OTTO GRAF´S RESEARCH ON CONCRETE ROADS - A RETROSPECTIVE VIEW

OTTO GRAF´S FORSCHUNG ÜBER BETONSTRASSENBAU - EIN RÜCKBLICK

LA RECHERCHE D'OTTO GRAF SUR LES ROUTES EN BÉTON - UNE RÉTROSPECTIVE

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KEYWORDS: Concrete, road, design, mix, abrasion, traffic safety

SUMMARY

Otto Graf has tested the components of concrete very extensively in the laboratory. Cement was most important which led to a small shrinkage and a high tensile strength. The fineness of the cement was one very important influencing quantity. He investigated the aggregates which should have a high compressive strength, high tensile strength and high resistance against freezing and abrasion. Grading curves were investigated and the compressive strength of concrete was related to the water-cement ratio. SN-curves have been received through tests in the laboratory and in-situ. Loading tests on concrete roads led to the optimum thickness of slabs which was 22 cm in 1939. Many questions of the time of Otto Graf are still relevant however with other boundary conditions.

ZUSAMMENFASSUNG

In umfangreichen Laborversuchen hat Otto Graf die Bestandteile des Betons untersucht. Es ging um den Zement in erster Linie, der zu einer möglichst schwindarmen und zugfesten Zementsteinmatrix führen sollte. Die Mahlfeinheit wurde dabei als eine wichtige Einflussgröße herausgearbeitet. Dem Zuschlag galt ebenfalls große Aufmerksamkeit, der hohe Druckfestigkeit, Zugfestigkeit und Widerstandsfähigkeit gegen Gefrieren und Abrieb haben sollte. Sieblinien wurden untersucht und die Festigkeit des Betons wurde anhand des Wasserzementfaktors dargestellt. Wöhlerlinien wurden im Labor und im Feldversuch ermittelt. Belastungsversuche an Betonstraßen führten zur optimalen Dicke der

Platten, die schließlich auf 22 cm festgesetzt wurde. Viele Fragestellungen von damals sind auch heute noch aktuell, allerdings mit neuen Randbedingungen.

RESUMÉ

Des essais de laboratoire ont été exécutés par Otto Graf dans une large mesure pour étudier les composants du béton. Une place importante tenait la recherche d'un ciment qui montre un petit retrait et une grande résistance à la tension, une fois durci. Une grandeur importante semblait la finesse de mouture du ciment. Grande attention etait aussi donnée aux agrégats qui devraient avoir une grande résistance contre le gel et l'abrasion. La granulometrie du sable et des agrégats a été explorée et on a donné la résistance de compression comme fonction du rapport eau-ciment. Graf a déterminé des lignes Wöhler dans le laboratoire et in-situ. Des essais de chargement des dalles en béton menaient à l'épaisseur optimale qui a été fixée à 22 cm finalement. Beaucoup de questions posées à cette époque sont encore de l'actualité, pourtant avec des conditions nouvelles.

INTRODUCTION

Otto Graf was a pioneer in the field of concrete roads. He has published 53 papers on the subject. He was member of the relevant committees in Germany and has influenced the development of concrete roads very strongly. His work covers concrete technology, design, and traffic safety.

CONCRETE TECHNOLOGY

In 1927, he published a paper on the general requirements on road concrete. There were seven items mentioned: 1. high compressive and high impact strength, 2. high tensile strength to avoid cracks, 3. small shrinkage and swelling, 4. high abrasion resistance, 5. weather resistance, also with repeated freezing and thawing in saturated condition, 6. elasticity with reversible and irreversible deformation, 7. high resistance against chemical attack [1]. It follows that a concrete with crushed ductile rock as aggregate is suited for concrete. The concrete should have a minimum compressive strength of 30 MPa at the age of 28 days. The mortar content should not exceed 55% and the concrete should be cured for a long period.

He states also that concrete with a large amount of coarse aggregate does less shrink than another one with a high content of fine material. However, the workability of the concrete should be improved [2]. Fig. 1 shows a concrete cross-section with 26% by vol. sand in the aggregates [3].

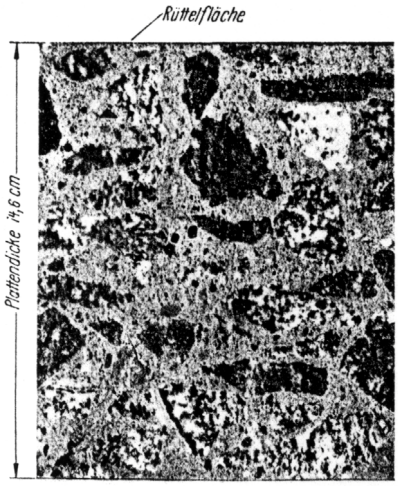

Fig. 1. Concrete cross-section with 26% by vol. sand in the aggregates [3]

The use of cement is a very important subject and Otto Graf has formulated seven questions at the beginning of a publication in 1935 [4]:

1. Which properties define the quality of a cement for concrete roads?
2. Are the results of standard tests on cement sufficient for the assessment of the suitability?
3. Which tests are necessary additionally to standard testing?
4. How do we find suitable cements for concrete roads?
5. How can the consumer judge whether a delivered cement is especially suitable for concrete roads?
6. How should the acceptance of cements be organised?
7. Is the development of road cements only important for the road construction?

He found that test results of standard tests are not sufficient to find out whether a cement is especially suited for concrete roads. He designed tests in which the specimens were stored in a cyclic moisture environment. Some cements were superior than others in the bending test. Obviously shrinkage influences the test results such that large shrinkage caused eigenstresses which low-

ered the bending strength. An important criterion is fineness of the cement. Fig. 2 shows the influence of the fineness of the cement on the compressive strength, the bending strength, and on shrinkage.

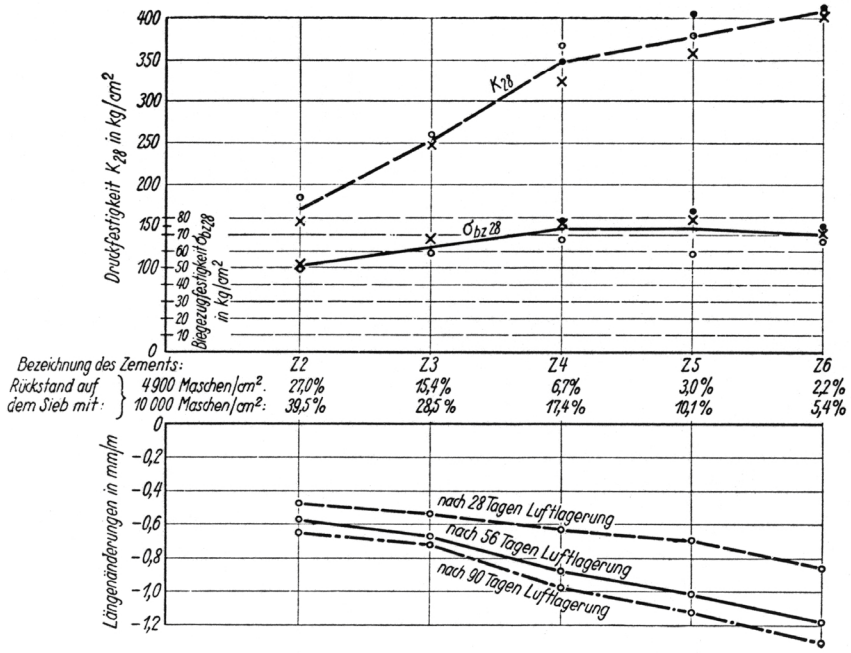

Fig. 2. Influence of fineness on the properties of cement [5] [1]

It is obvious that finer cement increases the compressive strength at 28 days as well as the bending strength. However, a finer cement causes also an increase of shrinkage. Graf requires that the compressive strength of a cement should be 45 MPa at the age of 28 days and the bending strength should be at least 5.5 MPa. In [6], the requirements were given more precisely and Graf points on the cracking, for instance due to capillary stresses during the summer. He states already in 1937 [7] that the production control in the cement factory is as important as the standard testing independent laboratories.

In 1935 [8] he published a paper on the most important parameters which determine the concrete strength. Fig. 3 shows the plot of the compressive strength of concrete as function of the water-cement ratio. It can be seen that the strength is mainly determined by the water-cement ratio. On the other hand, the scatter of results is important. He states also that the sand content of the concrete is important. Especially as the amount of sand exceeds 50%, the strength of concrete is much less.

[1] Throughout the paper the unit kg/cm^2 should be converted to 0.1 MPa.

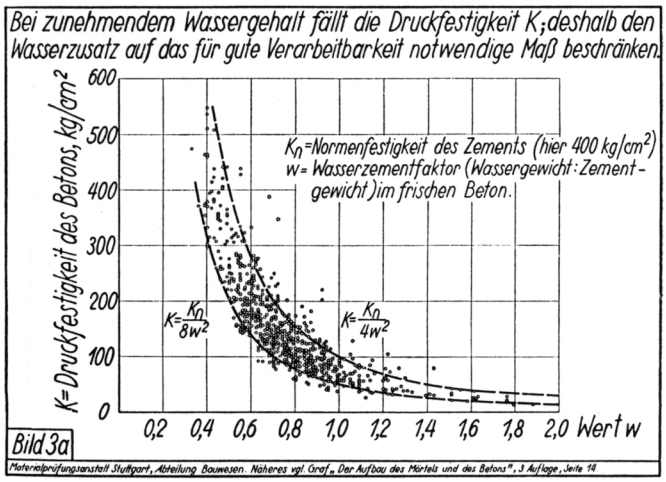

Fig. 3. Compressive strength of concrete as function of the water-cement ratio

Otto Graf carried out cyclic tests. He found that the concrete strength decreases due to cyclic testing, especially as the first million of cycles is concerned. The strength drops from the original value to about 80%. Fig. 4 shows the diagram which illustrates the reduction of compressive strength due to 5 million cycles. It is a Goodman-diagram with the upper stress at the top of the figure.

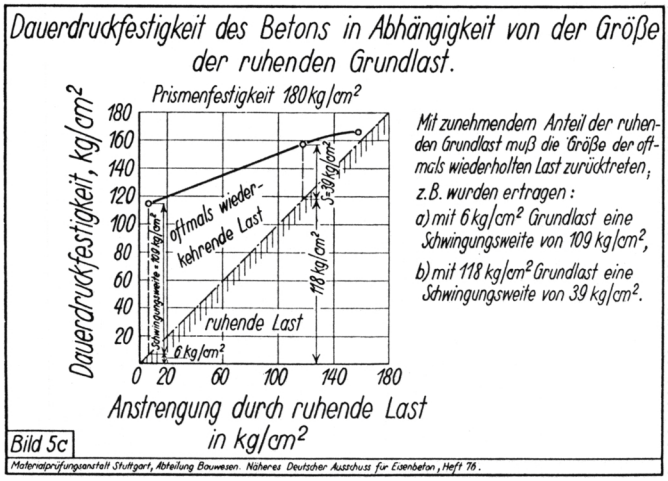

Fig. 4. Goodman-diagram of concrete [8]

Shrinkage is of paramount importance for road concrete because it may cause large eigenstresses in a concrete slab. Graf investigated several cements and found in Fig. 5 that there are large differences as shrinkage of cement is concerned. Cement *a* shows a shrinkage of about $0.8 \cdot 10^3$ whereas cement *e* shows a shrinkage of $1.5 \cdot 10^3$. As Fig. 5 shows that the tests lasted 10 years.

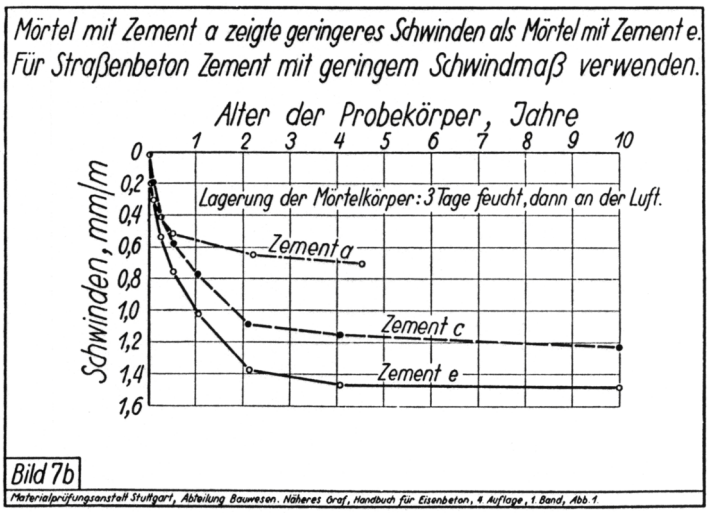

Fig. 5. Shrinkage of various cements [8]

He investigated also different aggregates in concrete and found that the shrinkage of concrete with furnace slag is small whereas with granite shows a larger shrinkage. After drying the specimens where stored in water and there the swelling of concrete with limestone aggregate is larger than with all other aggregates. In 1936, there appeared a paper on the general properties and requirements on concrete roads [9]. Graf states that the compressive strength should be at least 40 MPa at the age of 28 days, the bending strength should be 4.5 MPa. The slab thickness of concrete roads should be at least 20 cm [10]. He carried out many in-situ tests in order to establish the relation between the slab thickness and the loading capacity. Fig. 6 shows an illustration of the loading devices used at that time. Cars were used as reaction load for the pistons which were mounted under the loading bridge. By using this device he could apply also cyclic load on the concrete road.

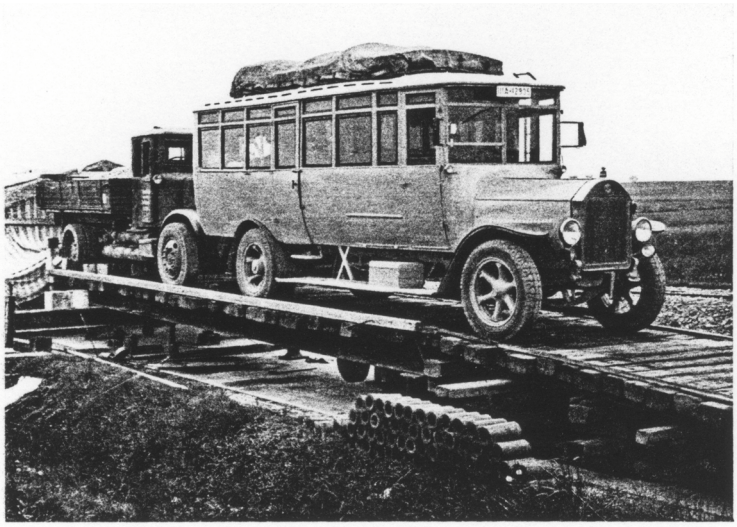

Fig. 6. Loading device for cyclic in-situ tests

DESIGN

As stated before, Graf introduced his papers very often by asking questions [11]. As the design rules are concerned, he formulated three questions:

a) What should be the thickness of concrete slabs for an axial load of 8 tons which occurs very often?

b) Which are the stresses which occur in 15, 20 and 25 cm thick slabs under moving loads? What are the thermal stresses due to climatic changes?

c) Which is the advisable width of joints between concrete slabs and what are the changes of joint width during a day and during a year?

To that end tests have been carried out on the expressways München-Holzkirchen and Stuttgart-Ulm. After testing he decides to design concrete slabs with a thickness of 20 cm. He refers to publications of Westergaard in 1926 [12]. He found that the strains which were predicted by Westergaard's formulae were smaller than those which were measured in-situ. The measurement on joint widths showed that a mean value of 0.007 mm are most probable for a slab length of 1 m and a temperature difference of 1°C.

The question whether concrete roads should be reinforced with steel was not decided yet [13]. Graf states that reinforcement is only an auxiliary measure since reinforcement cannot suppress cracking. Reinforcement acts when the concrete cracks and the cracking cannot be prevented. So, in the guidelines for the construction of concrete roads (ABB) [14] it is recommended that reinforcement should be used only where the subbase is very weak, for instance on high dams or infills. In these situations the reinforcement ratio should be 6-8 cm^2 on the slab width of 3.75 m which is very low. In a later publication [15] the necessary steel cross-section is given with 0.5 to 1% of the concrete cross-section which is more realistic. There should be dowels in the joints. Otherwise, there will be steps on the concrete roads which impair the traffic safety [16]. In 1950, Graf presented a paper which summarises the main questions but also the experiences which were made with the concrete road construction in Germany [17].

TRAFFIC SAFETY

Tests were carried out on the friction resistance of concrete roads. To that end a measuring device was designed as a roundabout which is depicted in Fig. 7 [18].

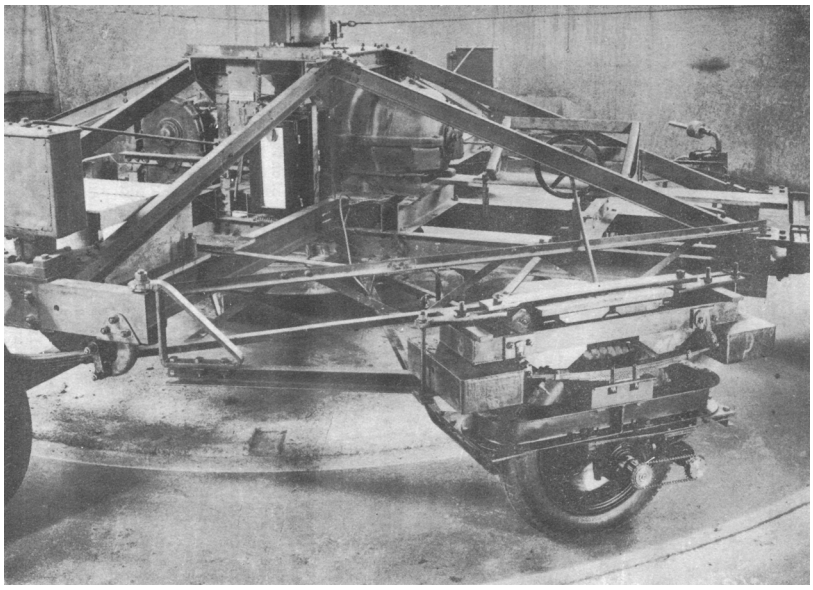

Fig. 7. Measuring device for the testing of friction between wheel and concrete [19]

A dry road led to a friction coefficient of 0.63, a wet surface to 0.41 and a slippery road (= dirty) to 0.33. During the test duration the friction coefficient increased.

CONCLUSION

Otto Graf was an exceptional personality [20, 21, 22]. Besides the already mentioned 53 publications on concrete road he published 570 papers on other subjects like reinforced concrete, steel structures and timber structures. Besides his scientific achievements he was a very practical organiser whose testing and research was mainly funded by industry. He was a member of several committees in all areas. So it was possible to publish a guideline for the construction of concrete roads already in 1939 which was a milestone in concrete road construction. The quality of German expressways was very good and the durability was high. At that time it was a challenge to work in this area. To acknowledge his achievements the civil engineering division of the MPA got the name Otto-Graf-Institute in 1953.

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