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Thin Bonded Overlays

About the Role of Fiber Reinforcement on the Limitation of Their Debonding

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This paper concerns metal fiber-reinforced repairs and toppings of slabs or concrete pavements. The durability of thin bonded overlays (less than 100-mm thick) depends upon the durability of their bond to the base slab onto which they have been applied. This paper focuses on the improved bond durability of fiber-reinforced overlays. Because fiber reinforcements at usual dosages have no significant effect on either the changes of length of the overlays or on the shear strength of their bond to the base, another cause of this better durability was sought. The research demonstrates, by finite elements computation and experimental verification, that the debonding of overlays is caused, in large, by the coupled effects of vertical cracking through the overlay and traffic loads. It is by restraining cracking that fibers enhance the bonding durability of overlays. ADVANCED CEMENT BASED MATERIALS 1996, 4, 21–27

KEY WORDS: Durability, Fiber-reinforced concrete, Metal fiber, Repairs

Thin bonded overlays (less than 100-mm thick) are used for repairs and toppings of slabs or concrete pavements. This paper focuses upon their durability versus mechanical actions (direct actions, such as traffic, and indirect actions, such as the effects of length changes, mainly due to shrinking and temperature changes). The durability of overlays is conditioned by the durability of their bond to the base onto which they have been applied [1–3].

It is generally agreed that metal fiber-reinforced overlays produce better durability. The durability of the concrete or mortar of the overlay is enhanced by the crack-restraining effect of fibers, and the durability of the bond between the overlay and the base slab is also improved by fibers [4,5].

This paper sets out to seek the causes of this improved durability of the overlay-base bond. It is the continuation of a study carried out by Grandhaie [6–8]. A finite elements computation will show that debonding of overlays is first initiated and later propagated by the coupled effects of vertical cracking through the overlay and traffic loads. Experimental testing will confirm this point and show that the positive effect of fibers on bond durability is reliant, for a large part, upon their capacity to restrain cracking.

Previous Findings

The experimental repair of Motorway 40 in Montreal (Canada), thoroughly studied by the team of Aitcin [4,5], yields interesting results. This six-lane motorway, supporting traffic of 3000 vehicles a day, was repaired in 1986 by the thin bonded overlay technique. Different types of overlays were considered and compared: plain concrete ones (100-mm thick) and ones reinforced by 22–34 kg/m^3 of steel fiber (75-mm thick). Moreover, on both side lanes, the overlay was connected to the base pavement by steel nails about 50-mm long, previously driven to half of their length into the old pavement. No nail was driven into the central lane.

The crack growth, quantified by the length of observed cracks per unit length of lane, is presented in Figure 1. In plain concrete overlays, a sharp rate of crack growth was associated with a quick deterioration of the pavement; cracks led to the parceling and debonding of the overlay, or to its debonding and parceling, and in less than 2 years all the overlay had been worn away. However, in the fiber-reinforced overlays, the crack growth was much slower and almost stabilized past the first year. After more than 8 years of use, the fiber-reinforced repairs are still sound, with limited cracking and no lack of bonding, whether on the nail-less central lane or on the nailed side lanes. The fiber reinforcement could not prevent the opening and widening of the cracks reflected from the base pavement, but it has been most efficient in restraining the development of other cracks. These remained narrow

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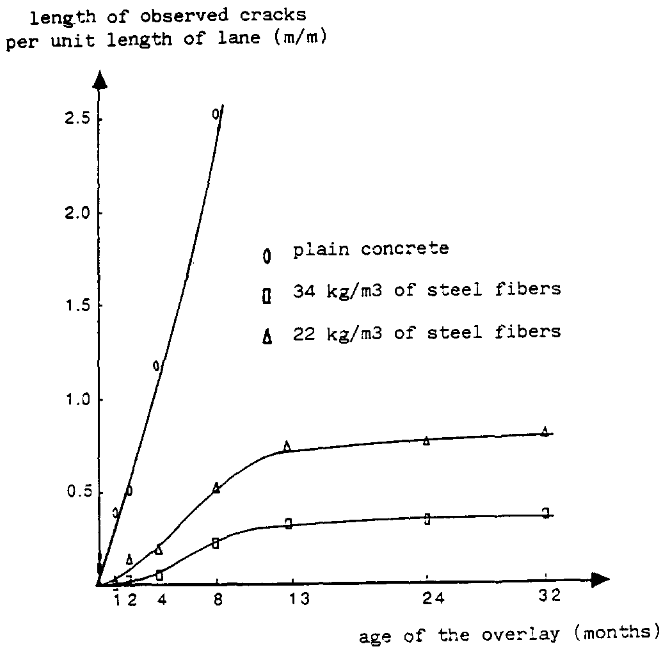

FIGURE 1. Crack growth in Montreal motorway [4,5].

and limited in number, and mostly they developed to less than half the depth of the overlay.

Debonding of overlays is usually considered as the consequence of shear stresses along the overlay-base interface. These stresses may be induced, for instance, either by the difference in length changes between the overlay and the base or by external mechanical actions, mainly those due to traffic.

Our previous studies [6–8] have shown that the addition of metal fibers at usual dosages has no significant effect on the shrinkage and swelling of concrete, on its thermal dilation coefficient, or on the strength of the overlay-base bond measured by shear along the interface (in fact, that strength can be fairly high: 6 MPa measured on 28-day-old laboratory specimens). Only a slight increase was noticed (≈15%) in the creep and relaxation capacity of fiber-reinforced overlays; this acts as a means of reducing the stresses caused by length changes, but only slightly.

Fatigue tests carried out at the University of Sherbrooke (Canada) [9], with the aim of causing debonding of the overlay by shear along the interface, complete the scope. The tests were performed in the conditions presented in Figure 2. The tensioned face of the base was reinforced by a metal plate to allow it to stand important loads. In the case of a vertical loading with no previously debonded zone, debonding could never be achieved or initiated (increasing the vertical load ended by the crushing of the compressed concrete of the overlay). It was only possible to propagate a previously existing debonding by the action of an oblique force simulating the effect of breaking.

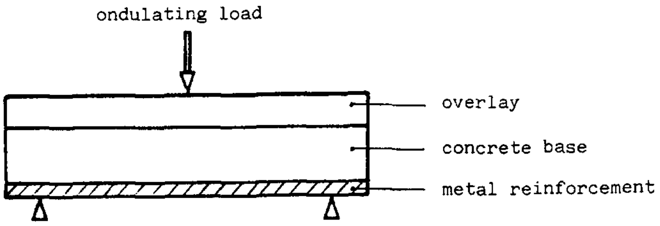

FIGURE 2. Fatigue tests carried out in Sherbrooke [9], experimental device.

In light of these observations, it appears that (1) at the usual fiber dosages, the best bond durability of fiber-reinforced overlays does not come from smaller length changes of fiber-reinforced concretes or mortars or from a higher overlay-base bond strength; and (2) the debonding of the overlay is not initiated by the shear stresses induced under or in the vicinity of applied loads.

Proposed Debonding Mechanism

The proposed debonding mechanism is presented in Figure 3. The most critical zone for debonding is not under or near applied loads but is apart from them in the sections of extreme negative moment. In such sections, a cut through the whole depth of the overlay (for example, a well-developed crack as found in plain concrete) acts to debond. Fibers, linking together the two sides of cracks and restraining their openings and developments, are beneficial.

This mechanism has been made clearer by a finite elements computation and has been experimentally confirmed.

Finite Elements Study

The calculations were carried out on a bidimensional model, comparing the slab or the pavement with a strip resting on an elastic support (Winkler model) with the assumption of plane strains. Because our interest was in the calculation of the stresses caused by the passage of

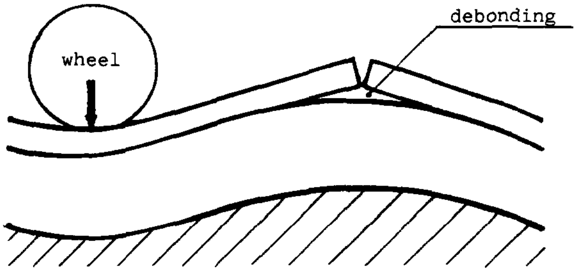

FIGURE 3. Proposed debonding mechanism.

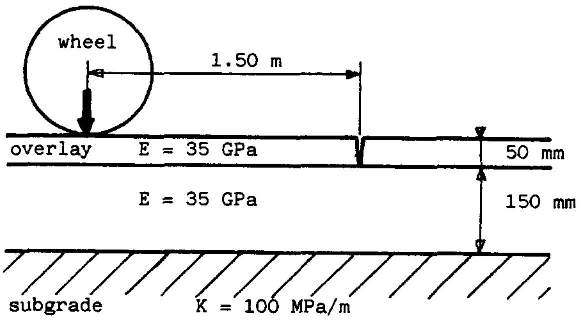

FIGURE 4. Hypotheses of the finite elements computation.

wheels of vehicles (which are short lasting actions), creep was not to be considered. Therefore, the elastic calculation was convenient.

We considered a slab 200-mm thick (a 50-mm thick overlay on a 150-mm thick base) resting on a compacted subgrade with a 100 MPa/m modulus of reaction. Considering the case of hardened repairs, we chose the same elastic modulus for the base and the overlay: 35 GPa. We assumed a Poisson's ratio of 0.20 and a perfect bond between the overlay and the base slab. These hypotheses are summed up in Figure 4.

In the case of a plain concrete overlay, the cracks are wide and developed throughout its whole depth. Such a crack was modeled by a cut through the overlay.

In the case of a metal fiber-reinforced overlay, the cracks are narrower. Their openings are restrained by the fibers, and many of them do not develop through the whole depth of the overlay. This type of crack, through which fibers go on transmitting efforts and which are probably prolonged by a highly deformed zone, weakens the overlay but does not cut its continuity. As a first approximation, it was modeled by a slice of the overlay of lower elastic modulus. According to the size of the finite elements considered for the computation, this slice was set at a 50-mm width. Its modulus was assumed to be equal to one-third that of the uncracked overlay.

Referring to the Montreal motorway repair, where it was observed that most of the cracks developed to less than half depth of the overlay, this coefficient one-third seems pessimistic.

The results of the calculations, presented in Figure 5, show that in the case of plain concrete overlays (well-developed crack), the passage of a vehicle induces sharp extra stresses at the interface: in particular a shear stress τ_{xy} and a debonding tensile stress σ_y. This asso-

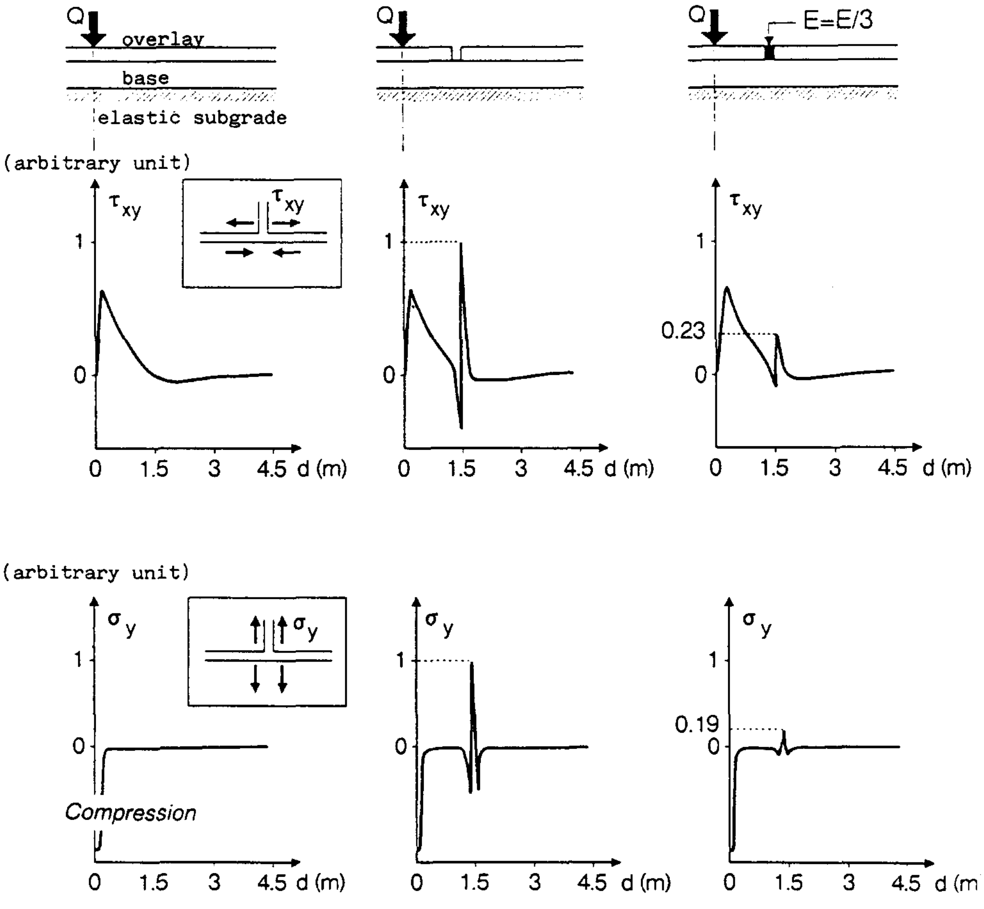

FIGURE 5. Results of the finite elements calculations.

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ciation of shear and tensile stresses is very detrimental. Further calculations showed that, once debonding has begun, these extra stresses are then applied at each end of the debonded zone. Their amplitudes are not sensitively altered, which makes debonding continue. In the case of fiber-reinforced overlays (ill-developed crack), the extra stresses are drastically reduced. They are divided by a factor of 5 in the case of our pessimistic hypothesis and probably more in usual cases. This is beneficial to the durability of repairs.

The mesh sensitivity of this calculation has been controlled in the case of a cut throughout the overlay. A complementary computation has been achieved with a much finer mesh in the vicinity of the cut. Its results confirm the previous findings. The pattern of the extra stresses, shear and tension, acting to debond the overlay remain practically unchanged. Only the compression peaks visible in Figure 5 on both sides of the cut are affected; they vanish when a finer mesh is used.

Experimental Study

These studies confirm the beneficial effect of fibers. The greater their capacity to restrain and spread cracking, the more delayed debonding is.

Experimentals

Composite specimens were prepared by casting a 40-mm thick overlay onto a metal base, as shown in Figure 6. After a 6-day cure at 20°C and 60% relative humidity, they were tested in flexure (mid-span load) where the overlay was situated on the tensioned face.

Control specimens (monolithic 100 × 100 × 500-mm prisms) were cast from the same batch, had the same cure, and were tested at the same age in third-point flexural mode (see Figure 7).

With the composite specimens, the aim was to test the effect of a bending imposed to the interface between the overlay and the base, whatever the origin of the bending.

The mid-span load flexural mode allows us to know where cracking will be initiated, in the vicinity of the load axis, and to concentrate measuring devices in this area.

Metal bases have three advantages: (1) They are reusable and their mechanical properties are not time-dependent. (2) They do not exhibit the length changes that concrete bases would have, and then their use discards an extra factor of discrepancy; indeed when a fresh overlay is cast onto on old concrete base, the later absorbs water from the former and swells [10]. (3) If needed, they may have a large stiffness.

The study used hollow steel profiles 100-mm wide, 150-mm high, and 3.4-mm thick. Their E × I product (elastic modulus × inertia moment) is approximately the same as the one of a solid concrete base of the same size. Consequently, at each given curvature, the depth of the neutral axis and the strains in these metal-based

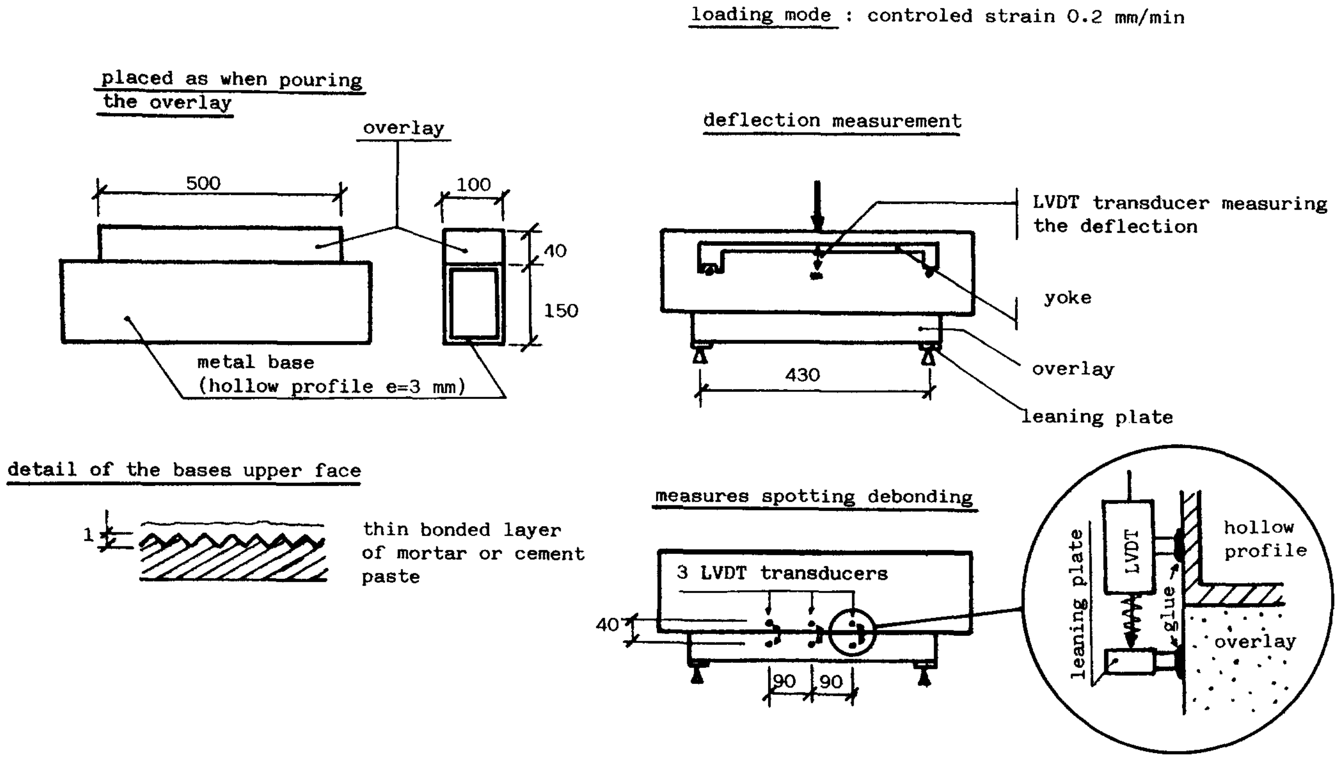

FIGURE 6. Composite specimens: characteristics and testing.

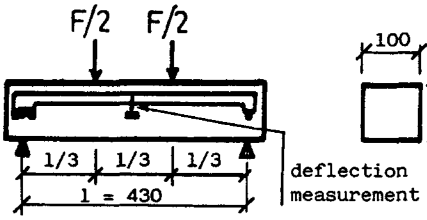

FIGURE 7. Control specimens: characteristics and testing.

composite specimens are good approximations of the ones in real repaired slabs.

The upper faces of the hollow profiles were milled rough and prepared by repeating the cycle—casting, curing, debonding a concrete overlay—until it was covered by a thin, uniform, and perfectly bonded layer of mortar or cement paste (see Figure 5). Consequently, it is along an actual cement based interface that the bond (and later the debonding) of the overlay was tested.

The tests on composite specimens were exploited as follows. The deflection at mid-span that reflects the bending imposed to the overlay was measured. The debonding of the overlay was spotted by 3 LVDT (linear variable differential transformer) transducers (see Figure 6). They were fitted on each specimen to measure the vertical gap that will appear between the base and the overlay when debonding occurs. They were connected in series to add their signals. Before debonding, the output indicates a vertical shortening; after debonding, it exhibits a fast elongation. The change between shortening and elongating sharply locates the start of debonding.

The test of the control specimens, in third-point flexure, provided the record of the load-deflection curves characterizing the used concretes.

Concretes and Fibers Used

All the mixes had the same concrete matrix but different amounts of fibers. This matrix had been optimized to best suit the maximum fiber dosage considered and to have no visible segregation in the absence of fiber addition. Of course the different mixes had different workabilities. Their compositions are presented in Table 1.

TABLE 1. Composition of the concretes used (for 1 m^3)

Components	Quantities
Portland cement type CPA-CEM 1 52, 5 (≈ type III American cement)	400 kg
Water	188 kg
Sand (0–5 mm)	900 kg
Gravel (5–12.5 mm)	900 kg
Superplasticizer (melamine sulfonate)	3.4 l
Fibers	0–80 kg
Water/Cement ratio (W/C)	0.47
Sand/Gravel ratio (S/G)	1

Two types of fibers were considered: Harex SF01–32 (chips) 32-mm long, added in quantities of 20, 40, or 80 kg/m^3 and Fibraflex FF30 L6 30-mm long, added in quantities of 20 or 30 kg/m^3.

Harex fibers (chips) are steel chips mill cut from a larger block of steel. They are rough, slightly twisted ribbons. The ones used here are 32-mm long, 3.5-mm wide, and approximately 350-μm thick.

Fibraflex fibers are metallic glass fibers. They are obtained by melt spinning: A thin flow of melted metal falls onto a cold spinning wheel at the contact of which it is cooled down very quickly to harden into an amorphous structure. This is why they are qualified as metallic glass fibers. They have a high tensile strength, are corrosion resistant, and are obtained as very thin shiny and flexible ribbons. Due to their high specific area, they have a very good bond with the matrix. The fibers used for this study were 30-mm long, 1.6-mm wide, and 26-μm thick.

The detailed characteristics of these two types of fibers are presented in Table 2.

Results

The results are presented in Figures 8, 9, and 10 and confirm the proposed mechanism.

TABLE 2. Characteristics of the fibers used

Characteristics	Harex SF01-32	Fibraflex FF30
Nature	Steel	Amorphous metallic alloy $(Fe,Cr)_{80}(P,C,Si)_{20}$
Obtained by	mill cutting	melt spinning
Length	32 mm	30 mm
Width	3.5 mm	1.6 mm
Thickness	350 μm	26 μm
Specific area	1.6 m^2/kg	10 m^2/kg
Density	7.8	7.2
Tensile strength	800 MPa	≈2000 MPa
Elastic modulus	200,000 MPa	140,000 MPa
Corrosion resistance	the one of steel	rustproof

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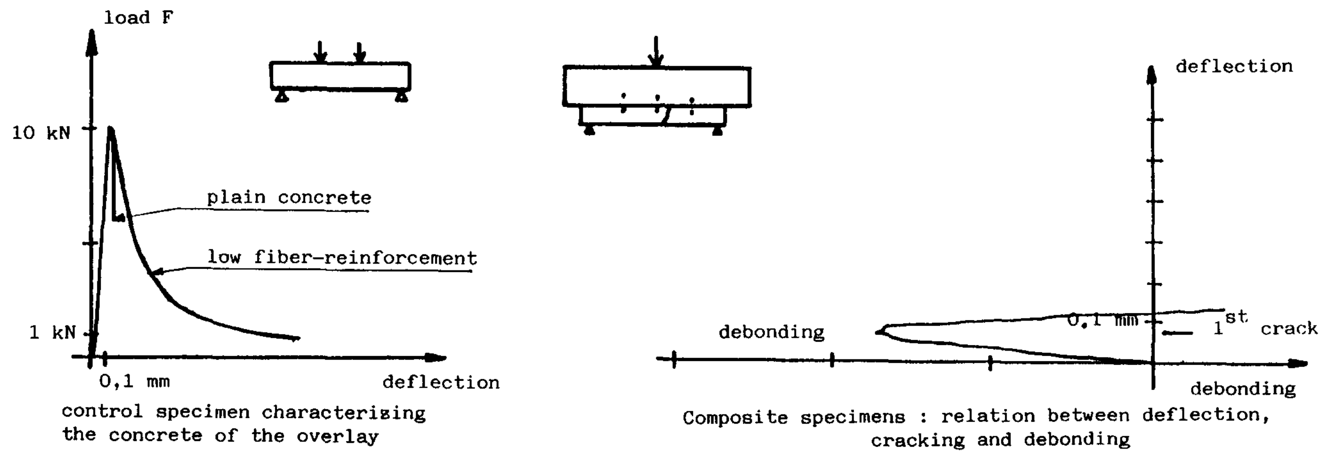

FIGURE 8. Overlays unreinforced or with low fiber reinforcement.

In plain concrete overlays (Figure 8), debonding and cracking begin together. Until the first crack, the output of the device spotting debonding exhibits a shortening; there is a perfect bond between the overlay and the base. At the instant of the first crack, the output turns to a sharp elongation, indicating debonding with instantaneous propagation.

In fiber-reinforced overlays, the lowest fiber addition (20 kg/m^3) has no sensitive effect; the observed behavior is like the one of plain concrete overlays and can be represented by Figure 8. As the fiber dosage was increased, the effect of fibers turned to more and more sensitive and significantly delayed debonding. In some cases, in the limits of the curvatures imposed to our specimens, debonding was completely prevented.

Figure 9 presents the case of an overlay reinforced with 80 kg/m^3 of Harex fibers. Debonding was initiated by the first crack, but the crack did not propagate. Its propagation remained delayed until a second crack occurred, then the deflection, reflecting the curvature of the interface, had increased to four times as large.

Figure 10 presents the case of an overlay, reinforced with 30 kg/m^3 of fibraflex fibers, in which debonding could not be reached.

Referring to the third-point flexural tests characterizing the concrete of the overlay, our results (partially represented in Figures 8–10) show that the less sharp the load peak of the load-deflection curve is, the more delayed debonding is. In other words, the most important factor to delay or prevent debonding is the capacity of the fiber reinforcement to restrain and control the very beginning of crack opening, no matter what the residual load-bearing capacity is at large crack opening. In this respect, the most efficient fibers are those that have the best bond with the matrix.

Moreover, the efficiency of the fibers is evident through their capacity to spread cracking. In the frame of our tests, we noticed that almost each time when cracking is concentrated in one lone crack, debonding and cracking start together and when cracking is spread into two or three cracks, debonding is delayed.

In these tests performed in monotonic loading,

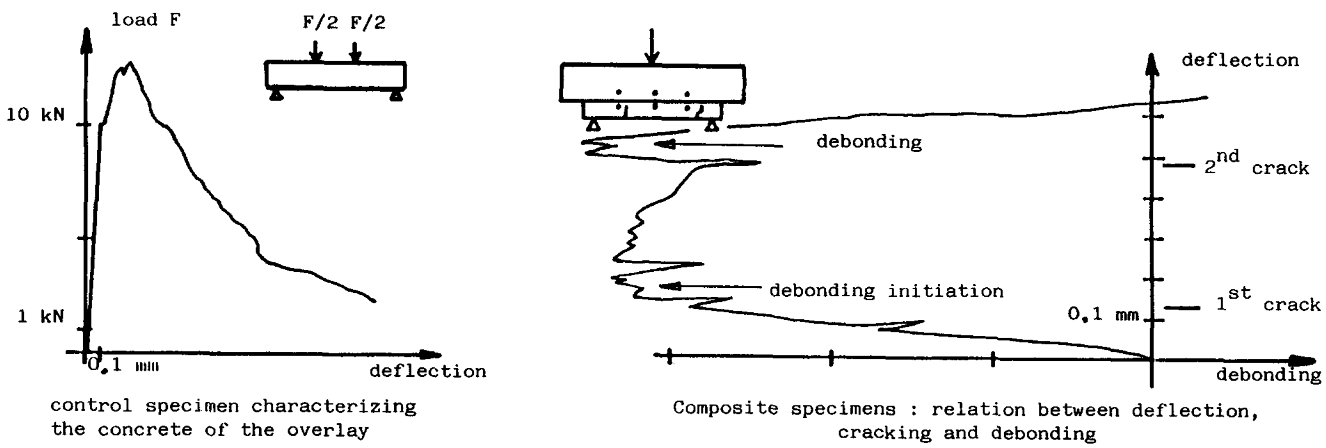

FIGURE 9. Overlays reinforced with Harex fibers (80 kg/m^3).

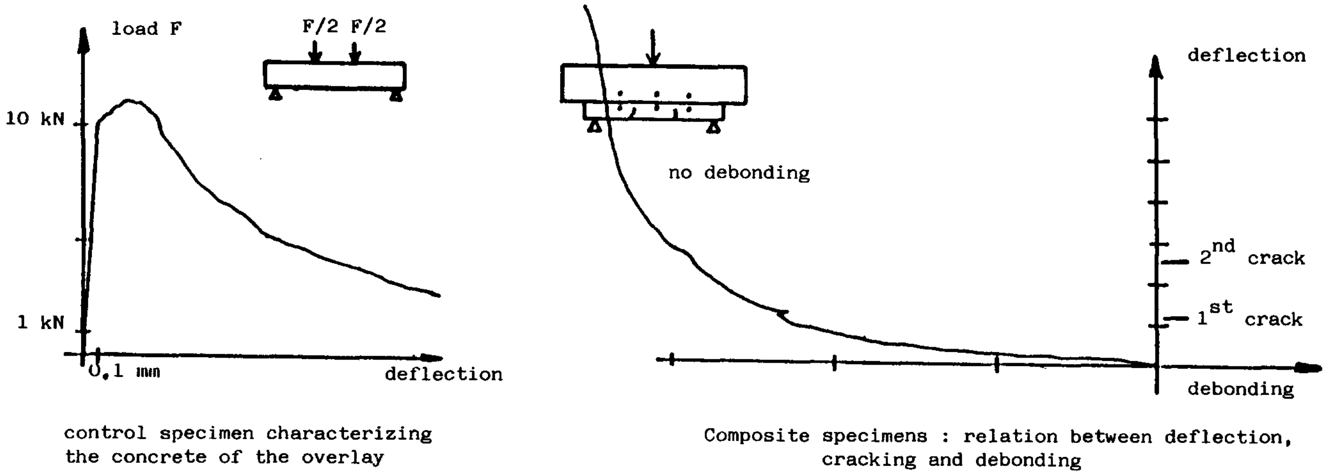

FIGURE 10. Overlays reinforced with Fibraflex fibers (30 kg/m^3).

marked positive effects were observed only with the highest fiber dosages considered. In fact, one may expect a better response with fiber addition in the case of fatigue loading, which is the case of real slabs or pavements. Debicki [11] observed that in third-point flexural tests of fiber-reinforced specimens, in monotonic loading, cracking was systematically concentrated in one lone crack. In the case of fatigue (ondulated) loading, cracking was often spread into several cracks (up to four). The observations made on the Montreal motorway complete the argument. In real conditions, 22 to 34 kg/m^3 of steel wire fibers have been enough to efficiently restrain the crack development and, until now, to prevent the debonding of the overlay.

Conclusion

This paper shows that one of the causes, probably the major one, of overlay debonding is the coupled effects of vertical cracking through the overlay and traffic loads. A well-developed crack, such as found in plain concrete overlays, is particularly detrimental.

The beneficial effect of fibers is reliant upon their capacity to restrain the development of cracks and to spread them into several finer cracks. In this respect, the most efficient fibers are those that have the best bond with the concrete matrix.

Joints cutting the overlay, sawed or not, act as cracks. To prevent them from inducing debonding, it is essential that they are located above the joints in the base slab.

The major factor improving the durability of fiber-reinforced overlays is the capacity of fibers to restrain cracking development. This capacity acts at two levels: first, it acts on the durability of the overlay itself; and second, it acts on the durability of its bond to the base.

Further research is in progress that combines experiments and finite elements analysis with the aim to enlighten the role of each of the involved parameters and to propose rules for optimal design of thin (fiber-reinforced) bonded overlays.

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