ANISOTROPY OF CONCRETE AND ITS PRACTICAL IMPLICATIONS

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The influence of anisotropy induced by different methods of casting on the uniaxial tensile and compressive strength of concrete is illustrated, and it is shown that the strength of concrete cast with the axis of loading vertical is about 8 percent less for tension and 8 percent more for compression than that of corresponding concrete cast horizontally. Consequently, the ratio of tensile to compressive strength for concrete cast with the axis vertical is about 15 percent less than that for corresponding concrete cast horizontally. Some practical situations where a knowledge of these effects should influence the evaluation of concrete quality from tests on standard molded specimens, drilled cores, and sawed beams are also discussed.

• THE anisotropic behavior of concrete with respect to its compressive strength has been mentioned in papers published over the past 35 years. However, the opinions and conclusions expressed are not unanimous, different investigators having reached directly opposite conclusions on the sense of the anisotropy. Moreover, none of these investigations indicates whether anisotropic behavior occurs with respect to tensile strength. Only very recently has this problem received any attention. Nevertheless, a knowledge of the effects of anisotropy in both tension and compression is essential to an understanding of the relationships among the strengths of the various standard molded specimens, the strengths of specimens sawed or cored from in situ concrete, and the in situ structural strength in a particular direction. The present paper reviews and supplements previous information on anisotropy in compression, provides additional information on anisotropy in tension, and attempts to assess the influence of mix parameters. The more important practical implications of the conclusions are also discussed.

LITERATURE REVIEW

Neville in a 1959 report (1) illustrated the uncertainty regarding anisotropy at that time. He referred to the work of Gilkey and Leavitt (2), who reported the strength of mortar cubes cast with the axis vertical to be 9 to 13 percent less than that of cubes loaded in the standard manner, and to his own results for ⅜-in. aggregate concrete cubes, which suggested the difference to be 4 to 7 percent in the same sense, although in some cases it was not statistically significant. Neville also mentioned contrary conclusions reached by Mercer (3), who reported a difference of 10 to 20 percent in the opposite sense for mortar cubes, and Johnson (4), who reported the value to be about 5 percent for concrete cylinders. Thus, four separate investigations were equally divided between opposing conclusions at this time. The cause of the discrepancy is not obvious, although it seems possible that capping in the three investigations involving cubes cast with the axis of loading vertical may have been a contributory factor. However, work by L'Hermite (5), who reported a similar difference of 13 percent for cubes, by Bloem (6), who reported an average value of 15 percent for

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cylinders regardless of whether the specimens were capped on both ends, and more recently by Petersons (7), who reported a value of 12 percent for cores, has substantially supported the conclusions of Mercer (3) and Johnson (4) that specimens cast with the axis of loading vertical are stronger in compression than those cast with the axis of loading horizontal. Moreover, it has added weight and generality to their conclusion because of the similar trends observed for cubes, cylinders, and cores.

TEST PROGRAM

The schedule of 23 mixes, given in Table 1, was adopted to permit investigation of the individual influence, if any, of slump, water-cement ratio, and aggregate maximum size on the results. Six 30-in. long prisms made using type 1 cement and gravel aggregate (except as marked) were cast from a single batch of each mix, three with the axis of loading vertical and three with the axis horizontal. The cross sections were 6 x 6 in. for mixes with $1\frac{1}{2}$-in. aggregate and 4 x 4 in. for mixes with $\frac{3}{4}$- or $\frac{3}{8}$-in. aggregate. After the mixes had been moist-cured for 28 days, the uniaxial tensile strength was determined by using a friction grip technique described and analyzed in detail by Johnston and Sidwell (8). The uniaxial compressive strength was determined by using prisms of a height-width ratio 2.0 sawed from fractured sections of the tension specimens, thus eliminating the problem of capping and its possible influence on the results. All strengths quoted are mean values calculated from three tests.

RESULTS AND DISCUSSION

The results for uniaxial tension (Fig. 1) show that the tensile strength of specimens cast with the axis of loading vertical is generally less than that of corresponding specimens cast horizontally. In compression, on the other hand, the strength of specimens cast with the axis vertical is generally greater than that of specimens cast horizontally, as shown in Figure 2. Thus, the effects of anisotropy in tension and compression are opposite in sense. However, the magnitude averages 8 percent in both cases for the 23 mixes. Although no comparative data are available for uniaxial tension, the value of 8 percent for compression is considerably less than the 18 percent calculated from the 8 mixes tested by Bloem (6). The difference is possibly attributable to inadequate compaction associated with the special horizontal cylindrical molds used in his work.

Comparison of mean strengths for both directions of casting to determine the statistical significance of the strength differences shows that the variances do not differ significantly in the F-test, a condition that must be fulfilled before applying either form of the t-test. Whereas the general t-test for difference of means fails to show a difference with a reasonably high probability of being correct, the more discriminating t-test for paired related data shows that the mean difference between the strengths of the two sets of specimens is highly significant, the probability level exceeding 99.9 percent for both tension and compression. Inasmuch as the mean strengths compared for each mix were derived from a single batch of concrete, the latter test is clearly valid, and the result adds strong statistical support to the conclusions visually evident in Figures 1 and 2.

The generality of these conclusions can be qualitatively illustrated for a much wider variety of mixes by comparing the ratio of tensile to compressive strength for specimens cast with the axis of loading vertical to the corresponding ratio for specimens cast horizontally. This comparison tends to accentuate the dissimilarity in the strength characteristics of the two types of specimens because the strength differences for tension and compression are of opposite sense. Thus, if the mean percentage difference of 8 percent for both tension and compression is assumed, the strength ratio for specimens cast with the axis of loading vertical should be about 15 percent [$(1 - 0.08)/(1 + 0.08) = 0.85$] less than for corresponding specimens cast horizontally. Comparison of the best-fit curves representing the two visibly distinguishable bands of data shown in Figure 3 reveals that this is essentially true over the normal range of compressive strength. And it is significant that, although the data from other investigations (8, 9, 10, 11) do not represent corresponding mixes and include a wide variation in water-cement ratio, aggregate maximum size, grading, and type, parameters that have been

Table 1. Mixes used in investigation.

Aggregate Size (in.)	Slump (in.)	w-c = 0.35 Tension	w-c = 0.35 Compression	w-c = 0.45 Tension	w-c = 0.45 Compression	w-c = 0.55 Tension	w-c = 0.55 Compression	w-c = 0.65 Tension	w-c = 0.65 Compression
1½	0	1.015	1.123					0.902	1.147
	2	0.989	1.036	0.958	1.086	0.988	1.000	1.049	1.157
	4	1.010	1.122					0.937	1.051
¾	0	0.841	1.047					0.924	1.169
	2	0.907	1.070	0.844	1.082	0.928	1.037	0.899	1.052
	4	0.856	1.072					0.878	1.049
⅜	2	0.931	1.107	0.972	1.094	0.872	1.098	0.852	1.025
¾[a]	–[b]	0.881	1.177	0.779	0.945	0.900	1.116		

[a]Crushed basalt aggregate. [b]Not recorded.

Figure 1. Comparative tensile strengths of specimens cast vertically and horizontally.

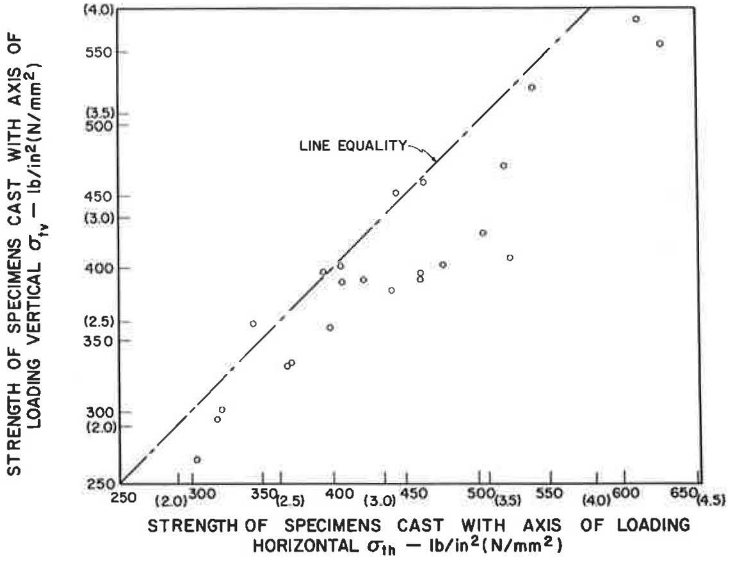
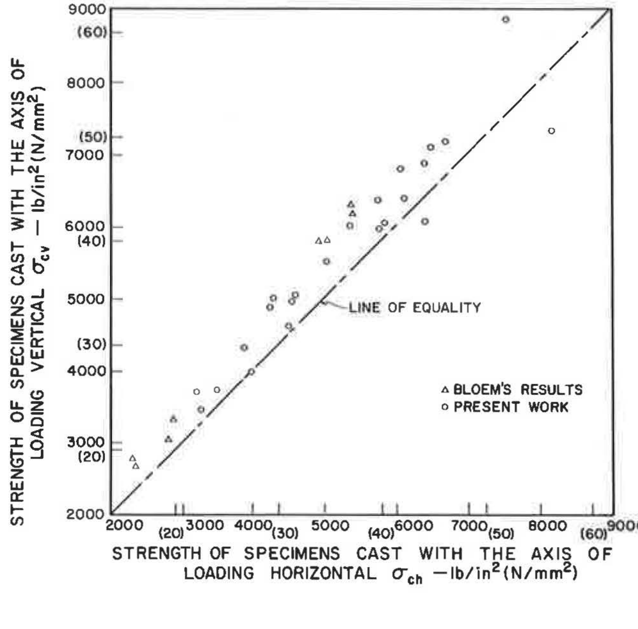


Figure 2. Comparative compressive strengths of specimens cast vertically and horizontally.



shown to influence the ratio (8), the overriding influence of direction of casting is still apparent. Also, the inaccuracy of using general rule-of-thumb factors to estimate tensile strength from the results of compression tests is again emphasized.

The strength differences associated with each mix are given in Table 1. The range of the data is quite large because both mean strengths are subject to a coefficient of variation that averaged 5.4 percent for tension and 6.4 percent for compression, and it is only when averages are calculated with respect to each mix parameter, as given in Table 2, that the influence of aggregate size, slump, and water-cement ratio can be assessed. From these values, it is evident that the magnitude of the strength differences associated with anisotropy is not clearly dependent on any of these mix parameters and for practical purposes can be regarded as constant and equivalent to 8 percent for normal weight structural concretes. Water gain, or the tendency of water to concentrate underneath the aggregate particles as cast (thus creating areas of weak cement-aggregate interface), a phenomenon first observed by Gilkey (12), seems to explain the observed trends. His statement that it occurs "even in relatively dry and stiff mixtures" is compatible with the lack of influence of mix parameters, and the opposite sense of the strength differences in tension and compression can be explained as follows. In a tension specimen cast with the axis of loading vertical, the weak interface is primarily parallel to the failure surface, thus lowering the strength relative to that of a corresponding specimen cast horizontally in which the interface is perpendicular to the failure surface. In contrast, in a compression specimen cast with the axis of loading vertical, the weak interface is primarily perpendicular to the longitudinal cracks that induce failure, thus tending to increase the strength relative to that of a corresponding specimen cast horizontally in which the interface is parallel to the failure cracks. These areas of weak interface are clearly visible as whitish zones on the failure surface of the lower portion of a vertically cast prism tested in tension and are not present on the failure surface of the upper portion, as shown in Figure 4.

PRACTICAL IMPLICATIONS

Assuming that the strength difference associated with anisotropy is about 8 percent for both tension and compression, as reported above, its influences on the evaluation of concrete properties in practice are as follows:

1. The relationship between the compressive strength of drilled cores and standard molded cylinders is subject to the effect of anisotropy when the direction of coring is horizontal, as is normal for vertical walls and columns, but not when it is vertical as in the case of slabs and pavements. Therefore, application of a correction factor of about 0.92 is appropriate in the former case, not merely a report of the direction of loading with respect to the horizontal as required by ASTM C 42. Furthermore, if the core strength is to relate to in situ strength in the direction of applied stress, rather than standard cylinder strength, a correction factor of 0.92 should be applied to the core strengths in the case of slabs and pavements and a factor of 1.08 in the case of walls and columns.
2. The relationship between the splitting tensile strength of cores and standard cylinders is not subject to the influence of anisotropy when the cores are drilled vertically, as for slabs and pavements, but could be affected by it in varying degrees depending on the test orientation when the cores are drilled horizontally, as for walls and columns. This latter situation is probably rare (e.g., the vertical walls of a pressure vessel), inasmuch as the splitting test is normally applied only to pavement work.
3. The relationship between the flexural strengths of sawed and molded beams with their longitudinal axis parallel to the slab or pavement is not subject to the influence of anisotropy. However, the value for compressive strength measured using portions of broken beams, as described in ASTM C 116, depends on whether the specimen is loaded top-to-bottom or side-to-side, the latter case giving a lower value. The specification allows either condition for square cross sections and requires the top-to-bottom condition when the depth-breadth ratio is greater than unity and the side-to-side condition when the depth-breadth ratio is less than unity. Realistic interpretation of

Figure 3. Influence of direction of casting on the ratio of uniaxial tensile to compressive strength [Komlos' data (11) based on uncorrected cube strengths].

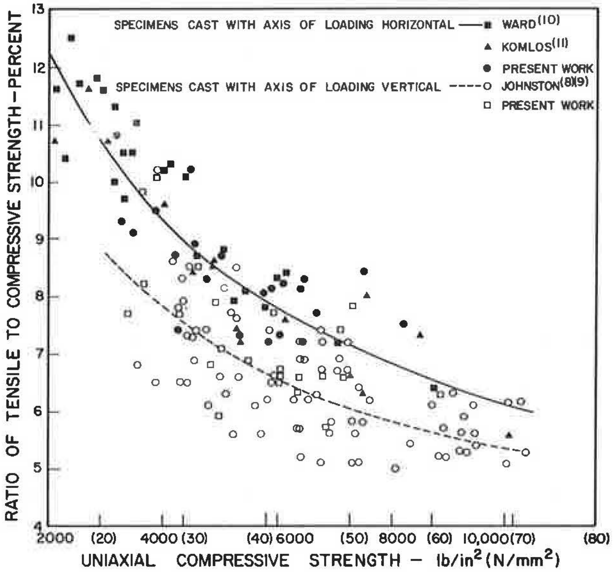


Figure 4. Failure surfaces in a vertically cast prism after testing in uniaxial tension.

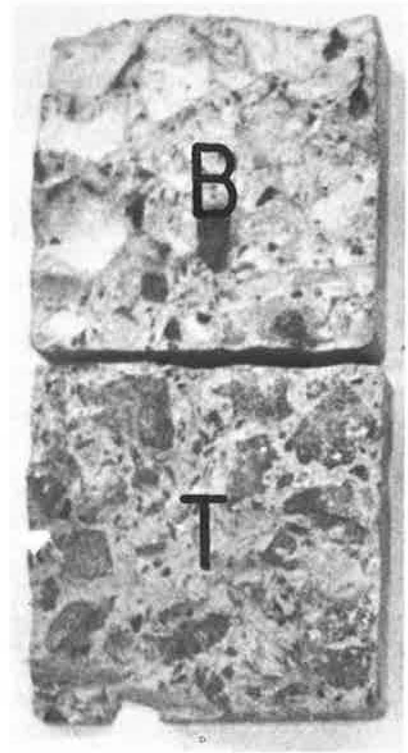


Table 2. Average values of ratio of the strengths of vertically cast prisms to those of horizontally cast prisms.

	By Aggregate Size (in.)			By Water-Cement Ratio				By Slump (in.)			
Test	1½	¾	⅜	0.35	0.45	0.55	0.65	0	2	4	Overall
Tension	0.981	0.875	0.907	0.929	0.888	0.922	0.920	0.921	0.932	0.920	0.918
Compression	1.090	1.074	1.081	1.094	1.052	1.063	1.093	1.060	1.070	1.074	1.080

the results therefore requires making appropriate corrections to account for the effects of both height-width ratio and anisotropy in each particular case.

4. With regard to the cube specimen used as a standard in other countries or in research work to measure compressive and splitting strength, the relationship between cube and cylinder compressive strength is subject to the opposing effects of anisotropy and height-width ratio, the latter being strength-dependent. In addition, the splitting strength depends on whether the cube is loaded top-to-bottom or side-to-side, the latter case giving a lower value, as shown recently by Soshiroda (13).

CONCLUSIONS

1. The strength of concrete cast with the axis of loading vertical averages 8 percent less for tension and 8 percent more for compression than that of corresponding concrete cast horizontally.
2. The magnitude of the strength difference is independent of aggregate size, water-cement ratio, and slump.
3. The ratio of tensile to compressive strength for concrete cast with the axis of loading vertical is about 15 percent less than that of corresponding concrete cast horizontally.

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