

The Role of Mortar-Aggregate Bond in The Strength of Concrete

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Mortar-aggregate bond in concrete is defined and factors which influence the bond are discussed. The discussion is built around original work by the author and work published by others.

The role which mortar-aggregate bond appears to play in the mechanism of concrete failure is discussed. Particular emphasis is given to the relationship of microcracks and mortar-aggregate bond.

The necessity of measuring bond with saturated specimens, to prevent drying shrinkage stresses, produces results which may not be representative of the bonds in concrete. Consideration of what influences bonds in normal concrete is given.

The effect of different measured mortar-aggregate bond strength on the strength of concrete is discussed with data provided.

*THE concept of bond has been widely used to explain many observed properties of concrete (1, 2, 3). Its use has been at least partially based on the intuitive concept that in a heterogeneous material the adherence of the various components to each other is important to the behavior of the material. No doubt intuition is correct, but it is deficient, at least for most people, in being quantitative and enlightening with regard to the mechanism involved. Before discussing recent findings that help to make up for the deficiencies of intuition, one must first carefully define the mortar-aggregate bond.

For this discussion bond may be thought of as the force required to separate two solid components in concrete at their interface. The components may be the paste and aggregate, or mortar and coarse aggregate. It so happens that either may be used without great changes in the interpretation of the results. Bond can be thought of as the effective adhesive force holding two surfaces together. It is derived from two sources, one being chemical and the other mechanical.

Chemical bonds appear to develop with all aggregates since it is difficult to find a material to which cement paste does not, to some extent, adhere. These are aggregates commonly described as being inert. Relative to cement they seem to be inert, but in a strict sense a chemical bond appears to develop. It is difficult to isolate the chemical bonds due to the coexistence of mechanical bonds.

Mechanical bonds may be thought of as those forces required to fracture paste interlocked in irregularities of aggregate and of shear forces which are developed along an irregular interface.

No practical means has been found to measure one type of bonding while excluding the other. Results of investigations of bonds reported in the literature are in terms of combined effects of both chemical and mechanical bond. This will, henceforth, be true of the term bond in this paper.

Measurement of bond has been made by a variety of methods each designed to measure the strength of an interface between the mortar (or paste) and the coarse

aggregate. These methods include use of a "mortar briquet" specimen (4, 5), cast prisms (1, 6) and the author's method of cores (7).

The author's method used a slab of rock, with one of its surfaces given a desired finish, on which was placed a plastic cement mortar. After a period of curing, this mortar-covered slab was cored with a diamond core drill and numerous individual specimens, approximately 0.6 in. in diameter, were obtained. This method enables a large number of specimens to be obtained with a reasonable effort. These specimens were tested in a cantilever loading with the aggregate end gripped in a vice arrangement and the mortar portion of the core loaded by a rolling frame. The distance from the mortar-aggregate interface to the point of loading was constant, 0.523 ± 0.001 in. The bond values for the investigation were used relative to each other. Therefore, the values reported are loads in pounds and not converted to modulus of rupture. For quantitative comparison to other investigations these bond values must be converted to modulus of rupture. In each of the above methods failure occurs along the mortar-aggregate interface of the specimen whether the test be one of tension, shear, flexure or torsion. The results are generally comparable for similar types of loading regardless of the form of the specimen. Preference as to the type of specimen is therefore dictated by economy and versatility.

An important and essential requirement in making such bond tests is never to allow the specimen to dry. General practice is to keep specimens in a saturated condition, otherwise great reductions in bond strength are noted. This reduction, 50 percent and more, is attributed to drying shrinkage and to surface conditions at the time of test. To the author's knowledge, no quantitative method has been developed to measure the effect of the surface and other bond factors in a less than saturated condition.

The bond test results obtained by the author (7) and by others (1) frequently have a coefficient of variation as high as 20 percent. This makes it essential that a sufficient number of tests be made in order to have reliable results. For example, with a difference in sample mean from population means of 5 lb considered significant at a $0.05-\alpha$ level, with a calculated mean of 50 lb, the "t" distribution shows that a sample size of 18 is needed. The high coefficient of variation appears to be inherent in the nature of the mortar-aggregate bond.

FACTORS AFFECTING BOND

Most factors that affect strength in a hardened cement paste or mortar affect bond strength in a similar way. These factors include water-cement ratio, cement, age, and cement factor. Alexander and Taplin have reported that bond strength at early ages does not increase as rapidly as the strength of cement paste under elevated curing temperatures. At later ages, however, when pastes cured at normal temperatures approach the strengths of those cured at elevated temperatures, bond once again has increased comparable to the paste strengths (8).

The aggregate has considerable effect on the mortar-aggregate bond with a significant difference being discernible among a great many different aggregates. The author investigated a wide variety of carbonate rocks used for concrete aggregate in Indiana, as well as several other types of aggregate (Tables 1 and 2). The results from tests on the carbonate rocks are all relatively close together. However, an analysis of variance showed that differences in carbonate rocks were statistically significant. It should be noted in Figure 1 that the highest bond strengths were obtained with quartzite. This agrees with the recently published work by Alexander (9) which suggests that silica content of the aggregate is an important factor. The general reputation of a quartzitic material in concrete, especially quartz gravels, is that it does not have especially high bond strength. This may not be caused by a low bond development but instead caused by quartz being more susceptible to having the bond destroyed by shrinkage stresses.

The effect of different surface conditions for the aggregate was also investigated by the author. Aggregate surfaces, smoothly ground with No. 1200 abrasive grit or roughly ground with No. 60 abrasive grit, did not give consistent results. Many carbonate aggregates tested did not give significantly different results with the two surface

TABLE 1
PETROGRAPHIC AND CHEMICAL PROPERTIES OF AGGREGATES

Aggregate		Petrographic Description		Chemical Analysis ^a		
No.	Name	Average Grain Size (mm)	Lithologic Properties	Percent by Weight		Insoluble Residue
				Dolomite	Calcite	
2	Jeffersonville (dolomite)	0.005	Carbonate, very fine grained, crystalline	98	1	1
6	Liston Creek (dolomite)	0.02	Carbonate, very porous, rhombic	97		3
7	Baraboo (quartzite)	0.16	Quartz, interlocking structure			
9	St. Genevieve (limestone)	0.01	Carbonate, fossiliferous detrital quartz, opaque metallics	10	88	2
10	St. Genevieve (limestone)	0.08	Carbonate, fossiliferous, opaque metallics	2	92	5
11	Lincoln "quartzite" (sandstone)	0.17	Angular quartz grains in a carbonate matrix			
12	Diorite					
13	Harrodsburg (limestone)	0.40	Carbonate, fossiliferous, detrital quartz and opaque metallics	6	95	1
14	Geneva (dolomite)	0.04	Carbonate, very porous, rhombic	99		1
15	Louisville (dolomitic limestone)	0.03	Carbonate, some large fossils, rhombic crystals, opaque metallics	60	37	3

^aCalculated from laboratory determinations of calcium, magnesium and insoluble residue contents.

TABLE 2
PHYSICAL PROPERTIES OF AGGREGATES^a

Aggregate		E × 10 ^{**}	Bulk Spec. Gravity	Absorption (%)	Particle Shape	
No.	Name				L/W ^{**}	W/T ^{**}
2	Jeffersonville (dolomite)		2.67	1.29	1.33	1.81
6	Liston Creek (dolomite)		2.58	1.78	1.41	1.52
7	Baraboo (quartzite)	13.8		0.20	1.42	1.43
9	St. Genevieve (limestone)	11.0	2.69	0.42	1.39	1.74
10	St. Genevieve (limestone)	12.1	2.68	0.46	1.34	1.53
11	Lincoln "quartzite" (sandstone)					
12	Diorite					
13	Harrodsburg (limestone)	10.1	2.65	0.66	1.36	1.69
14	Geneva (dolomite)	10.4	2.43	3.43	1.37	1.55
15	Louisville (dolomitic limestone)	15.1	2.76	0.62	1.38	1.59
16	Gravel (quartzite)		2.62	0.22	1.30	4.42

^aRounded and washed, passing 1 in., retained 3/4 in.

^{*}Modulus of elasticity, from stress-strain relationships determined with a Tuckerman optical strain gage. The average strain was used for the reported values.

^{**}The mean greatest dimension of pieces of aggregate.

W = the mean intermediate dimension of pieces of aggregate.

T = the mean smallest dimension of pieces of aggregate.

NUMBER OF TESTS TO MAKE UP THESE
AVERAGES VARIED FROM 21 TO 83.

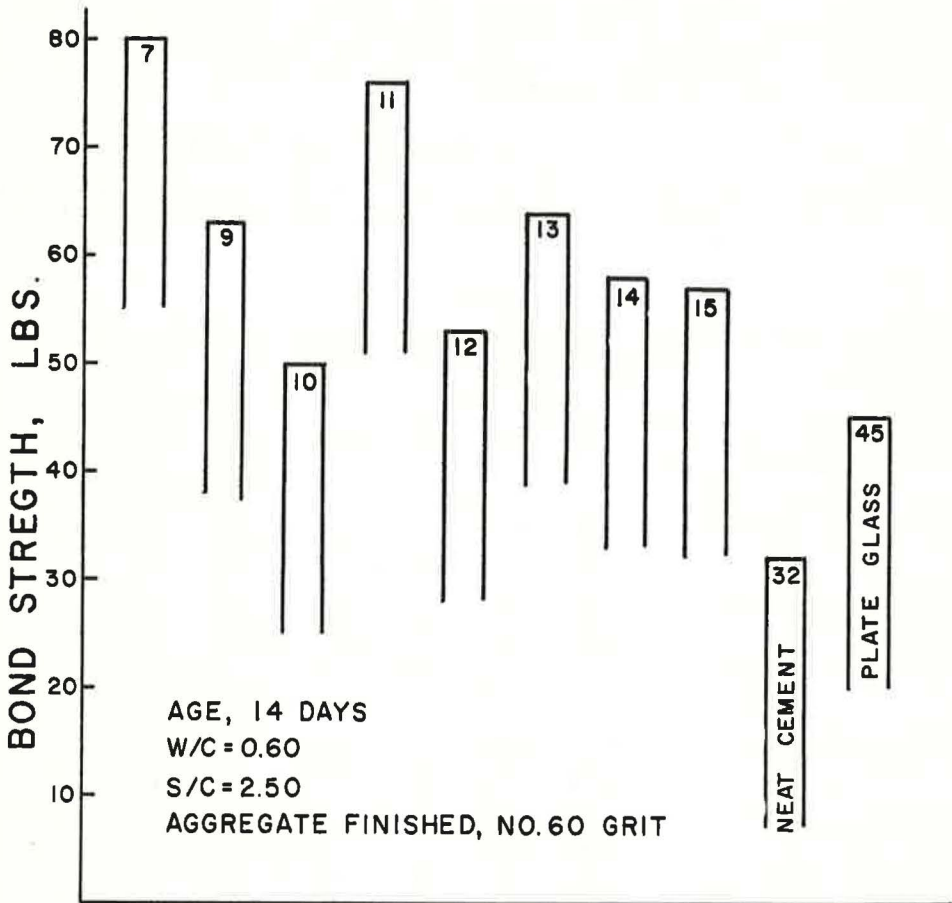


Figure 1. Mortar-aggregate bond variation with aggregate.

conditions. Several, however, were influenced by the surface in opposite ways. No statement as to the effect of surface finish on the mortar-aggregate bond of carbonate rocks can be made. Results on several rocks other than carbonates, notably the sandstones, indicated that surface finish was of greater importance to them. Other investigators have found a greater significance in the surface conditions under direct tensile tests (5).

It is the author's belief that these bond tests belie the true effect of surface in a practical condition of concrete because they cannot allow drying to take place in or on the test specimen. Aggregate surface may have considerable influence on the bond between mortar and aggregate in a condition where drying occurs. The rougher surfaces may well provide strong mechanical restraints upon shrinkage and its buildup of stresses at the mortar-aggregate interface.

The size of the mineral grains in the rock composing the aggregate was considered by the author in his investigations. Although a fine grained aggregate might be expected to have better bond due to the greater number of edges involved, the grain size

of carbonate aggregates did not influence the bond strength. This is based upon an investigation of three limestones of similar lithologic and chemical composition but with an average grain size of 0.01, 0.08 and 0.40 mm. Although significant difference in mortar-bond strength did exist, the low strength was with the intermediate grain size aggregate.

Insofar as the carbonate aggregates are concerned, no single property is easily relatable to mortar-aggregate bond strength. Evidence indicates that bond strength is influenced by the amounts of silica in the aggregate with a stronger chemical bond developing with the more siliceous aggregates.

EFFECT OF BOND ON THE MECHANISM OF COMPRESSIVE FAILURE

The results of the compression tests on 3 by 6-in. cylinders (Table 3) have been plotted versus the average mortar-aggregate bond strength of the coarse aggregate in

TABLE 3
RESULTS OF COMPRESSION TESTS WITH ROUNDED, ONE-SIZE, COARSE AGGREGATE
(3 × 6-Inch Cylinders, Age: 14 days)

No.	Aggregate Description	L/W	W/T	Cyl. No.	Sc (psi)	Inflection		Sc (psi)	SI (psi)
						Stress SI (psi)	Ratio (%)		
2	Jeffersonville (dolomite)	1.330	1.811	128	3,126	1,272	40.7	3250	1410
				129	3,281	1,697	51.7		
				130	3,338	1,272	38.1		
6	Liston Creek (dolomite)	1.409	1.518	115	3,055	2,744	78.7	3230	1940
				116	3,253	1,666	51.2		
				118	3,380	1,413	41.8		
9	St. Genevieve (limestone)	1.386	1.735	114	3,649	1,900	73.6	3140	1520
				117	2,730	1,305	47.8		
				119	3,027	1,344	44.4		
10	St. Genevieve (limestone)	1.337	1.533	134	3,479	1,131	32.5	3420	1460
				135	3,352	1,415	42.2		
				136	3,423	1,838	53.7		
13	Harrodsburg (limestone)	1.558	1.690	126	3,536	2,263	64.0	3250	2260
				127	2,956	2,261	76.5		
14	Geneva (dolomite)	1.372	1.553	131	2,999	1,697	56.6	3150	1930
				132	3,395	2,403	70.8		
				133	3,677	1,699	46.2		
15	Louisville (dolomite-limestone)	1.385	1.590	120	3,182	1,699	53.4	3150	1870
				121	3,005	2,353	78.3		
				122	3,253	1,555	47.8		
	Marbles (smooth)	1.00	1.00	104	1,641			1770	1340
				105	1,711	1,414	82.6		
				106	1,966	1,273	64.7		
	Marbles (rough No. 60)	1.00	1.00	107	2,546	1,980	78.0	2550	1760
				108	2,829				
				109	2,829	1,545	56.0		
				137	1,981				
	Mortar			110	4,653	1,697	36.5	4310	2810
				111	4,993	2,150	43.1		
				112	—*				
				113	—*				
				123	3,791	1,781	47.0		
				124	3,890	1,186	30.5		
				125	4,215	—**			
	Plexiglas			138	1,584			1420	
				139	1,259				

*Discarded due to defective molds.

**Impulse counting apparatus failed.

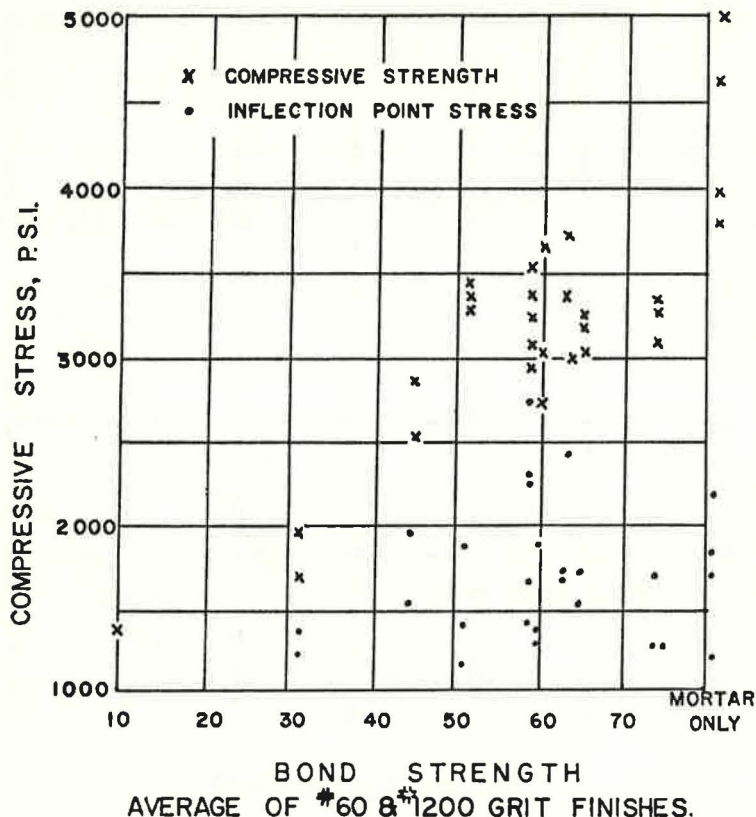


Figure 2. Compressive stresses vs bond strength at failure and inflection points.

Figure 2. Both glass marbles and pieces of plexiglas rod were used for aggregate to provide a range in bond strengths.

The values of bond strength for both plexiglas and mortar were not determined by bond tests for such tests could not be performed using these materials. The plexiglas formed too weak a bond to permit measurement although some bond did exist hence a value of 10 lb was selected as an estimate.

Due to difficulties in obtaining a perfectly true core when coring mortar, a problem not experienced in mineral aggregates, cores of mortar with no coarse aggregate did not perform satisfactorily in the test apparatus. The term bond strength is used for mortar although it is not a bond developed at an interface between two separate mortars. The bond strength for mortar without aggregate was selected in a manner similar to that used for the plexiglas. It was known that the mortar had a greater bond strength than most of the bonds. Some mortar failures occurred with aggregates having the higher bond strengths, hence it was assumed that the mortar's bond strength was not a great deal more, probably 80 lb or slightly higher.

The plot of the compressive test results vs the mortar-aggregate bond strength of the coarse aggregate shows that the influence of bond strength of the coarse aggregate on compressive strength is similar to its influence on flexural strength, which is discussed later in this paper. The carbonate aggregates produced concrete whose mean compressive strengths varied between 3,150 and 3,420 psi. These concretes are closely grouped compared to the mean compressive strength obtained for concretes made with marbles, 2,550 psi for roughened and 1,773 psi for the smooth marbles. The influence of bond is apparent, over the range of values included. The mortar cylinders, without coarse aggregate, are included in Figure 2 with the estimated bond strength for the

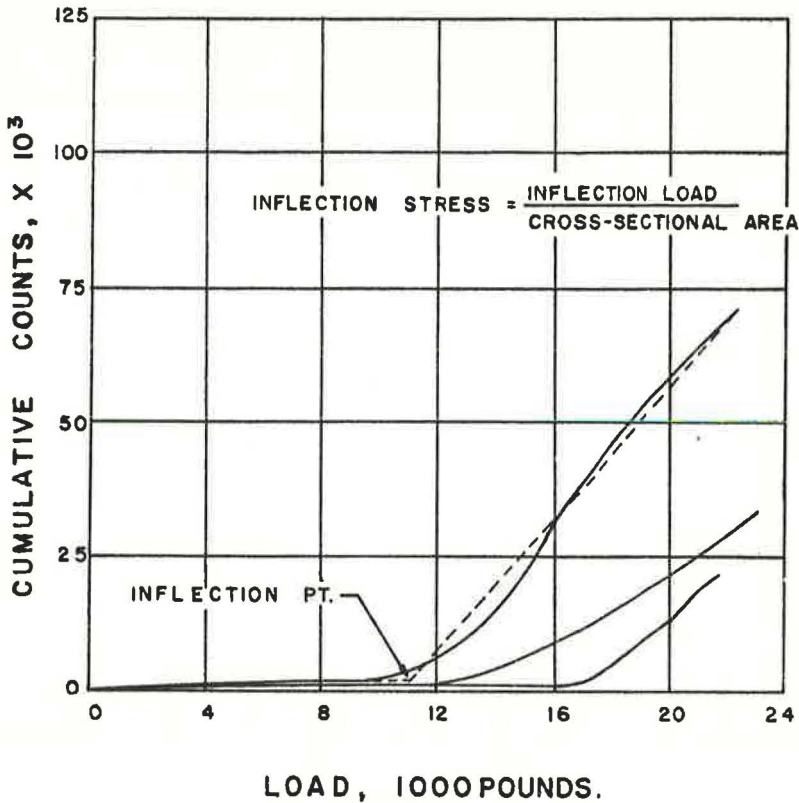


Figure 3. Cumulative impulse counts vs load in the compression of concrete cylinders.

mortar. The compressive strength was greater for concrete produced with a coarse aggregate having a greater mortar-aggregate bond strength if other factors remain unchanged.

MICROCRACKS RELATED TO BOND

The occurrence of microcracks in concrete is believed to occur most frequently at an interface between coarse aggregate and the mortar in a concrete (5). The location of these cracks, whether they exist before loading or form after load is applied, illustrates that the mortar-aggregate bond has broken at a load well below the ultimate load which will be sustained by the concrete. If intuition may be followed, it may be presumed that a stronger mortar-aggregate bond would delay the occurrence of these cracks, hence the concrete would be capable of sustaining heavier loads.

Investigations, by the author, of concretes made with rounded, one-size aggregates to reduce the effect of size, gradation, particle shape and particle texture indicate that low aggregate bond strengths do not necessarily mean a low stress level for the initiation of microcracks under compression loading.

Figure 3 illustrates typical results obtained using a vibration pickup to detect the occurrence of cracking impulses within a concrete specimen during a compression test. An electronic counter analyzer recorded the number of detectable impulses received. An oscilloscope was used in conjunction to obtain visibly a relative measure of the impulse picked up. Using this equipment, the initiation of cracking and its relative rate could be determined during a compression test of a specimen.

The plot of the inflection stresses obtained from the cracking impulse count data did not appear to be greatly influenced by the bond strength between the coarse aggregate

and the mortar. The inflection ratio or inflection stress/ultimate stress was generally greater for concretes whose coarse aggregate had the lower mortar-aggregate bond strength.

Data were not sufficient to be conclusive, but did suggest the following hypothesis for concrete failure.

When the mortar-aggregate bond strength characteristic is the only variable among aggregates, i.e., the aggregates have identical size, shapes, physical properties, etc., concrete made with these coarse aggregates and a mortar will form microcracks at a compressive stress that is primarily dependent upon the properties of the mortar. The amount of microcracking, as reflected by the increase in number of microcracks to reach incipient failure, is dependent upon the mortar-aggregate bond of the coarse aggregate.

The microcracks (separations) occurring in the concrete, as reflected by the impulse counts, take place at approximately the same rate (Fig. 3), once they commence. These microcracks occur in order to relieve stresses developing within the concrete. The initiation of cracking is dependent upon the formation of sufficient stress concentrations to cause microcracking or separations. If an increment of stress will be relieved by one crack, regardless of the mortar-aggregate bond involved, it becomes apparent that the area of separation required to relieve the increment of stress will be greater for concrete having the low mortar-aggregate bond. As the load on the concrete continues to be increased, the number of stress increments requiring relief will remain the same regardless of the mortar-aggregate bond. The total cumulative area of separation, however, will be greater for the concrete with the lower bond strength thus the condition in which the overall strength of the specimen is insufficient to withstand the load is reached at lower applied load for the concrete with the lower bond strength.

This hypothesis cannot be applied to the work of Jones and Kaplan (3) inasmuch as their aggregates were intentionally different in variables other than the bonding characteristics. One of their observations is nevertheless worthy of note and appears to be in agreement with the above hypothesis: "The relation between the flexural strength of concrete and the stress at which cracks first appear in compression was independent of the type of coarse aggregate." This suggests that other aggregate variables such as shape and physical properties may not greatly influence the initiation of microcracking.

Regardless of the mechanism by which mortar-aggregate bond contributes to strength, it has been shown that considerable variations in the bond strength will affect the compressive strength of concrete. The influence, however, is greatly overshadowed in concrete by the effect of the paste. Alexander related the compressive strength of concrete to paste strength and paste-aggregate bond strength. The compressive strength was a function of the expression, $B+2P$, where B equals the modulus of rupture of the cement aggregate bond and P equals the modulus of rupture of paste. Using the lowest bond strength, 700 psi, reported by Alexander (10) and his highest, 1,500 psi, with a constant paste strength would result in computed compressive strengths of 5,200 psi and 6,000 psi.

The author's investigation showed no appreciable difference in compressive strength for concrete made with the variety of carbonate aggregates. However, for special aggregates with lower bond strength a compressive strength change was noticeable. Relatively speaking, these results agree with those reported by Alexander, although the author emphasizes that what may be a statistically significant difference in aggregate bond strength will be of consequence in practical concrete only if the bond difference is very large.

The effect of bond on flexural strength is shown in Figure 4. The distribution of points indicated that the bond strength was indicative of the flexural strength. Some inconsistencies occurred but they did not disturb the overall trend.

Insofar as feasible, bond strength was the only variable, however, many other factors pertaining to the coarse aggregate may have influenced the strength of the concretes. If, for a given type of material, differences in bond strength of that material to a mortar

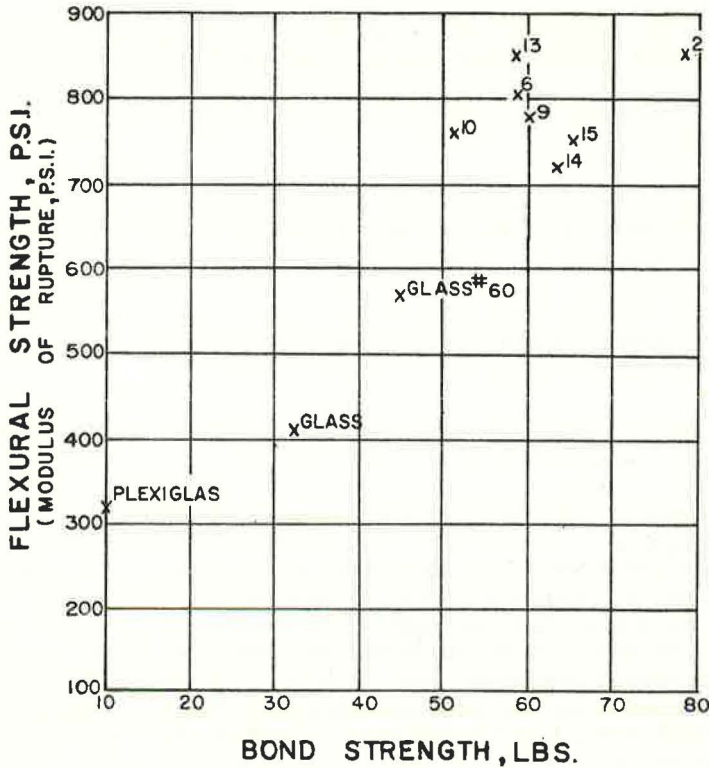


Figure 4. Bond strength vs flexural strength.

of a given composition is primarily dependent on surface finish, one would expect such differences to be reflected in the strength of concretes if bond affects strength. The glass marble aggregates were used for two different concretes with the only variable being the surface finish. It was gratifying to see that the relative positions for these concretes (Fig. 4) agreed well with the other results. Other factors being the same, the coarse aggregate with the greatest mortar-aggregate bond strength will result in the greater flexure and compressive strength for concrete.

If the bond strength values obtained in this investigation are converted to the modulus of rupture, the results of tests on concrete may be compared with those obtained by Alexander et al (10). The results agree reasonably well even though the type of bond test specimen was not the same.

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