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Effect of Paste-Aggregate Bond Strength on Behavior of Concrete[*]

ABSTRACT: Coarse aggregate was coated with a thin layer of polystyrene to reduce paste-aggregate bond strength. The resulting concrete was compared to concrete containing uncoated control aggregate for strength, stiffness, and type and amount of microcracking. Large changes in interfacial paste-aggregate bond strength caused only small changes in compressive strength, stiffness, and microcracking.

KEY WORDS: aggregate coating, interfacial bond strength, microcracking, paste-aggregate bond, plain concrete, stiffness, stress-strain curve, evaluation

The primary purpose of this study was to determine some effects of paste-aggregate interfacial bond strength on portland cement concrete under short-term uniaxial load. Over the past several years, work at Cornell University [1–3][3] and elsewhere [4–11] has dealt with the importance of interfacial bond strength, but has not measured directly the effects on concrete of changing and controlling bond strength as an isolated variable.

The approach used was to reduce interfacial bond strength by applying a thin layer of hard polystyrene to the coarse aggregate particles, and to compare the resulting concrete with concrete containing uncoated control aggregate. The effect of the coating on the tensile paste-aggregate bond strength, and on the compressive-shear bond strength was investigated. These tests were followed by uniaxial compression tests comparing concretes containing coated and uncoated aggregates for strength, stiffness, and amount and type of microcracking.

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[*] Independently offered for publication.
[3] The italic numbers in brackets refer to the references at the end of this paper.

Experimental Work

Complete details of the experimental work and results are given by Darwin [12]. High polymer polystyrene pellets (Monsanto Lustrex SF-55) were added to commercial grade toluene to give a 5 percent (or 10 percent) solution by weight. The aggregate to be coated was washed, dried at 105 C for 24 h, allowed to cool, then submerged in the polystyrene solution three (or eight) times, being allowed to drain and dry between each application.

Tensile Bond Tests

Materials—
1. Sandstone: hard, strong gray stone; consists of fine grains of silica cemented by siliceous and argillaceous material; has a homogeneous texture; absorption 0.16 percent.
2. Limestone: hard, brittle, blue-gray calcitic stone; absorption 0.18 percent.
3. Type I portland cement.
4. Sand: consists mainly of quartz; larger particles contain some shale, sandstone, limestone; fineness modulus = 3.20.
5. Five percent and 10 percent solutions of polystyrene in toluene.
6. Mortar: $W/C = 0.64$ by weight based on saturated surface-dry (SSD) sand; sand-cement ratio = 2.91.

Procedure—The tension bond tests were performed as described by Hsu and Slate [1], with the use of a standard briquet mold containing mortar in one side cast against a saw-cut piece of stone in the other side. Two thicknesses of coating were investigated: 8 coats of 10 percent solution (0.0010-in. coating) and 3 coats of 5 percent solution (0.0004-in. coating). Tests were made at 28 days.

Results—The results of these tests are presented in Table 1, along with results obtained by Hsu and Slate [1]. The results show that the coatings cause a very large reduction in bond strength, and that there is some difference in the amount of bond strength reduction obtained with the two coating thicknesses.

Compression-Shear Bond Tests

Materials—Materials are the same as for tensile bond tests above.

Procedure—The compression-shear bond tests were performed following the method of Taylor and Broms [2], using slabs of saw-cut stone inclined within a prism of mortar.

The slabs of aggregate were cut by a slow-feed diamond disk saw. For additional comparison several slabs were polished on one side, first wet with No. 180 silicon carbide grit, and then dry with 400A Carborundum paper. The shear slabs were then prepared and coated in the same

TABLE 1—*Interfacial bond strengths with and without coatings.*

	IN TENSION, PSI		
	Hsu and Slate, from Ref *1*	Test 1[a]	Test 2[b]
Mortar mix..............	S/C 3.0; W/C 0.65	S/C 2.91; W/C 0.64	
Mortar strength.................	374	439	452
Sandstone, uncoated.............	116	137	199
Sandstone, coated................ ...		5	76
Limestone, uncoated.............	207	154	...
Limestone, coated................ ...		15	...
	Average of 9	Average of 4 to 6	

IN COMPRESSIVE-SHEAR, PSI
Slab at 45 deg, mortar (S/C = 2.91, W/C = 0.64)

Limestone, uncoated................................	1020
Limestone, coated[b]...................................	200
Sandstone, unpolished and uncoated...................	1576
Sandstone, unpolished and coated[b]....................	1474
Sandstone, polished and uncoated......................	2530
Sandstone, polished and coated[b]......................	630
	Average of 2 to 5

[a] Eight coats of 10 percent polystyrene solution.
[b] Three coats of 5 percent polystyrene solution.

manner as were the tensile prisms, except that only 3 coats of 5 percent polystyrene solution were used. The specimens were tested at 28 days.

Results—In all tests, the failure was brittle. The results are presented in Table 1. The limestone and the polished sandstone showed a substantial loss of compressive-shear bond strength due to coating, while the unpolished, saw-cut sandstone showed no appreciable reduction. It is interesting to note that the polished, uncoated sandstone had a higher compressive-shear bond strength than did the unpolished, uncoated sandstone.

All six types of specimens were observed under the microscope after failure. On the unpolished, coated and uncoated sandstone and on the polished, uncoated sandstone, the microscope revealed portions of sheared paste in the natural indentations of the rock surface. This paste appeared to be forced against the side of the grooves that corresponded to the forward direction of sliding at failure. This phenomenon was not evidenced to such a great extent on the coated limestone and the coated, polished sandstone, while the uncoated limestone appeared to have some paste remaining above the mean level of the interface (failure through paste).

Uniaxial Compression Tests

The uniaxial compression tests were divided into three phases: preliminary tests, to show general effects and guide later work; major tests, to provide the bulk of the data; and final tests, to conform earlier results and study a thicker coating.

Materials—
1. Type I and Type III portland cement.
2. Sand: the same as for the tensile bond test.
3. Gravel: same deposits as sand; maximum size ¾ in.; lightly crushed; consists of approximately 40 percent sandstone, 30 percent limestone, 20 percent interbedded sandstone and shale, 10 percent miscellaneous.
4. Five percent solution of polystyrene in toluene.

Procedure—For the preliminary tests, Type III portland cement was used; mix proportions were 1:2.91:3.82 by weight, with a W/C of 0.64 based on SSD aggregates (all W/C-ratios in this paper are based on SSD aggregates). The mix was harsh and had a slump of about ½ in. A second mix with a W/C of 0.71 was also tested; it had a slump of about 2 in. Cylinders 10 in. by 4 in. were made using both coated (0.0004 in.) and uncoated aggregate for each of the two water-cement ratios. The specimens were placed in the moist room for one day, then stripped and placed in lime-saturated water until the fifth day, when they were removed and allowed to dry.

On the sixth day, the top 2 in. of each cylinder were sawed off to reduce any effects of segregation in the mix. Four SR-4, A-12 strain gages were then placed on each cylinder 90 deg apart and parallel to the axis of the cylinder at mid-height. The cylinders were capped with Hydrostone[4] and tested on the seventh day. Three layers of wax paper with two sandwiched layers of grease were placed on the ends of the specimens to reduce end restraint.

For the major tests, the concrete mix proportions used were 1:2.41:3.16, with a W/C of 0.58 by weight with Type I cement. This mix had a slump of about 3 in. The relatively high sand content was due to the coarseness of the sand (fineness modulus 3.20). The coating was 0.0004 in. thick. The specimens were cured in the same way as the preliminary specimens, except that they were left in water until the 26th day, at which time they were removed and allowed to dry. On the 27th day the cylinders were cut to 8 in., strain gaged, and capped. Four SR-4, A-12 strain gages were placed on those specimens used to determine the complete stress-strain curves. Two strain gages 180 deg apart were used on those specimens to be loaded to a specific maximum strain and then unloaded. Load tests were made on the 28th day, again using wax paper and grease. Specimens were taken to failure or to limiting strains of 0.0010, 0.0018, or 0.0022.

For the final tests, the concrete was the same as for the major tests, except that Type III cement was used. The specimens were handled in the same way except the tests were performed on the seventh day and only two strain gauges were placed on each cylinder. One batch of concrete

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[4] A product of U.S. Gypsum Co.

contained aggregate with a polystyrene coating approximately 0.0010 in. thick (or about $2\frac{1}{2}$ times the thickness of the standard coating), and was compared to concrete containing uncoated control aggregate and to concrete containing standard coated aggregate.

Results—The results of the preliminary tests are presented on Fig. 1. For the low slump concrete the curves are identical up to about 1200 psi or 36 percent of the "uncoated" ultimate strength. At this point the curve for the concrete containing the coated aggregate drops off sharply. The ultimate strength is about 25 percent lower for the "coated" specimens. Each curve is the average of three tests. The medium slump concrete shows an early divergence in the two stress-strain curves, at about 10 percent of ultimate. The curves continue to diverge, giving a 10 percent difference in ultimate strengths.
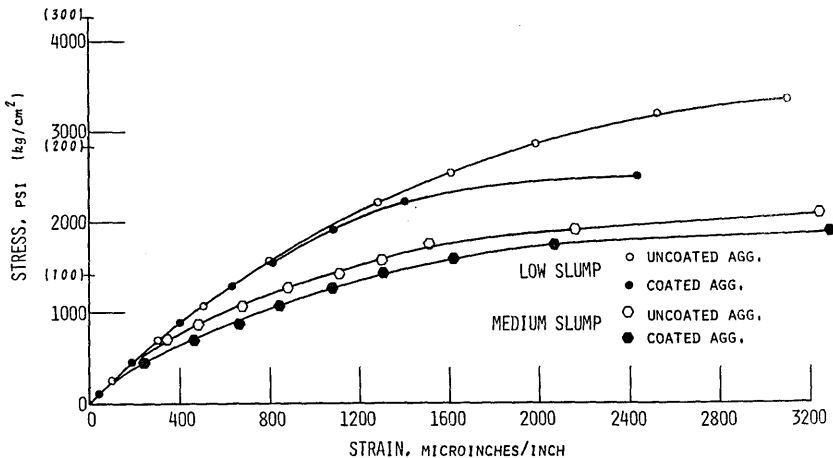

FIG. 1—*Stress-strain curves as influenced by coating of aggregates—preliminary tests.*

The same general trends are demonstrated in the major tests (Fig. 2). At low values of load, the curves remain close together, but at values of stress near the ultimate, the curve for the concrete containing the coated aggregate tends to drop below that for the control specimens. Curves are averages of 4 to 6 specimens. The "coated" specimens give a reduction in ultimate strength of 11.5 percent.

The average stress-strain readings for the specimens strained to maximum strains of 0.0010, 0.0018, and 0.0022 are available in Ref *12*. It was interesting to note that the residual strains, upon unloading, were essentially the same (for coated versus uncoated aggregate) for maximum strains of 0.0010 (average residual strain = 0.000155) and 0.0018 (average residual strain = 0.000366); no values were obtained for 0.0022.
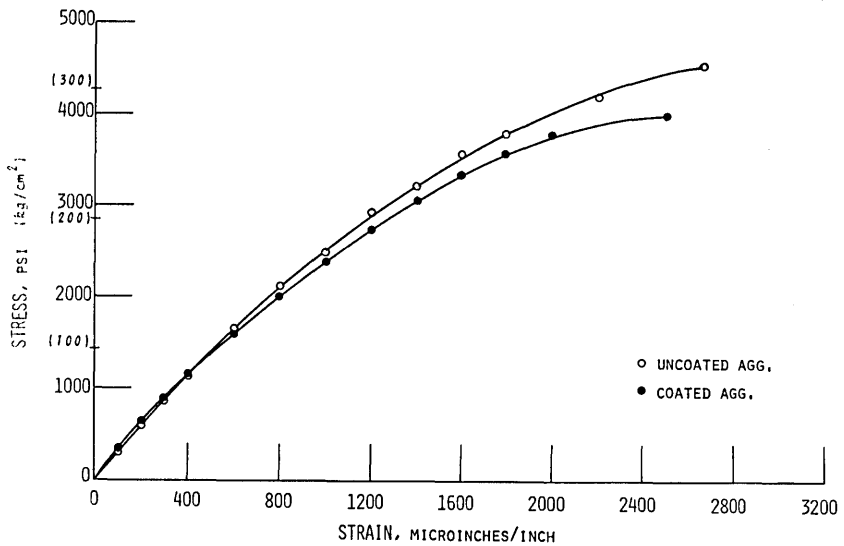
FIG. 2—*Stress-strain curves as influenced by coating of aggregates—major tests.*

Residual strain seemed to be governed only by amount of maximum strain applied. These tests also show divergence of the stress-strain curves for "coated" versus "uncoated" concretes at higher values of strain.

The secant moduli of elasticity at 10 percent and at 45 percent of the average ultimate strength of the "uncoated" specimens were measured. For those specimens not tested to failure, the ultimate was taken to be that obtained from similar "uncoated" specimens tested to failure. Comparison of the values of the secant moduli at 10 per cent showed that essentially no difference exists in initial stiffness. On the other hand, the "uncoated" specimens appeared to be stiffer (an average of 6 percent higher E, modulus of elasticity) in the upper range (45 percent f'_c, stress at failure) of working stresses.

To summarize, the general trend seems to be that the concrete containing the coated aggregate behaves like the concrete containing the uncoated aggregate at low loads, but is measurably more flexible at loads approaching the ultimate value and is somewhat weaker.

The results of the final tests are presented on Fig. 3. Each curve is an average of four tests. The standard polystyrene coating caused a 10 percent reduction in f'_c while the thick coating caused a 23 percent reduction.

Microcracking Investigation

Procedure—After the cylinders in the major tests were loaded to the required maximum strain and unloaded, they were sliced horizontally at mid-height with a slow-feed diamond disk saw to provide a slice 0.150
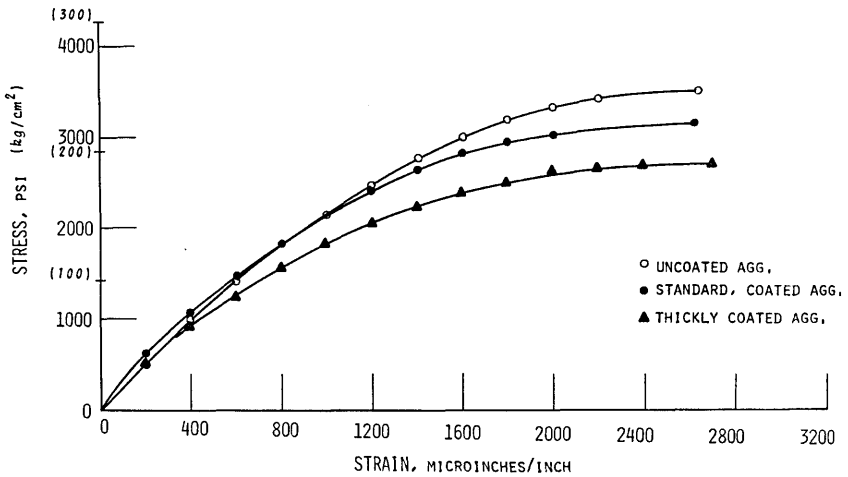
FIG. 3—*Stress-strain curves as influenced by coating of aggregates—final tests.*

in. thick from each cylinder. Each slice was carefully washed with detergent and water, lightly rinsed in acetone, and allowed to dry.

X-ray negatives were taken of each slice following the method of Slate and Olsefski [13]. These negatives were studied and the cracks were drawn on a positive photographic print of the negative. As observed by Slate and Olsefski, almost all cracks tended to appear as bond cracks.

Following the X-ray processing, the slices were stained with red drawing ink, ground, and studied following the method used by Hsu et al [14]. The slices were inspected using a 7-power stereomicroscope. Cracking maps were drawn on photographs of the unstained slices. Finally, total length of cracking was measured for each cracking map using both X-ray (quadruplicate specimens) and microscope (triplicate specimens) techniques.

Results—There was no significant difference in average total crack length between "coated" and "uncoated" specimens, for each maximum strain studied, from 0.0000 to 0.0022. The amount of mortar cracking on the "coated" specimens was somewhat larger for all strains. It is interesting to note that the average length of bond cracking was essentially the same for both types of concrete at zero strain. For detailed data, see Darwin [12].

Discussion

Effect of Coating

To determine the effect a coating of relatively soft material would have on the concrete, other than to reduce interfacial bond, the model of Darwin

[*12*] shown in Fig. 4 was used. To simplify the analysis, an average length parallel to the compressive load of 0.50 in. was adopted. This gives a half thickness (or length) of loaded aggregate of 0.25 in. This model behaves like the set of springs in Fig. 4. The stiffness of a column in compression is AE/L, where A is the area perpendicular to direction of loading, E is Young's modulus, and L is the length parallel to direction of loading.

The ratio of K_1 (stiffness of polystyrene coating) to K_2 (stiffness of aggregate) is:

$$\frac{K_1}{K_2} = \frac{A_1 E_1 / L_1}{A_2 E_2 / L_2}$$

For this model, $A_1 = A_2$, $L_1 = 0.0004$ in., and $L_2 = 0.25$ in.

The modulus of elasticity of the polystyrene used was about 4.5×10^5 psi, or approximately one tenth that of the aggregate. Insertion of these values with $E_1 = \frac{1}{10} E_2$ gives $K_1/K_2 = 62.5$. The stiffness of the two springs in series is $(K_1 K_2)/(K_1 + K_2) = 0.985 K_2$ for $K_1/K_2 = 62.5$. This shows that the stiffness of the aggregate-polystyrene column is essentially that of the aggregate column alone. In addition, the ultimate strength of the polystyrene in compression is about 13,000 psi. It therefore might
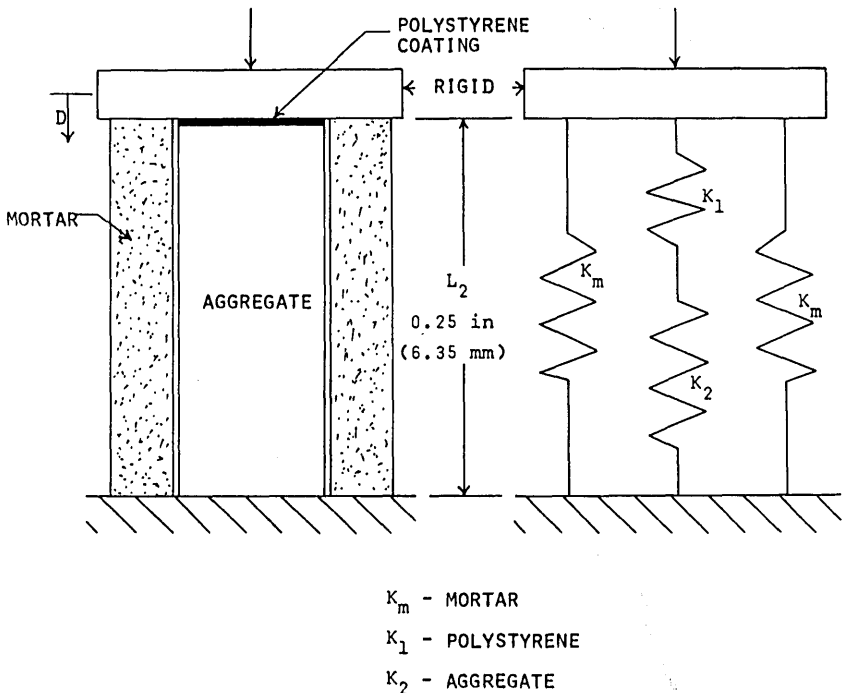

FIG. 4—*Model to investigate effect of coating of aggregate on strength and stiffness of concrete in compression.*

well be assumed that the coating would not affect the stiffness or ultimate strength of this model.

If, however, a coating of a thicker and more deformable nature were used, strength and stiffness should drop markedly. Shah and Chandra [5], using a coating of silicone rubber (very soft), 0.0026 in. thick, report a 90 percent drop in f'_c. Substituting this layer in the model in place of the polystyrene results in a different picture. For this case, let $E_1/E_2 = 1/1000$ (an assumed value; the ratio is probably even smaller), giving $K_1/K_2 = 1/1000 \times L_2 L_1 = 0.096$. The equivalent spring stiffness is $(K_1 K_2)/K_1 + K_2) = 0.095 K_2$, or less than one tenth the stiffness of the aggregate. This demonstrates that during loading a relatively thick, soft coating would effectively prevent the aggregate from contributing to the stiffness of the model.

Assuming that concrete attains its ultimate strength at a strain of 0.002, a value for the total deflection of the model (D in Fig. 4) of 0.0005 in. results. This is less than one fifth of the thickness of Shah and Chandra's coating. Therefore, without further calculation, it is readily seen that at this strain the thick, soft coating will absorb almost all of the deformation, and the aggregate will be effectively isolated from the mortar. The behavior of the resulting concrete might then be dominated by many high stress concentrations, and it would be expected to be much weaker and less stiff than concrete with uncoated aggregates. Dantinne [10], using a thick and soft bituminous coating, and Nepper-Christensen and Nielsen [11], using a soft plastic coating (0.0005 in. thick), reported that the coatings caused large reductions in concrete strength.

This type of behavior is illustrated by the effect of the thicker (0.0010 as compared to 0.0004 in.) polystyrene coating as used in the final tests (Fig. 3). The authors feel that the additional drop in f'_c for the thicker coating was the result both of a further reduction in bond strength and of the effect of the greater thickness of coating, as discussed above. The "uncoated" and "thickly coated" curves begin to diverge at a comparatively low value of stress, demonstrating that the thickly coated aggregate is partially prevented from contributing to the stiffness of the concrete. This phenomenon is not shown by the standard "coated" concrete.

Thus it has been shown that the thin coating of 0.0004 in. of "hard" polystyrene as used in this work acted only to reduce the bond strength as an isolated variable, and that it did not appreciably influence concrete properties by being deformed within itself. By the same token, thicker and softer coatings will influence concrete both by changing bond strength and by being deformed excessively.

Tensile and Compressive-Shear Bond Tests

These tests show that the nature of the compressive-shear failure of the paste-aggregate interface is as yet incompletely understood, and that the effect of the polystyrene coating upon the shear bond is at best uncer-

tain. The tests do show, however, that there is a substantial reduction in compressive-shear bond strength on smooth aggregate with the coating, and a very large reduction in tensile bond strength for all aggregate.

Microcracking Investigation

There was essentially the same amount of microcracking for a given strain, regardless of bond strength. This equality in crack length may explain why residual strain seemed to be a function only of the maximum strain. If the inelastic properties of concrete are due to progressive microcracking, which is likely, equal amounts of microcracking should result in equal residual strain.

The results tend to show that there is little relation between total microcracking and bond strength; however, in every case the average amount of mortar cracking was slightly greater for the "coated" specimens. This difference is significant, not only because it is consistent for all strains, but because the amount of mortar cracking for the "uncoated" concrete at given strains roughly paralleled the values obtained by Hsu et al [14]. This small yet consistent difference in length of mortar cracking could very well explain the differences in the stress-strain curves.

Behavior of Concrete Under Uniaxial Compressive Load

Based on this limited study, the picture developed of portland cement concrete under short term compressive load is now one in which paste-aggregate bond strength plays a limited role.

The major part of stiffness and strength in concrete seems not to depend upon bond strength, but on mix proportions. This is emphasized by the fact that the average values of the secant moduli of elasticity at 10 percent ultimate are essentially the same for the "coated" and the "uncoated" concretes. This suggests that the initial sitffness of concrete is not affected by the paste-aggregate bond strength. The average values of the secant moduli of elasticity at 45 percent f'_c show a 6 percent reduction with the concrete containing the coated aggregate, thus showing a measurable effect at high working loads. Near failure the lack of bond strength seems to have its greatest effect, causing an average reduction in ultimate strength of 10 to 15 percent.

Prior to loading, the initial bond cracking is due to volume changes, and most values of tensile bond strength (high or low) are too low to prevent cracking. Upon loading, the initial stiffness is a function of mortar stiffness, aggregate stiffness, mix proportions, and aggregate gradation. As the load increases, the mortar matrix continues to deflect until, at about one third of the ultimate strength, local deformations, and thus loads, are such at the paste-aggregate interface that bond cracking begins to increase over its zero-strain value. The bond strength, whether tensile or compressive-shear, adds some strength, but is not a major factor. As load further

increases, differences in modulus of elasticity and Poisson's ratio between the coarse aggregate and the paste cause the initiation and propagation of mortar cracks. Interfacial bond strength appears to have a small effect upon the amount of mortar cracking that occurs. For most mixes, all else being equal, failure of concrete seems to be governed, for the most part, by the tensile strength of the uncracked paste as also indicated by Jones [15], and to a minor degree (10 to 15 percent) by the paste-aggregate bond strength.

These findings are directly corroborated by Shah and Winter [16] who subjected concrete to repeated loading for which the maximum load was above 83 percent of the f'_c obtained from a single loading. They found that for those specimens cycled above 83 percent of f'_c (and therefore containing a large amount of bond cracking) but below about 90 percent of f'_c (start of rapid increase in mortar cracking), there was no reduction in the ultimate strength. Bond cracking from prior loading constituted a catastrophic reduction in bond strength, exceeding the reduction caused by use of a coating.

In general, it appears that if an aggregate is adequate in other ways it will produce concrete of adequate strength and stiffness under short-term load regardless of its bonding ability, since the paste-aggregate bond strength, even if low, will be greater than those herein obtained for the "coated" specimens.

Conclusions

The following conclusions are based on the concrete materials used and described for this project and are believed to be generally valid for most commercial concretes.

1. Large reductions in interfacial paste-aggregate bond strength cause only a small reduction in modulus of elasticity and in ultimate strength of portland cement concrete under short-term uniaxial compressive load.

2. The polystyrene coating reduces tensile paste-aggregate bond strength to a small fraction of its initial value. The coating reduces compressive-shear bond strength, but only for those coarse aggregate particles having relatively smooth surfaces.

3. A large reduction (60 to 95 percent) in tensile paste-aggregate bond strength for all the coarse aggregate particles, and a significant reduction (75 to 80 percent) in compressive-shear paste-aggregate bond strength for a large fraction of the coarse aggregate particles, causes a relatively small (10 to 15 percent) reduction in the ultimate strength of concrete.

4. Variations in interfacial bond strength have no effect upon initial stiffness of concrete loaded in uniaxial compression, and they have only a small effect on the stiffness of concrete in the upper levels of working stresses.

5. Thick, soft coatings on aggregates should cause large reductions in strength and stiffness of concrete.

6. Variations in interfacial bond strength have little effect upon the amount of interfacial microcracking prior to loading.

7. Reduction of interfacial bond strength has, upon loading, no appreciable effect on amount of interfacial microcracking, but a small yet significant effect on the amount of mortar microcracking.

8. For a single cycle of loading and unloading in uniaxial compression, residual strain is not a function of interfacial bond strength but is a function of microcracking, which in turn is largely a function of the maximum strain reached during loading.

9. The strength of the interfacial bond is apparently of much less importance in the behavior of concrete than has been thought in the past. However, further research on its significance appears to be warranted.

Acknowledgment

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