Magazine of Concrete Research : Vol. 23, No. 77 : December 1971

Comments on the long-term strength of plain concrete*

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Contribution by J. Bhargava, DrTech

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Dr Komloš has presented some very useful data for the tensile and flexural strength of concrete at various ages. I feel that the use of term 'long-term strength' to denote the strength at different ages can be misleading. The term is mostly used to denote the strength under sustained or 'long-term' loading, and has been used in this sense in connection with studies of the rheological behaviour of concrete.

It is not clear what the moisture condition of the specimens was at the time of the test, especially in the case of specimens tested at later ages. Were these specimens tested in a saturated surface-dry condition, or were they allowed to stand in the laboratory air (at a lower humidity) for some time before the test? This is of significance for the analysis of the results such as the ratio of tensile strength to cube strength at various ages.

Dr Komloš's results confirm the observation made by earlier investigators that there is a significant difference between the rate of deceleration of the development of various strengths of a concrete[1,2]. It had been observed by Popovics[3] that the effect of change in water/cement ratio was relatively less for the flexural and tensile strengths than for the compressive strength; a possible mechanism, based on the difference between the slow crack propagation under tension and compression, was proposed by him[4]. A similar trend can be seen in Dr Komloš's results for tensile strengths, although the difference in the case of flexural and compressive strengths is relatively much less.

Alkalis present in the cement have a significant influence upon the development of strength with age[5,6]. From the chemical composition of the cement given by Dr Komloš, the cement appears to be alkali-free. I would like to know whether Na_2O/K_2O content was determined. It would also be of interest to know the specific surface of the cement used. The increase in the cube strength, between 90 and 360 days, was rather large in Dr Komloš's tests (see Table I). These values are substantially higher than the values generally obtained with modern Portland cements[1].

TABLE I: **Cube strength ratios.**

	Water/cement ratio		
	0·40	0·52	0·63
σ_{90}/σ_{28}	1·224	1·003	1·307
σ_{180}/σ_{28}	1·381	1·476	1·736
σ_{360}/σ_{28}	1·635	1·527	1·727

Contribution by C. D. Johnston and M. A. Ward

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We would like to comment on several of the relationships and conclusions given in Dr Komlos's paper in the light of our earlier work[7-9]. We feel that the impression given in his concluding paragraph, that the ratio of tensile to compressive strength is dependent only upon the age of the concrete, presents an incomplete picture of the changes in this ratio which can occur and the contributory factors. Dr Komloš's results show that the ratio decreases with increasing age, whilst Figure 7 of reference 7 shows that it decreases with decreasing water/cement ratio. Both these parameter changes are responsible for a major increase in the over-all strength of the concrete, and, on the basis of the combined data[7-9] shown in Figure I, it can be concluded that the ratio of tensile to compressive strength is mainly dependent upon the magnitude of concrete strength rather than any single parameter, at least for concretes with a similar aggregate grading. This conclusion appears justified for a general relationship in view of the wide range of parameter variation represented in the Figure, age, water/cement ratio and aggregate/cement ratio in Komloš's data, water/cement ratio, aggregate/cement ratio and aggregate type in Ward's[8] data and water/cement ratio,

*Pages 232–238 of *Magazine* No. 73

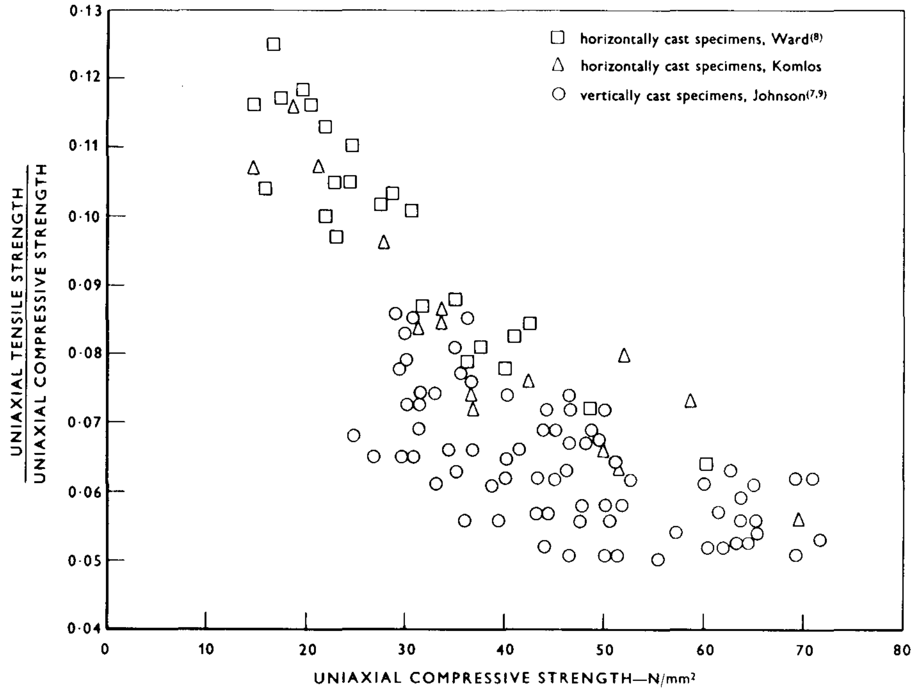

Figure 1: Relationship between compressive strength and the ratio of tensile to compressive strength.

aggregate maximum size, grading and type in Johnston's[7,9] data. However, the ratio is not solely strength-dependent, because Figure 7 of reference 7 and Ward's[8] results for mortars show that a decrease in the mean aggregate particle size, a parameter change responsible for a minor increase in strength[9], results in a greater rather than a lesser value of the strength ratio. In addition, whilst it is not strictly correct to compare Komloš's values with the other data because his compressive strengths are based on cubes rather than prisms, it should be noted that any correction would tend to raise each data point slightly and would further distinguish the trend for the horizontally cast specimens of Komloš and Ward[8] to give values of the ratio noticeably higher than those for the vertically cast specimens of Johnston[7], particularly at lower levels of compressive strength. Thus, the influence of direction of casting and mean aggregate particle size are certainly separate and distinguishable from that of strength alone.

Turning now to the relationship between splitting tensile strength and uniaxial tensile strength, we would like to point out that, whilst the relationship shown in Figure 7 of Dr Komloš's paper holds true for his particular mixes, in which the aggregate maximum size and grading appear to have remained constant, it would probably not be applicable to mixes containing much smaller or much larger aggregate. Figure 8 of reference 7 clearly shows that the difference between splitting tensile strength and uniaxial tensile strength for specimens similar to those of Dr Komlos increases as the mean aggregate particle size increases. In other words, the slope of the relationship given in Figure 7 of Dr Komloš's paper can be expected to increase as the proportion and maximum size of the aggregate in the grading increase.

In conclusion, we would like to state that caution should be exercised in developing general correlations between the results of different strength tests, as it has been proved that, whilst the relationships obtained by different investigators are qualitatively similar, they can differ quantitatively due to differences in materials, mix parameters and casting and testing techniques.

CORRIGENDA

notified by A. B. Lingam, BSC, BE and G. Ramakrishna, BE

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The second and following lines on page 238 should read as below, and corresponding corrections apply to Figures 6 to 9 on the previous page.

cube strength and direct tensile strength:
$f_t = 1{\cdot}2568 + 0{\cdot}0445 f_c$; $r_{tc} = 0{\cdot}921$
cube strength and splitting tensile strength:
$f_s = 1{\cdot}1750 + 0{\cdot}0477 f_c$; $r_{sc} = 0{\cdot}992$
cube strength and flexural strength:
$f_f = 1{\cdot}7525 + 0{\cdot}1142 f_c$; $r_{fc}' = 0{\cdot}947$
direct tensile strength and splitting tensile strength:
$f_s = 0{\cdot}9332 f_t = 0{\cdot}2404$; $r_{st} = 0{\cdot}943$
direct tensile strength and flexural strength:
$f_f = 2{\cdot}3933 f_t - 0{\cdot}9584$; $r_{ft} = 0{\cdot}958$
splitting tensile strength and flexural strength:
$f_f = 2{\cdot}4335 f_s - 1{\cdot}1794$; $r_{fc} = 0{\cdot}965$

Reply by the author

I am grateful to Dr Bhargava, and Dr Johnston and Dr Ward, as well as to Mr Lingam and Mr Ramakrishna, for their discussion of some of the assumptions and results of my paper.

I agree with Dr Bhargava that the term 'long-term strength' is mostly used in connection with studies of the rheological properties of concrete under sustained loading. Nevertheless, this term was used to avoid the term 'strength of concrete at various ages', which seemed to me a little bit too clumsy.

The specimens were not allowed to stand in the laboratory air for some time before the test. They were tested immediately after they had been taken out of the curing chamber.

It is a well-known fact that the kinetics of strength increase of concrete are to a high degree dependent upon the kind of cement used. The cement used in our investigations was not a pure Portland cement and so not comparable with the cement mentioned in Popovics's paper. The specific surface of the cement applied in our tests was 3400 cm^2/g (according to the Blaine method). The Na_2O/K_2O content was not determined.

In connection with the contribution by Dr Johnston and Dr Ward, I would like to point out that I did not want to give in my paper the impression that the ratio of tensile to compressive strength is dependent only upon the age of the concrete. My aim was to show that the age of concrete is an important factor influencing this ratio. On the other hand, I agree with Dr Johnston and Dr Ward that the age of concrete is not the most important factor, but only one among many others. I am also of the opinion that the maximum particle size of the aggregate influences the relationship between splitting tensile strength and uniaxial tensile strength.

Dr Johnston and Dr Ward state in their conclusion that caution should be exercised in developing general

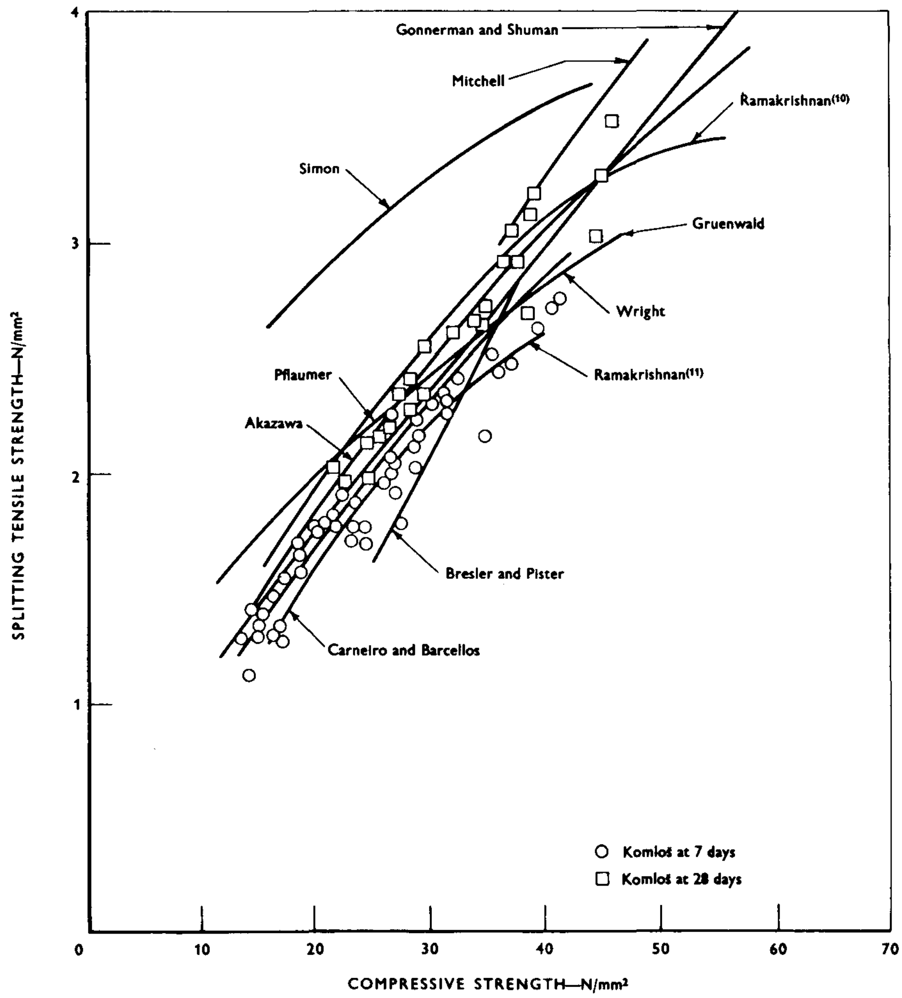

Figure 11: Relationship between splitting-tensile and compressive strength according to various authors, and results by Komloš.

correlations between the results of different strength tests. I agree with Dr Johnston and Dr Ward that the results differ owing to differences in materials, mix parameters and casting and testing techniques. However, I think that it will be very difficult to include all these factors in a general correlation formula[10-12]. The relationships between strength characteristics of concrete have been studied by many investigators and the results of their investigations differ to a greater or lesser extent. As an example, I would like to show some relationships between splitting-tensile and compressive strength obtained by various authors:

Ramakrishnan (normal concrete)	$f_s = \dfrac{f_c}{20} + 8$
Ramakrishnan (lightweight-aggregate concrete)	$f_s = \dfrac{f_c}{15} + 6$
Akazawa	$f_s = 0{\cdot}675 f_c^{0{\cdot}730}$
Carneiro and Barcellos	$f_s = 0{\cdot}554 f_c^{0{\cdot}735}$
Vinayaka	$f_s = 0{\cdot}880 f_c^{0{\cdot}716}$
Ramesh and Chopra	$f_s = 2{\cdot}172 f_c^{0{\cdot}604}$
Sen and Bharara	$f_s = 0{\cdot}2345 f_c^{0{\cdot}84}$
Sen and Desayi	$f_s = 0{\cdot}628 f_c^{0{\cdot}73}$
Dewar	$f_s = 1{\cdot}23 f_c^{2/3}$
ACI Building Code 318-63	$f_s = 5{\cdot}4 f_c^{0{\cdot}5}$
Evans	$f_s = 0{\cdot}056 f_c + 7$

where f_s = splitting tensile strength, f_c = compressive strength.

Some other relationships can be found in Figure II. The above survey of formulae indicates that it will not be easy to find a common basis for a unified expression of the relationships.

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