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Practical Improvements in the Mechanical Treatment of Concrete [1].

Praktische Weiterentwicklung der Verfahren zur mechanischen Behandlung von Beton.

Progrès pratiques des méthodes de traitement mécanique des bétons.

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The considerations put forward in the first two parts of this paper are, as the Author will show presently, of some importance not only from a speculative point of view but still more from that of practical application on works. Starting from these theoretical grounds he has been led to the attainment of conditions which are unprecedented and which amount to a revolution in the combined usage of steel and concrete — conditions which render possible not only a large saving in the cost and weight of materials necessary to build a structure of specified dimensions and strength but which open up altogether new technical possibilities of the highest interest. These, it is clear, depend on the combination of steels of high strength and high elastic limit with grades of concrete likewise of high strength.

Difficulties attending the use of high-elastic limit steel.

A reduction in the cost of the steel required to build a structure of given dimensions and strength must depend on reducing the ratio $\frac{\text{price per unit weight}}{\text{ultimate stress}}$

[1] This paper by *Freyssinet* forms part of a work on "New aspects of the problems of reinforced concrete", the first two parts of which, briefly summarized below, appeared in the 4th volume of the Memoirs of the I.A.B.S.E.

In the first part *Freyssinet* developed a theory of strains in cement and concrete based on the principles of thermodynamics and on the hypotheses of physics. This was expressed in a series of theorems, valid for any substance of the kind referred to by him as a "pseudo-solid", which has the form of a network of very fine interstices which can be filled either by a liquid wetting their boundaries or by a gas.

In the second part, by introducing new hypotheses, the Author determines the general properties of cements and the mode of formation of the pore structure in cement pastes. From this he deduces some important practical consequences and in particular he explains why it is that the strength of a cement depends more on the mechanical and physical conditions of its use than on any other factor. He proceeds to show that with any cement a considerable degree of hardness can be obtained almost at once, simply through an improvement in the compactness.

which varies in the same way as the ratio $\frac{\text{price per unit weight}}{\text{elastic limit}}$. At a price slightly higher than that of the mild steels commonly used, the mills can supply steels having strengths close to 100 kg per sq. mm (63.3 tons per sq. in.) wherein the elastic limit can easily be above 80 kg per sq. mm (50.6 tons per sq. in.), and in response to large orders specially treated steels could be delivered with an elastic limit well in excess of 120 kg per sq. mm (75.6 tons per sq. in.).

Since the steels in use at present are confined almost exclusively to an elastic limit of 24 kg sq. mm (15.2 tons per sq. in.) it follows that the present ratio $\frac{\text{elastic limit}}{\text{price}}$ can be divided by a coefficient of about 3 which is capable of being increased in the future to more than 4. In large spans the coefficient would be higher still on account of the indirect advantage due to reduction in dead weight.

Unfortunately, if, in a reinforced concrete structure, the ordinary steel be replaced by steel of higher strength — for instance by steel having an elastic limit of 120 kg per sq. mm (75.6 tons per sq. in.) — very serious cracks appear as soon as the structure is so loaded as to cause stresses in the metal notably greater than the usual values, and the performance is little better than if the reinforcements were of ordinary mild steel of the same section. The reason for this lack of success is that in ordinary reinforced structures the strain in the concrete is practically equal to that of the steel carrying the whole of the tensile forces, and increases in proportion to the stress, Young's modulus being independent of the grade of steel. Consequently the limits of elongations that can be withstood by the concrete correspond approximately to those governed by the usual stresses in mild steel.

The use of high-strength steels working in tension therefore adds very little to the practical value of a structure, and being subject to certain disadvantages it is not a feature of current practice[2].

Difficulties attending the use of high-strength concrete.

The Author has explained how, through improvements in the density of concrete brought about by mechanical means, its compressive strength may be made nearly to equal that of the solid stone from the fragments of which the aggregate has been formed.

Since in quarries it is easy to obtain aggregates derived from rocks having crushing strengths of the order of 1000—1500 kg per sq. cm (6.3—9.5 tons per sq. in.) or even much more, it results that present values for the ratio $\frac{\text{price per cubic yard}}{\text{crushing strength}}$ can be reduced in approximately the same proportion as can the ratio $\frac{\text{price per unit weight}}{\text{elastic limit of steel}}$. It may be remarked incidentally that in

[2] The Author would, however, recall the conclusion emerging from his work on strains in concrete to the effect that the use of hard steel for compression bars is very effective and is strongly to be recommended.

concrete of this kind the ratio $\frac{\text{elastic limit}}{\text{density}}$ is much higher than in ordinary steels and *approximates to that of the best aeronautical metals*, especially if in this comparison the disadvantages of erection are considered which are non-existent for concrete.

In the conventional mode of association between steel and concrete, however, these qualities of price and specific lightness are ill exploited. Increasing the density of concrete leads to an increase in compressive strength but the tensile strength is much less affected by this and remains much more subject to the conditions under which concrete is prepared; and further still, the various possibilities of deformation are greatly reduced. Hence in the first place the value of the ratio $m = E_s/E_c$ is reduced, which raises the neutral axis and so increases the compressive stress in a member subject to bending, thus taking away much of the advantage sought.

Secondly, it is the case that tensile strength is at least as important as compressive strength, for the performance of a structure in respect of shear effects depends entirely on the former, as do many other destructive agencies which may come outside the scope of calculation but of which account must be taken in practice — a fact which engineers express by saying that in practice certain minimum thicknesses must be provided.

Thirdly, every structure of whatever kind, suffers what Mr. *Caquot* has called permanent adaptative deformations, which result in the stresses becoming uniform and their maxima being diminished: if however the concrete has an insufficient capacity for plastic strain this adaptation is not well accomplished.

For all these reasons the advantages that really accrue, in ordinary forms of structure, from the introduction of highly compacted concrete are much less than might be expected on the basis of compressive strength alone.

Theoretical conditions for fully utilising the qualities of high-strength concretes and steels. — The difinition of pre-established stressing, or pre-straining.

It follows that good usage of high-strength materials is governed in the case of the steel by keeping the elongations of the concrete within their usual practical limits, and in that of the concrete by keeping the total tensile strain well below the tensile breaking stress therein.

Theoretically this double condition can be satisfied by making use of the steel, not to carry such tensions as will produce in it elongations which the concrete cannot follow, but to cause permanent strains in the concrete in directions opposite to those resulting from the loads — that is, to produce compression in the tension zones and tension in the compression zones.

This result can be attained by subjecting the steel to tension before the concrete is poured: for this purpose the reinforcing bars are gripped near their ends by two temporary attachments and are pulled upon by means of jacks which take purchase on abutment members so as to produce a known amount of stress in the bars; after the concrete has hardened sufficiently to afford anchorage to the ends of the bars the jacks are removed and the tendency of the bars to contract imposes in the concrete a compressive force equal to the tension in the former. By another method, tension is created in bars anchored in concrete which has already hardened.

Thus there is developed in the steel-concrete system a double system of permanent strains similar but opposite in direction to that which arises in ordinary reinforced members as the result of shrinkage, the harmful effects of which are already known. A first consequence of pre-straining, then, is the disappearance of undesirable effects due to shrinkage. With this final aim in mind researches have been made in many countries and for a long time, to find the proper practical means, but all these trials failed completely, and were abandoned except that in hoop reinforcement for pipes a certain mode of application was found.

Causes of checks encountered in the first attempts-absolute necessity, for obtaining permanent counter-strains, of using very high-elastic limit steels and very dense concrete.

The ill-success prior to the present Author's researches was neglect of the laws of stress and strain in concrete on the part of those concerned. It was assumed that tensions of the order of a few kg per sq. mm in the steel should suffice to compensate shrinkage, while on the other hand the concrete used — being of the only kind which it was understood practically how to make — had a high water-cement ratio and was therefore very sensitive to all sources of strain, contracting, as the combined result of initial tension and of continual changes in hygrometric conditions, to a total extent greatly in excess of the elongation imposed on the steel. Hence the conclusion put forward, notably by Koenen in Germany, that permanent pre-strains are impossible of attainment.

It is now known that the total strains in concrete though greater than was previously supposed are nevertheless limited. The upshot of all the experiments is that the laws of contraction under load are represented by curves terminating in asymptotes along the time axis, the ordinates of which are governed principally by the water-cement ratio in the concrete at the moment of initial set. Consequently, if the steel is given an elongation such that the maximum contraction of the concrete is only a moderate fraction thereof, the greater part of the pre-strains so obtained are permanent and absolute reliance may be placed upon them even after very long periods of time.

In ordinary concrete the contractions may amount to 3/1000 or even more, depending on the conditions of shrinkage and load; this would imply a relief of tension in the steel which may exceed 60 kg per sq. mm (38 tons per sq. in.) and there is, therefore, no reason for surprise that tensions of 10 or 12 kg per sq. mm (6 or $7^1/_2$ tons per sq. in.) have given negative results.

By the use of very dense concrete the deformations therein, and consequently the drop of tension determined thereby, can be considerably reduced. The matter is one to be decided for each case in accordance with the particular data of the problem, the load on the concrete, its instantaneous and long-term mechanical properties, and the average hygrometric conditions; generally speaking the figure in question will fall between 10 and 30 kg per sq. mm (6 and 19 tons per sq. in.)

this upper limit being reached only where compression is of the order of 200 to 300 hectopiezes.

The Author is accustomed to use initial tensions so calculated as to produce permanent tensions of between $^1/_2$ and $^2/_3$ of the elastic limit of the metal which, in the applications hitherto made, has been of the order of 80—90 kg per sq. mm (50 to 57 tons per sq. in.).

Study of the changes in mechanical condition resulting from pre-strains in members subject to bending in a uniform direction.

a) *Stabilisation of strains in steel and concrete under tension due to varying loads.*

In the case of moments in a constant direction, there arises the need to subject the concrete which is under tension from the loads to permanent pre-compression of the same order as this tension and generally a little in excess. The concrete will then remain under such compression after the loads are applied.

The deformations occurring under varying load are governed by the inertia of the whole section including steel; in reinforced concrete they are governed by the inertia of the compression zone alone combined with the steel. That zone being only a fraction of the whole section it results that a first effect attributable to the counter-strains is a reduction in the deformation of the tension zones in a proportion which frequently reaches 5 to 1 by comparison with ordinary reinforced concrete.

Not only is the concrete relieved of all risk of cracking, but the contraction stresses suffered by the steel, which are proportional to a deformation equal to that in the concrete, vary much less than in reinforced concrete.

b) *Reduction of compressive strains in concrete compared with ordinary reinforced concrete.*

In reinforced concrete members the raising of the neutral axis above the centre of gravity, which results from the elastic elongation of the steel being greater than the elastic contraction of the concrete, brings about a very notable increase in the maximum compressive stresses by comparison with the values they would have in a homogeneous member of the same dimensions; the denser the concrete and the greater the strain in the steel the more pronounced is this effect.

In pre-strained members, however, the neutral axis of the concrete drops below the centre of gravity of the section whatever the density of the concrete, and the strains are in consequence much reduced. Hence if the concrete in an ordinary reinforced member is stressed equally with that in a pre-strained member the latter will carry much heavier loads than the former.

The advantage is considerable, and to show its order of magnitude the example will be taken of a reinforced concrete beam of rectangular section stressed at 50 kg per sq. cm (711 lbs. per sq. in.) compression in the concrete and 15 kg per sq. mm (9,5 tons per sq. in.) in the steel. Assuming $m = 10$ the neutral axis will be at $^1/_4$ of the distance between the extreme compression fibre and the reinforcement. By the introduction of pre-strain the neutral axis can be lowered as much as desired and may be brought close to the reinforcement: the compression zone will then extend over the whole of the beam and will be four times as large as in the previous case, and while it is true that the lever arm will thereby be reduced from $^{11}/_{12}$ to $^{2}/_{3}$ of the distance between the reinforcement and the extreme compression fibre yet the load carried with the same maximum stress of 50 kg per sq. cm will be increased in the proportion —

$$4 \times \frac{\frac{2}{3}}{\frac{11}{12}} = \frac{96}{33}$$

or nearly 3 times.

As a set-off against the improvement in the employment of the concrete, the force imposed on the reinforcement will be multiplied in the ratio $\frac{33}{24}$, but there can be little objection to this as the actual weight of the steel will still only be 33/84 of what it would be in an ordinary beam.

The effect of this reduction in stress will, of course, be all the greater if the logical step is taken of combining the application of pre-straining with that of high-density concrete. On these lines one may imagine slabs of a given thickness covering three times the usual spans, without, as here explained, the strains exceeding an acceptable magnitude. The practical importance of this conclusion will at once be appreciated as regards, for instance, the limiting spans of full-webbed plain beams or of mushroom slab floors.

c) *Shear.*

Pre-compression gives advantages at least equally great from the point of view of shear as from that of bending which has just been discussed.

To show these it is only necessary to plot Mohr's diagrams relating to simple shear and to shear accompanied by one or two tensile forces or one or two compressions. Such diagrams disclose how the stresses that accompany shear are exaggerated by the effect of shrinkage; how greatly on the contrary, the maximum tensions may be diminished by introducing a compressive force in one direction; and how the introduction of two strains at right angles can be made to bring about their total disappearance[3]. The most favourable system is that which contains two compressions equal to the amount of shear and in such a case the most dangerous strain is that corresponding to a compression equal in intensity to twice the shears stress. The limiting shear stress for use in design may then be equated to one half of the limiting compressive stress in the concrete, an assumption which will ensure excellent use being made of high-strength concrete and an enormous saving by comparison with the usual dimensions.

d) *Resistance to repeated loading.*

Ordinary reinforced concrete structures, like those in riveted steelwork, do not stand up well against alternating loads. Experience has shown that pre-strained members do so incomparably better.

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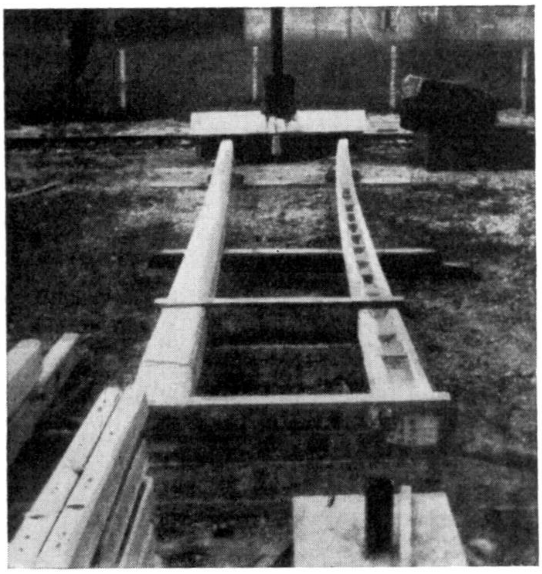
[3] For the experimental confirmations of this fact see "Science et Industrie", January 1933.



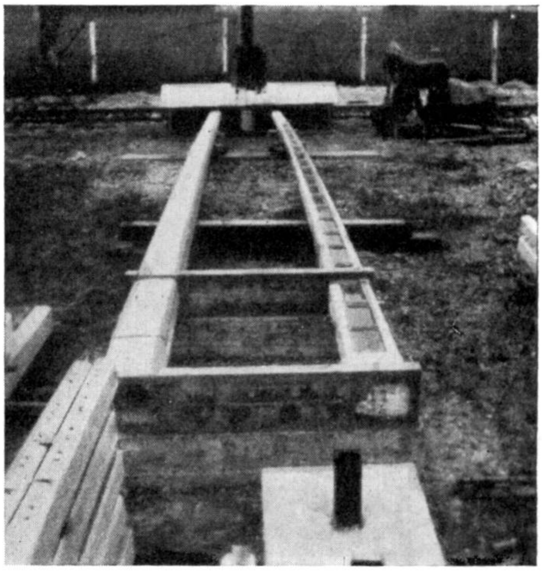


Fig. 1 and 2.

The posts A (left) an B (right) are subjected to forces which pulling them together an thrusting them apart.

Such alternating loads were applied to a pre-strained column A and an ordinary column B each 12 m (39 ft. $4^1/_2$ in.) high and embedded up to 2 m (6 ft. 6 in.) from their bases. (Fig. 1, 2, 3, 4.) Column A was 5 months old; it contained 50 kg (110 lbs.) of steel and weighed 750 kg (1654 lbs.). Column B was 18 months old; it contained 130 kg (287 lbs.) of steel and weighed 980 kg (2160 lbs.). The breaking load as measured on columns identical with these was about 900 kg (1984 lbs.) in each case, and the load actually applied to

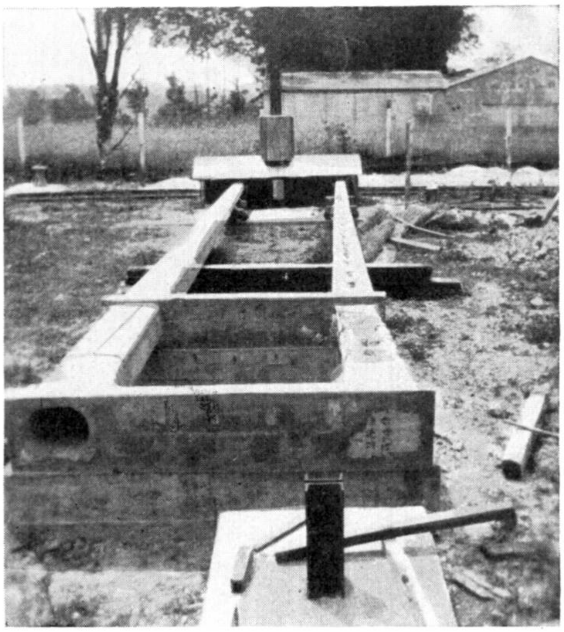


Fig. 3.

The posts A and B at the conclusion of tests (Posts B completely fractured).

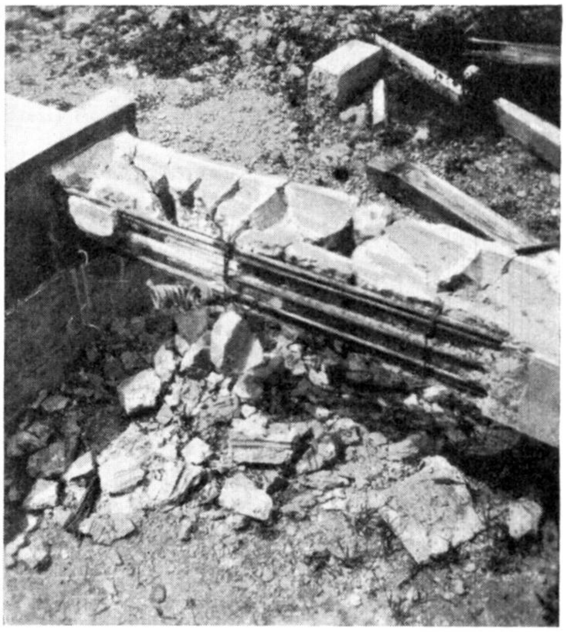


Fig. 4.

Close-up of post B after testing.

their ends was varied between — 450 and + 450 kgs (± 992 lbs.) about 8 times a minute.

After a few hundred alternations Column B was heavily cracked and after a few thousands it was completely broken. Column A, on the other hand, resisted 500 000 alternations without measurable damage.

General conditions for the practical use of pre-straining: — The necessity for applying the stresses at very low cost.

It has been shown theoretically possible to subject reinforced concrete members from the time of their construction to such mechanical conditions as will allow of fully realising the qualities possessed by high-strength steel and concrete. It has further been explained that in this way various advantages may be gained such as great reductions of the maximum compressions in members subject to bending and of the maximum tensions in members subject to shear; also a greatly improved resistance to repeated loading.

To convert these possibilities to actualities two problems must be solved: firstly that of stressing the steel, secondly the practical manufacture of high-strength concrete at a cost low enough to maintain as large as possible a share of the savings in materials.

The cost of ordinary steel reinforcement having an elastic limit of 24 kg per sq. mm (15 tons per sq. in.) may be estimated at 1 franc per kg including preparation. Reinforcement weighing 3,5 kg per metre (2,35 lbs. per ft.) will, therefore, cost 3,50 francs per metre, and it can be replaced with the same factor of safety by reinforcement of steel having an elastic limit of 84 kg per sq. mm (53,2 tons per sq. in.), weighing only 1 kg per metre (0,67 lbs. per ft.) and costing 0,90 franc as supplied; this, however, must be tensioned up to about 8000 kg (7,9 tons). The saving, therefore, is 2,60 francs per metre less the cost of the following operations:

1) Cutting of bars and preparation of their permanent anchorages in the concrete.

2) Arrangement of temporary anchorages at two points within the forms near the ends of the bars to withstand a pull of 8 tons.

3) Production of this pull of 8 tons between the anchoring points, and maintenance of it while the concrete is being poured and is hardening.

4) Dismantling of temporary anchorages buried in the concrete within the forms and transfer of the tension carried by them to the permanent anchorages against the concrete; making good the holes left in the concrete after dismantling.

In order to result in a saving the cost of these various operations must be less than 2,60 francs multiplied by the length of the bar in metres, and it is further to be borne in mind that the removal of shuttering will nearly always have to be delayed until after the concrete has been placed in compression, which implies and advanced stage of hardening; the costs attributable to an increased period of immobilisation of the forms must, therefore, also be taken into account.

Except where the reinforcing bars are very long the margin calculated on these lines is very small, and the whole practical problem of using high-strength steels may be said, therefore, to hinge upon a reduction in the cost of the means of anchorage and of tensioning the bars.

As a rule the cost of tensioning increases less rapidly than the amount of tension produced; it is scarcely at all affected by the length of the bars; on the contrary the margin for economy rises in proportion to the cube of the linear dimensions. It follows that, contrary to what one might expect at first sight, the greater the absolute dimensions of the members and the heavier the forces to be developed the easier to solve are the practical problems involved in tensioning the steel bars. As regards small members wherein the forces are

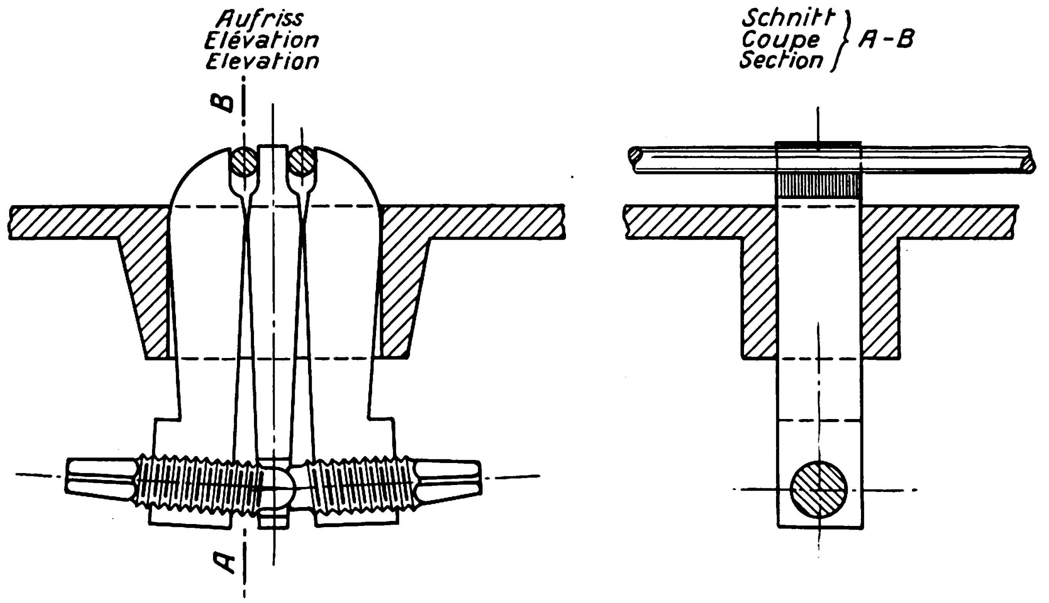


Fig. 5,

Jaws for clamping bars.

small there is no satisfactory solution except in the case of repetition work on very long series.

As the anchorages must offer the same resistance as the bars themselves so as not to form a link weaker than the latter, most of the usual types of anchorage are ruled out including those which depend on a screw and nut. The Authors has, however, successfully made use of fixtures in which the steel bars are wedged between jaws or corners or are secured by loops formed by electric flash welding (Fig. 5).

Frequently there is a lack of space between the reinforcing bars, so that the size of the anchoring arrangements has to be reduced to a minimum: this implies the use of metals of the highest possible quality so treated as to produce the maximum improvement in their tensile strength and resistance to wear. Difficulties are avoided by enclosing the bars in pre-cast concrete pieces held in place against the shuttering either by simple adhesion or by means of suitably arranged grooves, or by other methods depending on the special conditions of each case.

Relationship between the problems of tensioning the steel bars and the rapid hardening of the concrete.

The necessity for very low costs in tensioning the bars has led to a search for improved gear minimising the labour involved. But such gear has to withstand very large forces; this makes it expensive and it is immobilised throughout the period of hardening of the concrete. Hence the great importance of shortening this period; it may be said, indeed, that the possibility of practical application for pre-straining is linked with the development of processes to secure rapid hardening of the concrete.

The Author has already described the means whereby he has been able to combine very intense hardening with great speed. These means consist of treating the concrete by vibration and compression, and in the case of Portland and slag cements by heating to about 100^0 C (see below). With good Portland cements the time required to obtain sufficient strength to withstand pre-straining is about $1^1/_2$ hours from the filling of the forms. In the case of slag cements very good hardening is obtained in 2 to 5 hours according to the cement and the heating conditions.

The heating is accomplished very easily by means of steam, suitable arrangements for the purpose being made in the forms. The temperature of the concrete is sometimes considerably higher that that of the steam in consequence of the heat of reaction, and for the same reason the steam consumption is low, only some 10.000—20.000 calories having to be added to raise a cubic metre from 10^0 to 100^0 C; in practice the cost of heating the concrete is no more than a few francs per cubic metre.

One result of instantaneous hardening of the concrete is that members can be built up from elements successively deposited along continuous reinforcements which are tensioned after the pouring and hardening of certain parts only of the members, thus requiring only a limited amount of gear for the purpose which is easily managed and not expensive. It will be shown that this procedure is capable of very wide application.

Supply of high-elastic limit steel.

Each application must be preceded by arrangements for the supply of steel bars of suitable quality at a price and in a form which will make their use feasible in practice. Such steel bars must have a high and uniform limit of elasticity, must not be brittle and must be perfectly straight. This last condition is very important because the straightening process usually applied on the job ist impossible in the case of high-elastic limit reinforcements which act like springs.

In France, high-elastic limit steel bars are not commercially available at a price of the same order as ordinary concrete reinforcing bars. Drawn rods are too expensive and do not give good adhesion to concrete. The commercial metals that have properties closest to those required in the applications here contemplated are machine-made rods giving a breaking stress, in their condition as supplied, of some 100 kg per sq. mm (63 tons per sq. in.) but an elastic limit, in that condition, very variable and sometimes scarcely higher than that of mild steel. These are supplied in coils often of irregular shape and weighing 50—150 kg (110—330 lbs.), in diameters up to 16 mm ($^5/_8$ in.), at a price which, mainly because of the limited demand for metal of this kind, is at present slightly higher than that of ordinary round reinforcing bars.

These coils require, then, to be converted into straight wires of high elastic limit without appreciably adding to their cost. The Author has produced machines capable of effecting this conversion at a cost of some centimes per kilogramme (Fig. 6). To avoid any loss through short lengths the end of each coil is flash-welded to the beginning of the next, the weld being subsequently annealed

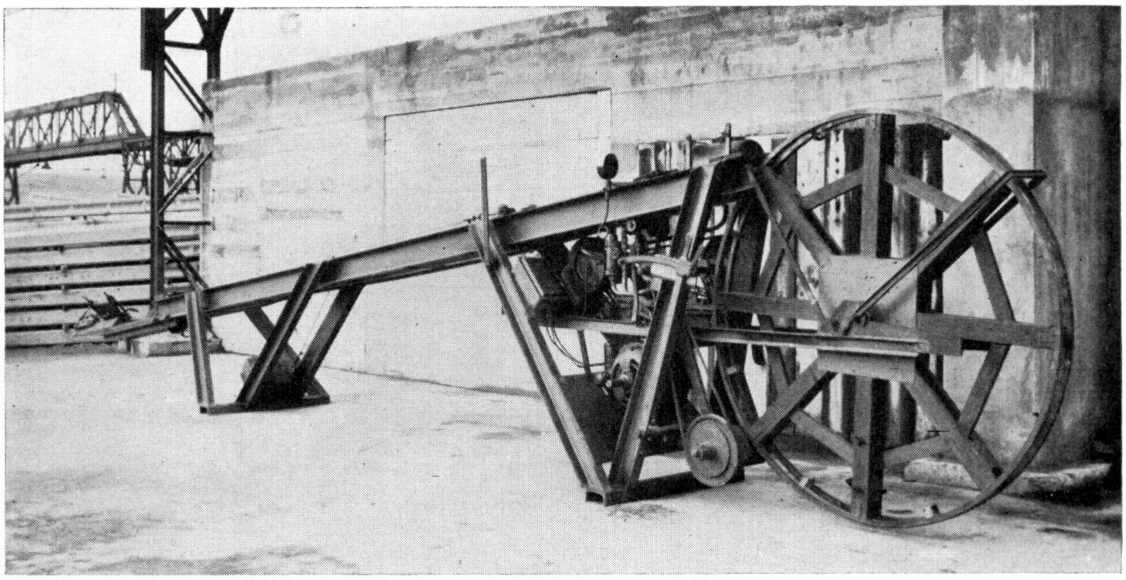


Fig. 6.

Device for increasing the yield point of steels.

by the welding machine itself — operations which take up only a few seconds and which produce a weld having exactly the same strength as the wire. The wire is next drawn into the machine where it is first roughly straightened between rollers in two planes at right angles and is then stretched between pincers closed by hydraulic jacks, n metres apart: one of these pincers is fixed and the other mounted on a trolley moved by a screw so as to pull on the wire; immediately the n metres of wire have been tensioned to the desired amount a frictionless valve operates to release the engagement with the screw and return the trolley to its original position at a speed determined by an adjustable hydraulic brake. The accuracy obtained in tensile stressing by this means is of the order of 1 %.

A fraction $\frac{n}{p}$ of the wire is then drawn out beyond the machine, where it can either be kept straight or be coiled to a radius such that only an elastic strain is set up. The operation then automatically begins over again. The welds, too, pass through the machine and undergo the same stretching treatment. A wire of unlimited length is thus obtained which has an elastic limit approximately equal to the tensile stress exerted and in which every point, including the welds, has been testet to this intensity of stress P times over.

Elastic limits of between 80 and 90 kg per sq. mm (50 and 57 tons per sq. in) are easily obtained, which is $3^1/_2$ times as high as in ordinary steel bars. In the course of the operation the wire is lengthened by about 5 %.

Given a sufficient demand for hard wire the mills would no doubt be able to make direct deliveries of metals with chemical compositions specially designed to favour very high strengths, ready stretched, tempered, annealed and stretched over again, for which the ratio $\frac{\text{price}}{\text{elastic limit}}$ would be very notably less than can be obtained at present; such wires with a diameter of the order of 16 mm ($^5/_8$ in.) would be equivalent in strength to ordinary steel bars of about 35 mm ($1^3/_8$ in.); they could be easily transported in coils of large diameter wound in such a way as to produce in them only elastic strain so that when unrolled they would be practically straight.

The use of metals of this kind involves special problems of detail — since cutting, the formation of hooks, etc. cannot be done in the same way as on ordinary bars — but none of these problems involves any real difficulty such as might increase the cost.

Applications.

The applications achieved by the Author fall under two distinct heads:

1) pieces or structures moulded all at once, such as electric transmission line poles, sleepers, beams of limited dimensions, pipes formed in the factory in separate lengths;

2) the much more important case of cylindrical or quasicylindrical constructions (using this term in the most general sense) carried out in successive lengths by means of a mould which travels continuously along the work in hand.

The Author has given a summary account of the manufacture of electric poles by his methods in Science et Industrie for January 1933, which he will not repeat here. Today the development of nearly automatic plant for such work has attained almost absolute perfection, and the Author has been able to manufacture railway sleepers in a similar way. These machines turn out concrete pieces with strengths exceeding 1000 kg per sq. cm (14,220 lbs per sq. in.) after being subjected to an initial compression of 100—300 kg per sq. cm (1422—4267 lbs per sq. in.) according to circumstances, and the surface is made perfectly smooth and compact.

An application falling under the second of the above headings will now be described in some detail. This was carried out in the course of the renewals to the sub-structure of the Transatlantic Station at Havre, where it derives importance equally from the technical difficulties encountered and overcome and from the great value of the work it was possible to protect by these means. The station in question is about 600 m (1968 ft.) long by about 55 m (180 ft.) wide, and over the greater part of its area it includes two floors each loaded to 2500 kg per sq. m (512 lbs per sq. ft.) in addition to a terrace. It has been founded on piles cast *in situ* reaching down to level 0.00, the level of the quays being + 9,50 m (+ 31.17 ft.); these piles pass through a recent filling of dredged material overlaying a shingle beach of no great thickness which in turn rests upon mud down to level — 20 m (— 66 ft.) where a very firm bed of gravel exists (Fig. 7). One of the long faces of the building is solid with a quay founded on the gravel, and in front of this the mud has been dredged down to level — 12 m (— 39 ft.) — that is, 22 m (72 ft.) below the edge of the quay — in order to form a tidal basin. A loading of 6000 kg per sq. m (12,289 lbs. per sq. ft.) is specified over the ground floor.

After the main part of the work had been completed it was found that the ground into which the foundation piles had been driven was sinking together

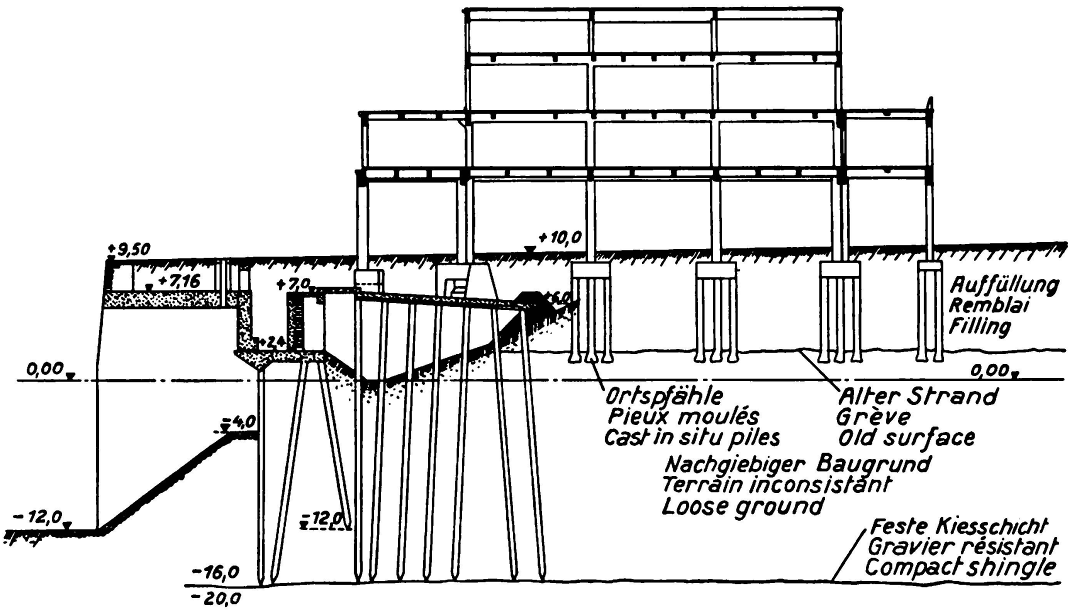


Fig. 7.

Cross section through Dock yard Station in Le Hâvre.

with the building in a single mass, its time law being nearly linear and the rate being of the order of one centimetre per month. It was essential that these movements should be arrested within a very short time. Only one method of doing so could be contemplated: the weight of the building, that of its old foundations and that corresponding to possible live loads together with a proportion of the weight of the filling sufficient to restore equilibrium in the mud where this had been disturbed by constructing the quay, by filling and dreadging, and by imposing the weight of the building must all be picked up and transferred unto the solid beds encountered at about — 20 m (— 66 ft.). This implied the placing of piles 30 m (98 ft.) long.

The underside of the ground floor, however, is about 5 m (16 ft.) above the ground, and water is met at a small depth; pile driving would not be possible as this would allow the mud to flow, thereby impairing the stability of the building and perhaps of the quay: hence the only admissible procedure was pressure piling by means of jacks.

Other possible dangers lay in so affecting the equilibrium of the subsoil as to prejudice the system as a whole: the mud might become liquid as the result of its repeated handling, and pressures might develop owing to the reduction in volume caused by placing the piles.

It was necessary, therefore, to have some means of controlling the pressures due to the placing of the piles. Further it was known that obstacles would be encountered which would have to be broken up, and beds of gravel which would have to be dredged. The heavy loading and the space occupied by the old foundations were such that most of the new piles must unavoidably receive loads of the order of 200 tonnes each or often more. The aggregate of the forces to be picked up at level — 20 m (— 66 ft.) under these conditions was in excess of 150,000 tonnes, equivalent to the driving of no less than 60 km (37 miles) length of large ordinary reinforced concrete piles carrying 75 tonnes each. Very powerful weapons of attack were, therefore, demanded.

Principle of the solution now in hand.

Trough the combined application of the pre-straining method and of rapid hardening of concrete the Author was able to improvise a solution to this problem, which, within about eight months of the decision to undertake the

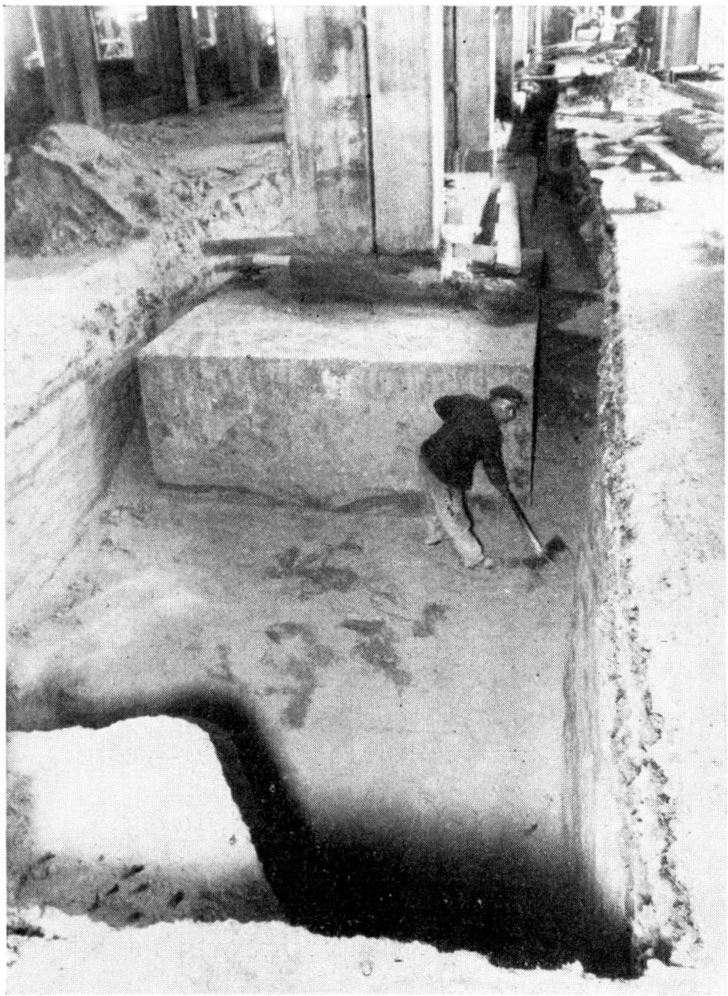


Fig. 8.
Present state of foundation slabs.

work and four months of its effective beginning, has stopped the settlement of those parts of the structure which were sinking at the most rapid rate — an effect which if continued must soon have exposed the building to a danger which has now been entirely removed.

a) *Connecting beams between existing-foundations.*

The columns of the building were originally carried on reinforced concrete footings up to 4.40 × 3.40 × 1.40 m (14.4 × 11.2 × 4.6 ft.) in size (Fig. 8 and 9). A beginning was made by forming these footings into large continuous

Fig. 9.

Ties between foundation during concreting Foreground showing form work lining pits for piling and for fixing ties.

girders to carry the foundation loads unto the new piles and furnish supports against which to jack down the pressure piles. This was accomplished by the following means. Masses of concrete, reinforced only against secondary stresses, were formed between the footings. The systems so constituted were placed in a general state of compression by means of steel tie bars wherein the elastic limit had previously been brought up to 80 kg per sq. mm (50.6 tons per sq. in.) and which were now tensioned to 50—60 kg per sq. mm (31—38 tons per sq. in.) between anchorages set in concrete headblocks at each end, one such anchorage fixed and the other actuated by jacks. Then, after packing tight so as to render the stress permanent, the jacks were removed (Fig. 10 and 11).

By these means a construction is produced which will resist considerable bending moments, shears and torsions, and this is done without either disturbing the sub-structure or making any important alterations to the existing footings, the concrete and reinforcement of these being turned to account.

Cylindrical cavities are formed running horizontally through the concrete cast in this way (Fig. 12); across each of these a pile is continuously manu-

Fig. 10.
Reinforcement for ties,

factured and is pressed into the ground at the same rate as it is made, this being accomplished by the operation of jacks which are bolted to the beams and which act upon collars capable of being rigidly attached to the piles as required.

b) *Description of the piles.*

The piles in question are hollow cylinders of 0.60 m (1 ft. $11^5/_8$ in.) external and 0.37 m (1 ft. $2^1/_2$ in.) internal diameter, the effective section being 1750 sq. cm (271 sq. in.). They are reinforced longitudinally by eight hard steel wires of 8 mm ($^5/_{16}$ in.) diameter and transversely by hooping of similar wire 6 mm ($^{15}/_{64}$ in.) in diameter. The total weight of reinforcement is 10 kg per metre run (6.7 lbs. per ft.) of the pile. Despite this low weight of steel the piles withstand a pressure of over 300 tonnes combined with a bending moment of 50 tonne-metres (161 ft.-tons), which constitutes a record.

c) *Method of forming the piles.*

Suppose a pile to be completed as far as the element N. The longitudinal reinforcements are delivered in unlimited lengths wound in coils to a diameter so large as to cause only elastic deformations, and normally they are continuous throughout the length of a pile (Fig. 13). The external mould consists of

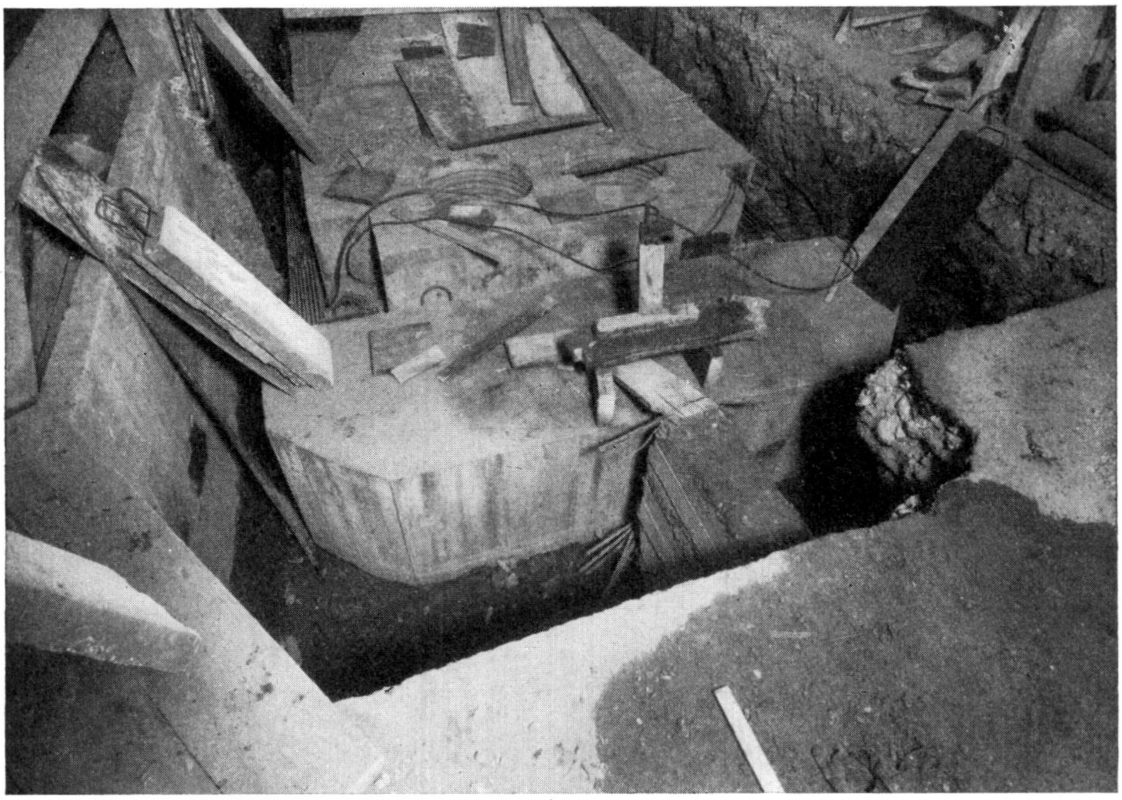


Fig. 11.

Movable head of tie during prestressing and wedging.

a set of 5 to 8 cylindrical sleeves each 0.40 m (1 ft. $3^3/_4$ in.) high and each split into two semi-circles with machined ends which can be pressed together by means of screws. (For the upper portion of the pile the sleeves have horizontal grooves inside them so as to produce horizontal ridges on the pile.) The internal mould consists of a steel tube covered by an envelope of rubber reinforced with cotton, and the bottom end of this tube is extended in a smaller diameter, also covered by a rubber pocket, so as to form a watertight cylinder (or obturator) normally of the same diameter as the steel tube but arranged to swell under hydraulic pressure. The space between the inner and outer moulds is closed at the top by an annular plate, through which are drilled 8 holes to pass the longitudinal reinforcements and 4 passages for filling.

When the lift N has been completed the sleeve-connecting presses are released in turn as the pile sinks, with the exception of the uppermost set. The mandril is raised through the height of one lift and the longitudinal reinforcements are bound to the spiral of the transverse reinforcement; then the sleeves forming the external mould are placed in their new positions; the longitudinal reinforcements above where they pass through the closing ring are seized between pairs of jaws mounted on supports which can be lifted by screws so as temporarily to stretch the reinforcements on which the rigidity of the pile depends; then the pocket on the internal mandril is filled under pressure so as to prevent any leakage of concrete taking place between the sleeve of the mandril

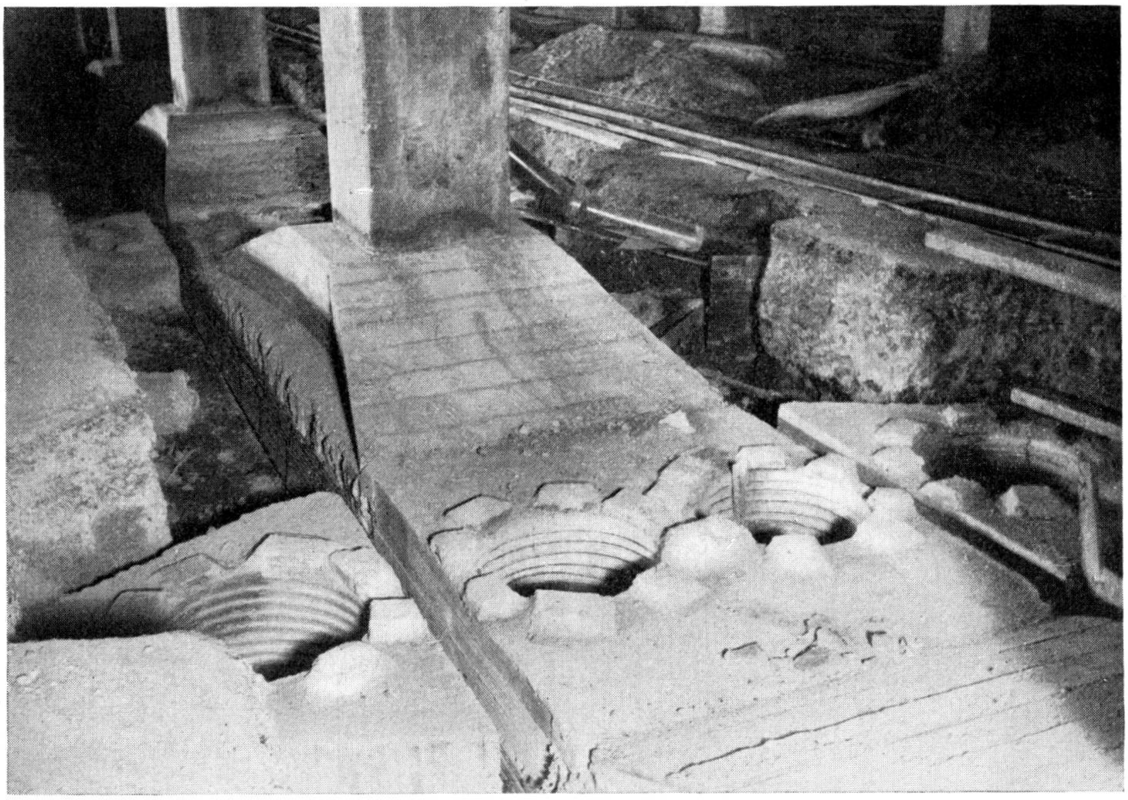


Fig. 12.

Group of 4 pile holes. The base for compressing the foundation will be placed in the slots seen left and right of the concrete foundation.

and the inner surface of lift N and so as to make good the joint between the steel tube and the sleeve.

These preparations being completed the mould is filled with concrete containing 450 kg of marine Portland cement per cu. m (28 lbs. per cu. ft.). The concrete is strongly vibrated by means of eccentric-mass electrical vibrators attached to the outer shell. Part of the excess water escapes through the joints between the sleeves and part rises to the upper surface which thereby tends to become softened, but the concrete is rendered homogeneous by strong pressure applied by screw plungers in tubes passing through the filling holes, vibration being maintained meanwhile. In this way excess water is expelled from the top portion of the pile. When this has been accomplished the filling holes are closed, vibration is discontinued, and water under a pressure of 20 kg per sq. cm (285 lbs. per sq. in.) is admitted between the mandril and its sleeve; immediately after the vibration the concrete acts as a fluid it transmits this pressure hydraulically to the plate at the top, lifting the latter and so stretching the steel bars to an extent approaching their elastic limit. This pressure is maintained for 20 minutes.

All the joints between the rings open and leak freely, and the concrete becomes very dry. The mould is surrounded by a heat retaining envelope into which steam at atmospheric pressure is admitted; in this way the temperature of the concrete is rapidly raised to over 100° C and a degree of hardness comparable to that of very good ordinary concrete after several months is reached at the end of a few hours even though the special cement for setting under sea water here used is very slow and normally gives rather poor final strengths (Fig. 14, 15, 16).

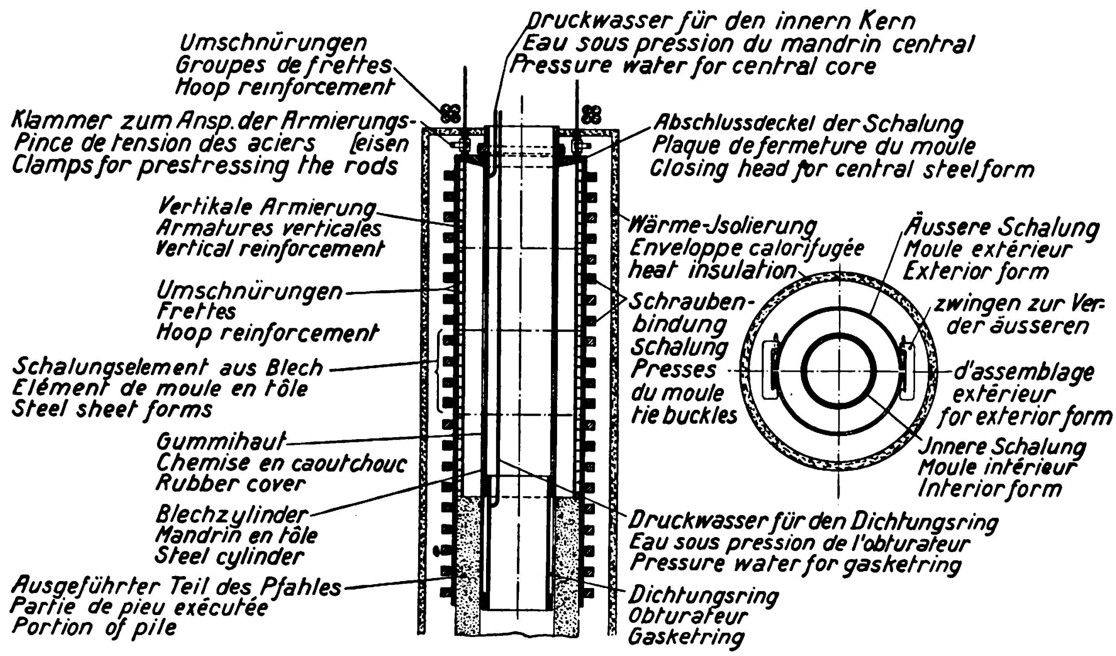


Fig. 13.

Formwork design for piles.

d) *Sinking the piles.*

Sinking follows immediately. Theoretically this calls for compressive forces up to 320 tonnes, to which must be added 20 kg per sq. cm (285 lbs. per sq. in.) of pre-strain, making a total of some 200 kg per sq. cm (2850 lbs. per sq. in.). It is shown by laboratory tests that strengths of the order of 300 kg per sq. cm (4267 lbs. per sq. in.) are reached after three hours heating in steam at 100° C; provision must be made, however, for bending moments — the existence of which is confirmed by experience — and these may reach a considerable magnitude, especially in the most recently executed zones. Now a moment of 50 tonne-metres (361 650 ft.-lbs.) will increase the stress to 500 kg per sq. cm (7112 lbs. per sq. in.), and the breakage of a pile in the ground would amount to a serious accident: the sinking is so conducted, therefore, as not to impose very heavy stresses on concrete less than about eight hours old. Practically no breakages of the piles have in fact occured except for a small number of mishaps which took place mainly during the period of initiation of the men concerned.

The equipment used for sinking consists of a collar formed of a water-tight tube concentric with the pile, inside which is arranged a rubber shield reinforced with cotton so as to give great strength and form a water-tight annular space between it and the tube. Between the rubber and the pile are placed staves

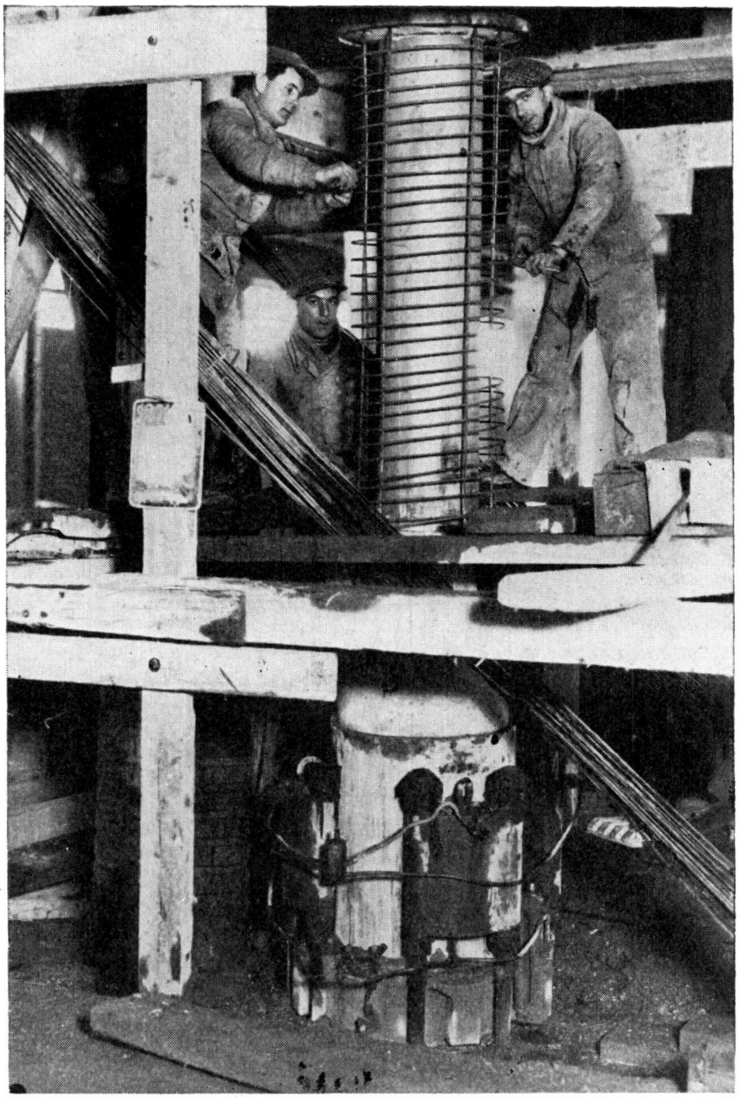


Fig. 14.
Reinforcement of piles (the lower position shows the screw winches).

parallel to the pile and almost touching one another, the parts of the staves in contact with the pile being of steel. When water under a pressure of 30 kg per sq. cm (427 lbs. per sq. in.) is admitted into the closed space the staves are pressed against the pile with a total force of 100 tonnes, and since the coefficient of friction between concrete and steel is over 0,40 a longitudinal adhesion sufficient to transmit at least 400 tonnes is produced between the staves and the pile. On removing the pressure all connection between the pile and the staves is destroyed (Fig. 17).

The staves are in contact with steel collars of which the upper one is very strong and serves to transmit the sinking pressure while the lower one serves for removing the staves and, if need be, for withdrawing the pile. These collars are welded to the tube and act in one piece with it. The upper collar has four welded lugs which receive the thrust of a corresponding number of pistons actuated by hydraulic jacks (Fig. 18), attached to the beam through which the pile is being sunk by means of eight hard steel bolts screwed into concrete, the

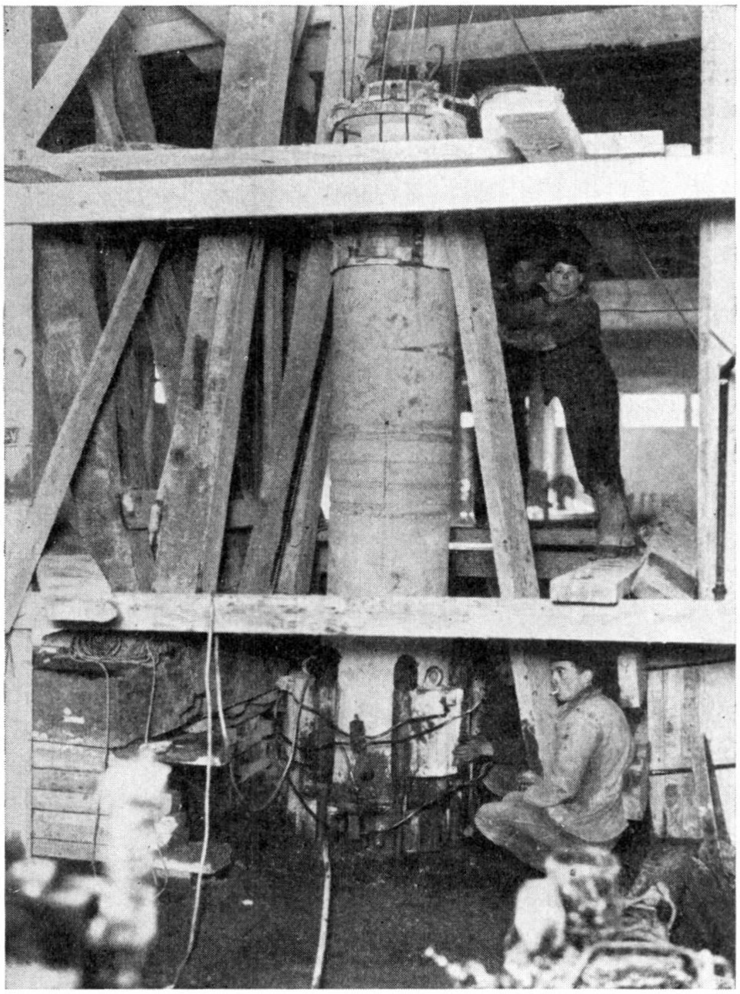


Fig. 15.
Piles after removing of formwork (lower position showing screw winches).

threads for this purpose being moulded in the actual concrete of the beam. Each of these bolts carries a load of 40 000 kg, but it has been confirmed by experiment that twice this amount could be withstood without giving rise to any trouble in the concrete which acts as a hold-fast.

The sinking operation is as follows:

1) The staves are pressed against the pile by admitting water at 30 kg per sq. cm (427 lbs. per sq. in.) into the sinking collar.

2) The pile is loaded by the simultaneous action of the four sinking jacks. Under a load which may reach a maximum of 320 tonnes no difficulty arises

in sinking the pile unless some obstacle is encountered, in which case this can be broken up or dredged out through the central cavity.

3) When the jacks have reached the limit of their travel the pressure in the sinking collar is released and the latter is raised by means of two special small jacks.

The cycle is then repeated.

When sinking is completed the pile is subjected to numerous alternations of 300 tonnes load on and off, and a check is then made as to whether any

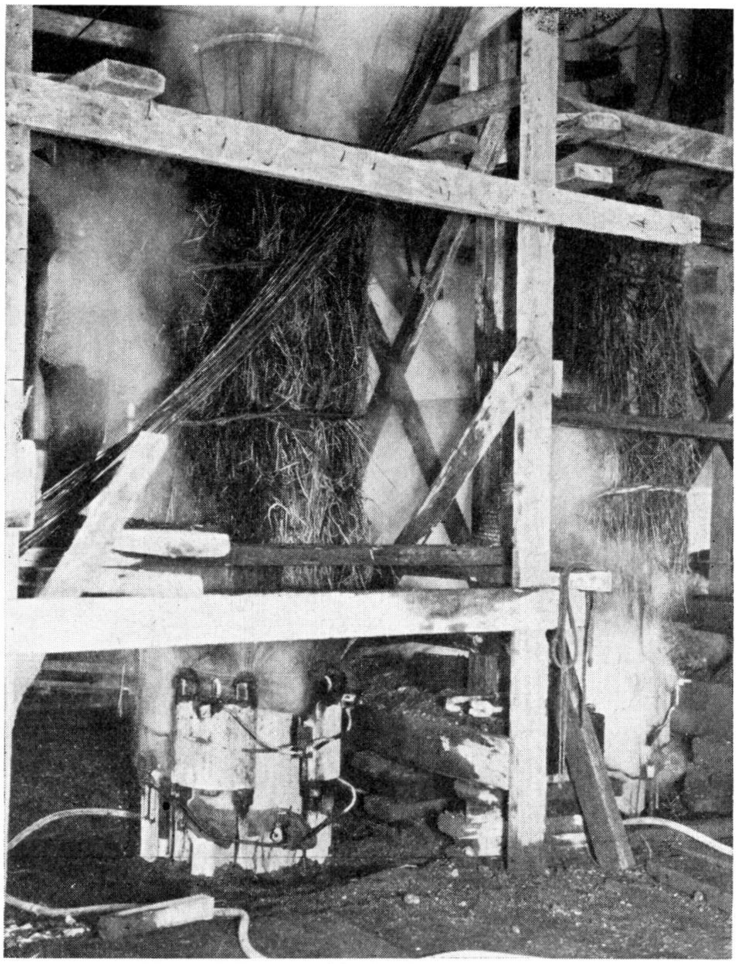


Fig. 16.
Two piles during heating.

appreciable sinkage occurs when the load of 300 tonnes is maintained for several hours on end. Generally speaking a definite refusal is soon obtained but in the case of certain of the piles these settling-down operations may take up a considerable time, perhaps several days, the pile continuing noticeably to go down little by little and its diameter changing under the effect of the alternating loads. Once the pile has settled down, concrete is poured into the annular space between the grooved pile and the grooved wall of the sinking space, and this concrete is allowed to harden while the pile remains under load. For the purpose of this last operation the sinking collar is replaced by an end plate.

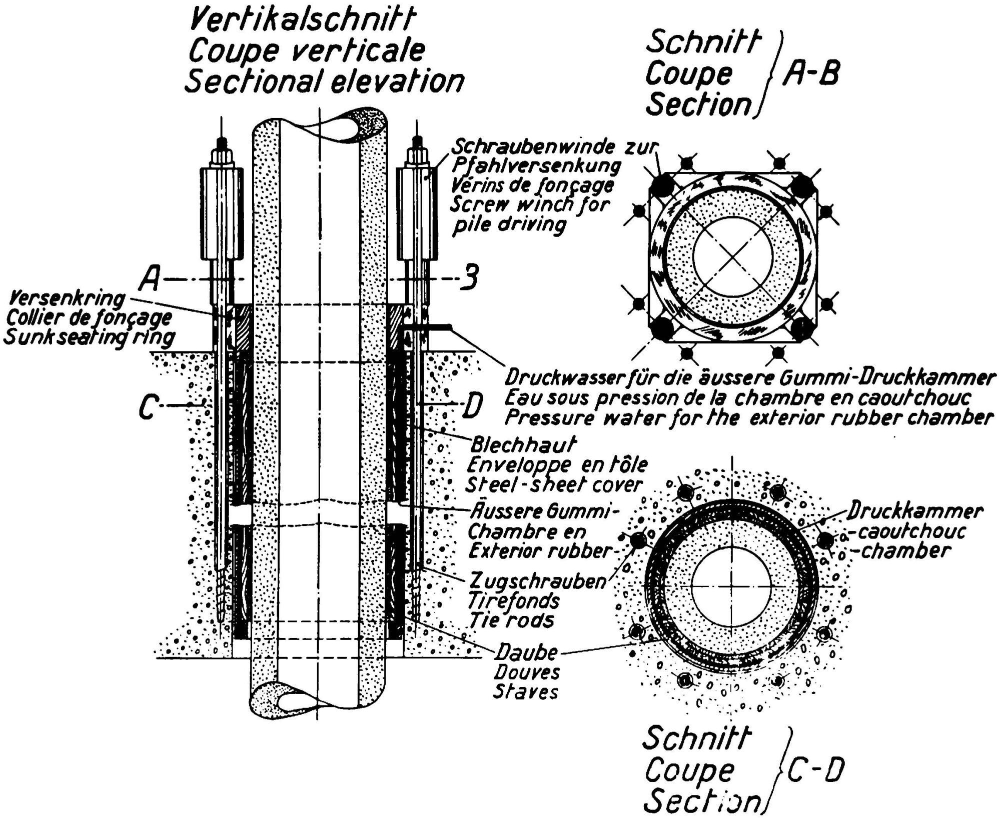


Fig. 17.

Sinking device for piles.

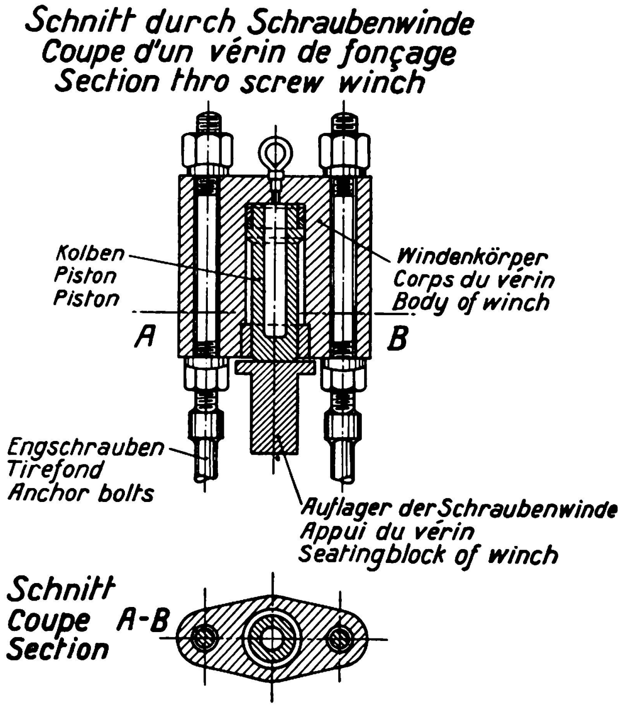


Fig. 18.

Detail of screw winch.

The piles formed in this way are perfectly true to dimension within and without, and generally they keep very straight. Sometimes, however, they are deflected by obstacles which bend them elastically and imply considerable bending stresses. As a rule these bends disappear if the pile is left alone, owing to the slow deformation of the ground actuated by the elastic forces.

Unless special obstacles are encountered a pile 30 m ($98^1/_2$ ft.) long may require about four days for its manufacture and sinkage. The work as a whole is proceeding under satisfactory conditions as to speed and cost.

Various applications of the Havre system of piling.

The methods described above are obviously capable of variations which would allow them to be applied to the making of any kind of pieces of practically cylindrical or prismatic shape, such as piles or any other members intended to be driven, screwed or forced in any possible way; columns or posts above ground; tunnel linings, inverts, walls, sheathings, floors, beams, arches, pipes, reinforced concrete roads, etc.

In almost every case some handy form of equipment can be designed which will be semi-automatic in its operation and will entail only a very limited expenditure on labour and on depreciation of moulds. Generally speaking the period of re-use of such equipment can be reduced to a few hours, or sometimes even to a few tens of minutes, allowing very high speeds of working with relatively simple plant. The economic advantages obtainable in these various applications can readily be inferred from what is said above.

One case of special interest is that of the pipe. The author has set up plant whereby pipes may be made automatically either in the factory or on the site, in a trench or underground, without joints, to any desired diameter, with both the transverse and the longitudinal steel bars all tensioned to their limit of elasticity. In this way a high degree of imperviousness is obtained under pressures which are limited only by stresses in the reinforcement of the order of 80 kg per sq. mm (50 tons per sq. in.). In the laboratory, staunch pipes have been obtained under pressures of 250 kg per sq. cm (3556 lbs. per sq. in.).

The resistance to bending and to possible shear is ten times greater than in the best made ordinary pipes of the same thickness. On account of the extreme degree of compactness the chemical resistance is remarkable, and the rigorous smoothness of the internal surface ensures a maximum discharge.

Another application which offers considerable scope for development is that of the mushroom-type floor. Under present conditions the span of such floors scarcely exceeds 30 to 40 times their thickness, whereas by the Author's methods this ratio can easily be doubled without adding either to the cost per unit of area or to the magnitude of the deflections. Mushroom floors are still looked upon as somewhat exceptional but by these means their use may become almost universal, especially in dwelling houses where it would considerably simplify the construction.

Long span girders in reinforced concrete.

In a number of earlier publications the author has indicated how reinforced concrete applied in the form of arches will allow the attainment of great spans such as can be exceeded only by suspension bridges. The methods that have just been described clearly enable the theoretical limits of span for such arches to be increased still further, while moreover the possibility of almost instantaneous hardening means that entirely new methods of construction are made available so as to extend the field of use for concrete into regions previously regarded as the preserve of steelwork alone. This subject, however, is so wide that its treatment must be relegated to a separate work.

The Author will confine himself here to the matter of straight girders. Until now it has not been possible to contemplate the economical use of reinforced concrete in the form of straight girders of large span, particularly in the case of relatively shallow solid-webbed girders. There are three reasons for this: the unsatisfactory use made of the concrete under compression; the impossibility of utilising any high degree of strain in the steel and the consequent necessity for a large amount of steel surrounded by a heavy concrete casing; and above all the very poor use that could be made of concrete in the members transmitting shear forces.

At all three of these points the Author's methods are capable of supplying a considerable improvement. He has found from the study of particular cases that by making use of these new forms of technique the limiting spans that can economically be obtained with reinforced concrete girders may be multiplied by a coefficient of the order of five to ten. Solid webbed girders of 100 m (328 ft.) span become feasible at low cost and without difficulty; they are appreciably lighter and beyond comparison cheaper than framed steel girders of the same loading and span, especially in the case of several similar girders.

The Author has prepared a scheme, complete to the smallest detail of the constructional equipment involved, for girders of 100 m (328 ft.) span carrying a double roof (a saw-tooth roof over a transparent floor), the general lines of the idea being similar to those followed at Havre. The following results have emerged from this design:

The weight of the girder is 3200 kg per m run (2151 lbs. per ft. run). It supports its own weight, and an imposed load equal to its weight, by means of reinforcement weighing about 350 kg per m (235 lbs. per ft.) formed of 180 bars of 16 mm ($^5/_8$ in.) stretched to 84 kg per sq. mm (53 tons per sq. in.) and permanently tensioned to 50 kg per sq. mm (317 tons per sq. in.); the stress in the concrete is 180 kg per sq. cm (2560 lbs. per sq. in.) — which figure is admissible in view of the fact that the strength of the concrete is no less than 800 kg per sq. cm (11 380 lbs. per sq. in.). Provision has been made in the web for vertical tensile reinforcements and horizontal reinforcements as necessary, with a double connection ruling out any possibility of cracking due to shear. The thicknesses have been designed for a maximum shear stress of 60 kg per sq. cm (853 lbs. per sq. in.); under these conditions the shear forces do not cause any tension but they cause compression well below the accepted limit of 180 kg per sq. cm (2560 lbs. per sq. in.).

In conclusion, some details may be given of an application of these methods recently described by the Author for the improvement of concrete roads. The use in roads of reinforcement in the ordinary form often does more harm than good in that it aggravates the stresses due to shrinkage and expansion and so encourages instead of prevents crumbling and cracking under alternating loads. The use of stretched reinforcing bars, on the other hand, considerably improves the road construction from every point of view.

In the first place, these bars have the effect of substituting compression for the shrinkage stresses; thereby eliminating shrinkage cracks and the need for most of the joints — for any variations caused by combined changes of temperature and hygrometric condition are converted to mere variations in the intensity of compressive stress on either side of a mean value.

Secondly, the elimination of tension in the concrete brings about a considerable improvement in its resistance to abrasion; it reduces the deformability and increases the resistance to bending: hence good performance under heavy loads even in the case of a yielding subsoil.

Using steel at 120 kg per sq. mm (76 tons per sq. in.) the weight of reinforcement would be about 4—5 kg per sq. m (0,8 to 1,0 lbs. per sq. ft.) and its cost from 5 to 6 francs per sq. m. Hence the total increase in cost per sq. m would be equivalent to that of a few centimetres greater thickness but the improvement would be worth very much more than this greater thickness. Finally, the road could be handed over to the users two hours after placing the concrete.

The Author does not propose further to extend the list of possible applications. He is of opinion that systematic use of the hypotheses and methods of physics has been proved capable of greatly and rapidly advancing our general knowledge on the subject of cement and concrete, with corresponding benefit to the industries concerned in the application of these materials: indeed the progress made possible in this direction may well be comparable to that already achieved by the same means in the fields of metallurgy and mechanical engineering.

Summary.

Starting from a number of new assumptions, the Author surveys the general properties of cements and the formation of the network of pares in cement slurries. The strength of cements depends more on the mechanical and physical conditions of its application, than on any other factors. Very considerable, and almost instanteneous setting for all kinds of cement can be attained by simple improvements of the density.