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METHOD OF PRODUCING ARMOURED CONCRETE

Ewald Hoyer, Berlin-Halensee, Germany; vested in the Alien Property Custodian

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As is known, the normal armoured concrete has a very small transverse or tensile strength and a small elasticity. Besides, the consumption of iron is relatively high. According to recent proposals, it has been tried to improve the resisting properties of armoured concrete by maintaining a preliminary tension in the armour until the concrete is hardened, using straight iron rods and subjecting the rods to a preliminary tension of 40 to 60 kgs. per mm^2. Although by this preliminary tension a certain preliminary compressive tension is obtained, it has not been possible to substantially improve the known properties of armoured concrete. Nor did this result in a material reduction of the quantity of iron consumed. Furthermore, the connection of the iron with the concrete is insufficient with these pre-tensioned rods, which have to give the concrete a relatively great tensile strength. This insufficient connection is due to the fact that the rods have a relatively small surface and that these rods are loosened inside the concrete owing to dynamic stresses caused by their inherent vibration. The small adhesive strength of the iron rods in the concrete makes it necessary to brace the rods in the concrete especially at the ends. Owing to this bracing, pieces of concrete with pre-tensioned armour can only be made in certain lengths. This limitation is also governed by the limited length of the iron rods available for armouring purposes. If girders of greater lengths or the like are required, the iron rods have to be welded or joined together in order to obtain the required length of armouring.

Even if, as mentioned above, high quality steel of a greater strength is used for armouring, it is not possible, as will be shown below, to obtain substantial preliminary tensions in the concrete, as elastic jumping of the concrete as well as contracting and shrinking causes a great reduction of tension in the armour rods. As the maximum preliminary compressive tension obtainable is 150 kgs. per cm^2 with a modulus of elasticity E_b=140000 kgs. per cm^2, the compressive strength of the concrete is utilised only to a very small degree, the concrete admitting a much greater preliminary tension.

The method according to the invention is distinguished from the above mentioned method of production by using thin, highly refined steel wires with a diameter of 0.5 to 2 mm, for example, and with a very great tensile strength of up to about 30000 kgs. per cm^2, the wires being subjected to a very great preliminary tension, about equal to the final tensile strength required, until the concrete is hardened.

These refined high carbon steel wires which, as is known, are drawn to this thickness possess apart from their extremely high tensile strength a great hardness and a small elongation of rupture of only 2 to 5%. It is the type of steel wire which is also used as piano wire and for wire ropes, but in the present case it is used in its natural raw state, i. e. unpolished. These steel wires have a tensile strength of about 12000 to 30000 kgs. per cm^2. They are very elastic and the very high limit of stretching strain amounts to about 90% of the tensile strength. If double safety is calculated with, these steel wires may by subjected to a permanent safe tension of about 5000 to 14000 kgs. per cm^2.

The method according to the invention enables to produce armoured concrete which may not only be regarded as a substantially improved ferroconcrete but represents a new building material of quite different properties. With the new method a building material of low iron contents is obtained which contains only 10% of the iron armour in normal ferroconcrete. By using steel wires of very high tensile strength, a preliminary compressive tension of up to about 800 kgs. per cm^2 can be obtained in the concrete which at the same time corresponds with the safe tensile strain of the concrete. This armoured concrete may therefore be regarded as to a high degree resisting extension and bending. As the steel wires used are made in any desired length, it is possible to make extraordinarily long pieces of concrete, their length being nearly unlimited, without welding the inserted armouring. Very long pieces of armoured concrete, e.g. girders, can be made by the new method and can then be sawn into single pieces of any desired size, e.g. single girders. This sawing does not in any way alter or impair the resisting properties.

A considerable advantage of the new method may be seen in the fact that no bracing of the armouring is required, i.e. that smooth drawn wires may be used.

In order to work out the new method, great difficulties had to be overcome. It did not at all suggest itself to the expert to use thin, highly refined steel wires for this purpose, besides, it seemed impracticable to use such highly pre-tensioned wires for producing armoured concrete.

Hitherto, only highly alloyed steels were known possessing a strength of up to 120 kgs. per mm^2. Though it was known that highly refined steel wires have a greater tensile strength, it was thought that this great strength, produced by refining, would only be temporary and that these wires would not be suitable for permanent strains, as their strength is weakened by symptoms of fatigue and as they were liable to a certain amount of permanent stretching. However, exact experiments have proved that a permanent strength actually exists in the case of these highly refined steel wires and that only if they are subjected to a load of above 80% of the tensile strength, a reduction of strength and a certain amount of stretching occurs. The invention is therefore based on the knowledge that highly refined steel wires withstand a great permanent tension and are thus rendered suitable with regard to their strength for producing armoured pre-tensioned concrete.

In addition, the invention recognises the fact that, contrary to iron and steel rods, thin highly pretensioned steel wires do not require bracing. Experts could not assume that smooth, highly tensioned thin wire should not require bracing in the concrete, as highly pre-tensioned armour rods made bracing indispensable. Therefore, it was thought that thin, smooth, drawn wires would slip into the concrete when the latter is hardened and the tension at the ends of the wire is removed, and that, in consequence of the small adhesive strength of the wires, the tension of the wires could not be conferred to the concrete. But, just on the contrary, exact experiments have proved the adhesive strength of the wires, used for armouring, to be very great, whereas the adhesive strength of rods is so small as not to be sufficient to confer the tension to the concrete.

The following calculation is to show the preliminary compressive tension which may be obtained in the concrete in the case of the known methods as compared with the new method. These preliminary compressive tensions are equal to the final tensile strength of the concrete.

Let be:

σ_{evx} the preliminary tension of the steel armour before being conferred to the concrete,

σ_{ev} the permanent tension acting in the steel armour after the tension has left off,

V_x the decline of tension occurring:

(a) owing to the elastic jumping ϵ_b of the concrete,

(b) owing to the shortening δ_1 of the concrete caused by contraction, and

(c) owing to the sortening δ_2 of the concrete caused by subsequent shrinking.

σ_{bv} the preliminary compressive tension produced in the concrete,

E_e, E_b the modulus of elasticity of iron and concrete respectively.

The decline of tension V_x in the steel armouring is:

$$V_x = \sigma_{evx} - \sigma_{ev}$$

The elongation ϵ_e of the steel, which equals the decline of tension V_x:

$$\epsilon_e = \frac{V_x}{E_e} = \frac{\sigma_{evx} - \sigma_{ev}}{E_e}$$

must be equal to the jumping ϵ_b of the concrete

$$\epsilon_b = \frac{\sigma_{bv}}{E_b}$$

from which follows:

$$\frac{\sigma_{bv}}{E_b} = \frac{\sigma_{evx} - \sigma_{ev}}{E_e}$$

Introducing the value

$$n = \frac{E_e}{E_b}$$

we have:

$$n \cdot \sigma_{bv} = \sigma_{evx} - \sigma_{ev}$$

This equation shows the connection between the necessary preliminary tension σ_{evx} and the preliminary compressive tension σ_{bv} in the concrete. It is to be seen that it is independent of the degree of armouring.

If the moduli of contraction, shrinkage, and elasticity are known for the respective concrete, it is possible to find the maximum preliminary compressive tension σ_{bv} max of the concrete independent of the cross section of the concrete.

Then, in the equation, the value of the limit of stretching strain σ_{es} must be put for σ_{evx}, and the value σ_{ev} for the permanently acting steel tension. The value $\sigma_{es} - \sigma_{ev}$ represents the value of the decline of the tension.

The equation for the maximum preliminary compressive tension of the concrete becomes:—

$$\sigma_{bv}\ \text{max} = \frac{\sigma_{es} - \sigma_{ev}}{\frac{E_e}{E_b}} - \frac{\delta_1 + \delta_2}{\frac{1}{E_b}}$$

The first part on the right of the equation gives the value of the preliminary compressive tension of the concrete without regard to the contraction and shrinkage. The second part represents the value of the contraction and of the shrinkage.

If rods of ordinary constructional steel are used for armouring with a limit of stretching strain $\sigma_{es}=2400$ kgs. per cm², with a safe load of $\sigma_{ev}=1200$ kgs. per cm², and using concrete with $E_b=140\,000$ kgs. per cm², with a modulus of contraction $\delta_1=0.0005$ cm/cm, and a modulus of shrinkage $\delta_2=0$, the maximum preliminary compressive tension of the concrete at the maximum preliminary tension σ_{es} of the armouring becomes:

$$\sigma_{bv}\ \text{max}=10 \text{ kgs. per cm}^2$$

If high quality constructional steel with a limit of stretching strain $\sigma_{es}=3600$ kgs. per cm² and $\sigma_{ev}=1800$ kgs. per cm² is used for the same concrete, the maximum preliminary compressive tension is σ_{bv} max=50 kgs. per cm².

For rod armouring of steel with maximum strength (chromium-nickel-steel) having a tensile strength of 11,000 to 12,000 kgs. per cm², and a limit of stretching strain $\sigma_{es}=8000$ kgs. per cm², and $\sigma_{ev}=4000$ kgs. per cm², we get for the same concrete with a modulus of shrinkage $\delta_2=0.0003$ cm/cm:

$$\sigma_{bv}\ \text{max}=153 \text{ kgs. per cm}^2$$

It is pointed out that the maximum preliminary compressive tension of the concrete cannot be increased by adding to the quantity of armouring or by decreasing the cross section of the concrete.

In comparison with the foregoing calculation of the preliminary compressive tension of the concrete, the maximum preliminary compressive tension is calculated, resulting, if, for example, steel wire according to the invention is used with $\sigma_{es}=24{,}000$ kgs. per cm² and $\sigma_{ev}=12{,}000$ kgs. per cm², when these pre-tensioned wires are imbedded in a very resisting concrete with a modulus of contraction $\delta_1=0.0004$ cm/cm and a modulus of shrinkage $\delta_2=0.0004$ cm/cm. Using these values, the maximum preliminary compressive tension of the concrete becomes

$$\sigma_{bv}\ \text{max}=688 \text{ kgs. per cm}^2$$

If a very high quality concrete is used, for which E_b is somewhat greater than 140,000, it is possible to obtain a permanent preliminary compressive strength of up to 800 kgs. per cm².

The following will serve to prove that concrete armoured according to the invention with steel wires, can be produced, in which the steel wires are imbedded without any bracing. The fact that the highly tensioned wire confers its tension to the concrete is partly due to the very large surface of numerous relatively thin wires, contrary to the case when rods are used. In addition, when cutting off the tensioned wires, the diameter at the ends of the wires is enlarged owing to the transverse extension, whereby the steel wires are pressed against the concrete. The friction between the wire and the concrete, set up by these compressive forces, prevents the wires from being drawn into the concrete, as will be seen from the following calculation.

Let be:

d_0 the diameter of the pre-tensioned wire,

d_1 the enlarged diameter of the wire after the decline of tension,

m_b, m_e Poisson's values for concrete and steel respectively.

The enlargement of the diameter of the wire from d_0 to d_1 causes in the concrete the compressive tension:

$$\sigma_{ro} = \frac{m_b . E_b}{m_b + 1} \cdot \frac{\sigma_{evx} - \sigma_{ev}}{E_e . m_e - \sigma_{evx}}$$

The frictional resistance R_1 for 1 cm length of wire is:

$$R_1 = f \cdot \sigma_{ro} \cdot U$$

where f represents the coefficient of friction between steel and concrete, and U the circumference of the wire.

For the length of adhesion λ the frictional resistance is derived from:

$$R_2 = \int_{x=0}^{x=\lambda} f \cdot \sigma_{rox} \cdot U \cdot dx$$

where

$$\sigma_{rox} = \frac{m_b . E_b}{m_b + 1} \cdot \frac{\sigma_{evx} - \sigma_{ev} \cdot \frac{x}{\lambda}}{E_e . m_e - \sigma_{evx}}$$

The tensile force acting in the wire inside the concrete is:

$$Z = F \cdot \sigma_{ev}$$

When R is greater than Z, the wires cannot be drawn in anymore. Therefore, the length of adhesion is:

$$\lambda = \frac{2 \cdot F}{U} \cdot \frac{1}{f} \cdot \frac{m_b + 1}{m_b} \cdot \frac{E_e \cdot m_e - \sigma_{ev}}{E_b} \cdot \frac{\sigma_{ev}}{2 \cdot \sigma_{evx} - \sigma_{ev}}$$

For example, having $f = 0.25$; $m_b = 6$; $m_e = 3$: $E_b = 300{,}000$; $E_e = 2{,}100{,}000$; $\sigma_{evx} = 15{,}000$ kgs. per cm^2; $\sigma_{ev} = 12{,}000$ kgs. per cm^2, we find:

$$\lambda = 33 \cdot d$$

and with a threefold safety against sliding:

$$L = 100 \cdot d$$

The lengths of adhesion λ and L respectively therefore are:

$d = 1$ mm $\lambda = 3.3$ cm $L = 10$ cm
$d = 3$ mm $\lambda = 10.0$ cm $L = 33$ cm
$d = 5$ mm $\lambda = 16.5$ cm $L = 50$ cm
$d = 10$ mm $\lambda = 33.0$ cm $L = 100$ cm
$d = 20$ mm $\lambda = 66.0$ cm $L = 200$ cm

This comparison proves that bracing the ends of the thin wires, as used according to the invention with thicknesses of 0.5 up to a maximum of 5 mm, may be omitted, which however is not possible when using wires or rods with a thickness exceeding 5 mm, as the length of adhesion is too great.

The application of the new method requires a very resisting concrete with a compressive strength of 400 to 1200 kgs. per cm^2, which is densified by using fine-grained additions and high quality special cement, and by agitating, especially at high frequencies of 50 to 150 Hz. Using the above mentioned values, the maximum compressive tension between the wire and the concrete at the free end of the wires is for example $\sigma_{roo} = 615$ kgs. per cm^2, whereas towards the interior this tension drops to a certain value, amounting to only $\sigma_{ro} = 123$ kgs. per cm^2 at the end of the length λ of adhesion. These compressive tensions in the concrete are independent of the diameter of the wire and are therefore of the same magnitude for all thicknesses of wire.

The armour wires according to the invention are given a preliminary tension by using any desired means, for example winches, the wires being tensioned singly or in groups, for example combined in a rope, according to the purpose. The wires are subjected to a great preliminary tension, sufficient to cause an elastic elongation of the wires of 3 to 10 mm per metre.

The adhesive strength is very great when using thin steel wires and is not impaired by inherent vibrations as in the case of rods, the mass of the wires being too small. As in the case of wires the length of adhesion required to confer the preliminary tension to the concrete is very small, the larger pieces of concrete produced according to the new method, for example girders and plates, may be readily sawn into small or short pieces. As many thin wires pass through the concrete produced according to the new method, the plastic deformation of the concrete in conferring the tension is reduced to a minimum, and an extremely homogeneous building material is obtained, behaving similar to iron.

The above mentioned small elongation of drawn steel wires, being 2 to 5%, keeps the concrete, armoured with these wires, elastic nearly up to the point of rupture, so that this concrete may be regarded as completely elastic, capable of being stressed by up to 1½ times the safe load without forming fissures. The rupture does not, as in the case of the known ferroconcrete, occur surdenly, but commences for example with a great deflection when subjected to bending stresses about 10 times as great as in the case of ferroconcrete, finally also forming fissures in the concrete. As soon as the load is reduced, these fissures close again and the deflection goes back elastically and rapidly. The concrete produced according to the new method therefore affords a great safety, as it may be stressed without damage nearly up to the point of rupture.

As experiments have shown, the concrete produced according to the new method will readily stand great and varying permanent stresses (vibration stresses), contrary to ferroconcrete. It possesses a permanent strength also in the case of dynamic stresses and may be used in cases where ferroconcrete is unserviceable. The new method may be applied to all concrete constructions. According to the new method, new types of high buildings as well as halls and bridges with great spans can be made of elastic concrete, in a way which has not been possible hitherto.

The elastic concrete is of special importance as a new material in the manufacture of articles made of concrete. It is possible to produce girders of any desired shape or length, serving as a substitute for iron girders. Besides, all kinds of plates as well as new articles can be produced, which hitherto could not be made of concrete. Water pipes and pressure chambers can be made for the highest interior pressures of up to about 200 atmospheres. They are so elastic and durable that fissures in the concrete do not occur.

This concrete is also suitable as a material for railway sleepers of great durability, being superior to iron sleepers.

EWALD HOYER.