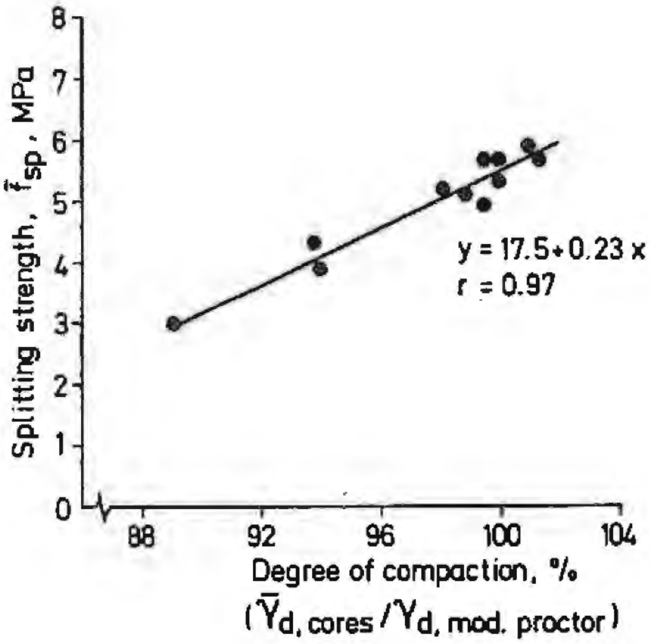

FIG 4. Relationship between splitting strength and degree of compaction for core samples, 100 mm diameter. Sample age 28 days.

On closer study, roller-compacted concrete proved to have comparatively high splitting strength in relation to its compressive strength, see FIG 5. The probable explanation of this is a larger quantity of aggregate and the higher rupture energy which the compact crushed rock skeleton may occasion.

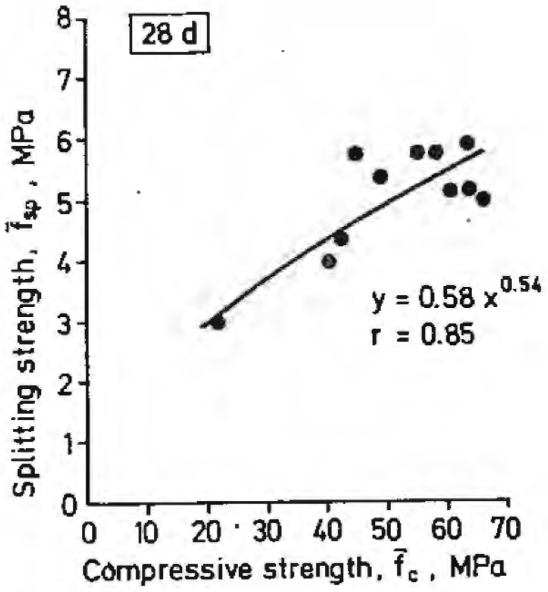

FIG 5. Relationship between splitting strength and compressive strength in core samples, 100 mm diameter. Sample age 28 days.

Frost resistance

One decisive property of a pavement is its durability. In the case of concrete pavements it is chiefly frost resistance that is of importance. In conventional concrete this is assured by the combination of a low water-cement ratio and a stable air entraining system. In roller-compacted concrete only limited success has yet been achieved in establishing a stable air entraining system, primarily on account of the low water content. For this reason frost resistance is assured in the present situation by a high cement content and a low water content combined with constructive measures such as good drainage.

In 14 of the 54 test pavements core samples were extracted for testing frost resistance, see Table 2. This testing was carried out in accordance with Swedish Standard SS 13 72 36 which entails a total of 56 24-hour temperature cycles. The samples stand with their top surface facing upwards and the test is carried out in the presence of a 3% sodium chloride solution on the top surface. Freezing is carried out for 13 hours with a minimum temperature of -18°C while thawing is carried out for 11 hours with a maximum temperature of 20°C. The requirement in regard to frost resistance is that maximum scaling is less than 1.0 mg/mm^2 after 56 freeze cycles. This corresponds to 0.0179 mg/mm^2 per 24 hours. If scaling after an initial low level during the 28-56 day period is higher than the mean value, this indicates that problems of frost resistance will arise in the future.

TABLE 2. Frost resistance tested in accordance with Swedish Standard SS 13 72 36. Two core samples (diameter 100 mm) per variable.

Variable (percentage by weight)			Degree of compaction (%)	Scaling after 56 cycles* (mg/mm^2)	Scaling per 24 hours between days 28 and 56** (mg/mm^{2}x24 h)
Binder	Water	Remarks			
OPC 12.6	4.6		99.4	0.315	0.004
OPC 15.0	4.6		94.2	8.743*	0.296**
OPC 15.0	5.0		99.9	0.901	0.011
OPC 15.0	4.6	0.6 % Kleenopor by weight	97.7	0.246	0.007
OPC 13.7+SiO_2 1.3	4.6		96.9	0.046	0.001
OPC 13.7+SiO_2 1.3	4.6		98.2	0.077	0.001
OPC 13.7+SiO_2 1.3	4.6		99.3	0.064	0.001
OPC 13.7+SiO_2 1.3	4.6		100.0	0.067	0.001
OPC 13.7+SiO_2 1.3	4.6		101.2	0.063	0.001
OPC 13.7+SiO_2 1.3	4.6	Aggregate 8-16 mm gravel	97.2	0.030	0.001
OPC 13.7+SiO_2 1.3	5.4		101.6	0.253	0.005
OPC 12.6+FA 2.4	4.6		94.5	0.980*	0.033**
OPC 12.6+FA 2.4	5.0		101.3	1.546*	0.025**
Conventional pavement concrete K40 slump = 90 mm water-cement ratio 0.45 5.5% air			-	0.231	0.001

* Maximum scaling according to the Swedish Standard is 1.0 mg/mm^2

** Scaling between day 28 and day 56 should be less than 0.0179 mg/mm^2 per 24 h.

These experiments are currently being followed up with additional studies aimed at explaining the fundamental parameters governing the frost resistance of roller-compacted concrete. The following comments are made on the basis of the first 14 tests.

All mixes containing 13.7% OPC by weight and 1.3% SiO_2 by weight displayed extremely good frost resistance. The two mixes containing 20% fly ash in the amount of binder were not frost resistant. Neither were the mixes with a low degree of compaction, 94.2 and 94.5%, resistant to frost.

Shrinkage

Apart from the heat of hydration in the cement, shrinkage in a pavement is decisive for crack size and crack frequency.

There are several reasons why shrinkage ought to be low in roller-compacted concrete. For example, since outdoor structures in Sweden display only a slight difference in relative humidity between the structure itself and the surroundings, for which reason the dry-out force is low. Furthermore, hydration rapidly diminishes in concrete with a low water content on account of natural internal self-desiccation. In this way shrinkage is reduced.

As a rule, a low water content in concrete will cause it to have little final shrinkage. At constant relative humidity, final shrinkage is primarily a function of the concrete's water content. The relationship is given in (3) according to equation (2).

$$\varepsilon_g = 3.75(w_o - 50)\ 10^{-6} \qquad (2)$$

where ε_g = final shrinkage at 50% RH (%)

w_o = concrete water content ($1/m^3$)

Test beams measuring 100x100x400 mm were sawn out of five of the pavements within 3 days of placement. The test specimens were kept in water for 7 days, following which they were stored at 20°C and a relative humidity of 50%. At this point in time the basic length of the beams was measured between measuring dowels cemented in place. The results of the test are shown in Table 3.

TABLE 3. Shrinkage in sawn-out test specimens, two specimens (100x100x400 mm) tested per variable. Testing in accordance with Swedish Standard SS 13 72 15. Theoretical final shrinkage according to (equation 2).

Variable (percentage by weight)			Degree of compaction	Shrinkage 119 days	Theoretical final shrinkage
Binder		Water	(%)	(o/oo)	(o/oo)
OPC	15.0	5.0	99.9	0.37	0.27
OPC(Anl)	15.0	5.0	99.7	0.37	0.27
OPC 14,3+SiO_2	0.7	5.0	100.0	0.35	0.27
OPC 12.6+FA	2.4	5.0	101.3	0.37	0.27
Conv pavement concrete K40, slump 90 mm, water-cement ratio 0.45, air 5.5%			-	0.46	0.44

For roller compacted concrete the results clearly show much greater shrinkage than could be theoretically expected. However, shrinkage in roller compacted concrete is still appreciably less than in conventional pavement concrete.

Compaction in height

The density of the pavement was measured with a nuclear density meter (of Troxler manufacture) to see how compaction varied in height for different concrete mixes. A typical result obtained from these measurements is shown in FIG 6.

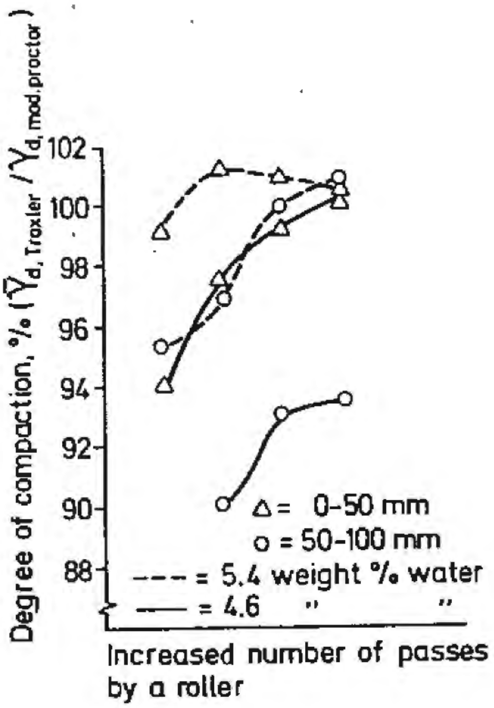

FIG 6. Degree of compaction measured with a nuclear density meter related to an increasing number of passes. The binder consisted of 13.7% OPC by weight and 1.3% SiO_2 by weight. Rolling was performed with an LP 65 vibratory tandem roller having a static load of 5 kN/m.

The results show how important it is not to have too low a water content in roller-compacted concrete. In connection with continuously checking the water content of roller-compacted concrete during placement, minimum water content should therefore also be checked and not only maximum water content as is often the case at present.

CONCLUSIONS

The study described has provided much fundamental knowledge about roller-compacted concrete. This applies in particular to roller-compacted concrete for pavements in Sweden but the results also add to the general fund of knowledge about the physical properties of roller-compacted concrete and how they are affected by the degree of compaction, for example.

Compressive strength and resistance to cracking are both strongly dependent on the compaction of the rolled concrete. At the same degree of compaction the compressive strength increases when the amount of OPC is increased from 12.6 to 13.7 and 15.0 percentage by weight. Exchanging 1.3% OPC by weight for the same percentage by weight of silica fume, SiO_2, resulted in increased strength. The addition of fly ash, on the other hand, has no strength-enhancing effect. Between day 28 and day 200, roller-compacted concrete displayed an average strength increase of 38%, an increase that is not found in conventional pavement concrete used as a reference in the experiments. The different effect of the pozzolans on strength and also the substantial increase in strength between day 28 and day 200 can be explained by fast natural internal self-dessication caused by a low water content in the roller-compacted concrete combined with the subsequent natural external addition of moisture in the form of rain and snow.

The frost resistance of core samples tested in the presence of a 3% saline solution showed the same tendencies as for compressive strength. Exchanging 1.3% OPC by weight for silica fume, SiO_2, resulted in somewhat superior frost resistance. Roller-compacted concrete both with and without SiO_2 was nevertheless frost resistant if the degree of compaction was higher than 96.9%. Roller-compacted concrete with a low degree of compaction, like roller-compacted concrete with fly asb as one of the binder constituents, was not frost resistant.

Shrinkage in the tested roller-compacted concrete was 0.35-0.37 o/oo in all test pavements after day 119 as against 0.46 o/oo in the conventional pavement concrete.

Variations in the degree of compaction with height proved to be extremely dependent on the water content of the roller-compacted concrete. In comparatively dry roller-compacted concrete there is therefore a fairly high risk that the lower part of the pavement will not be sufficiently compacted.

ACKNOWLEDGMENTS

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