Estimation of Coarse Aggregate Strength in High-Strength Concrete

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The discussers congratulate the authors for their timely paper on the nowadays very active research subject in the concrete literature, namely high strength concrete. The paper which discloses the effects of aggregate physical and mechanical characteristics on the strength of concrete is impressive and remarkable.

In the classical concrete literature, effect of aggregate on concrete is limited to the workability considerations. In selection of the aggregate, workability is the fundamental consideration and it is controlled by the grain size distribution and surface texture of the aggregate. By increasing the maximum aggregate size, or fineness modulus of the coarse+fine aggregates, provided that the maximum slump limits are satisfied, the water demand of the mixture will be decreased. This will lead to a decrease in the water/cement ratio (*w/c*), leaving the other mix components unchanged and according to the famous Abraham's rule, to an increase of the concrete strength for the same mixture. However, this increase will be very limited. After 1980's, especially with wider application of high strength concrete (>40 MPa); apart from the aggregate gradation (max. aggregate size, fineness modulus, surface texture), physical (water absorption, porosity, density) and mechanical properties of the aggregate gained importance for the following reasons:

- Physical characteristics of the aggregate effect its mechanical properties (compressive and tensile strength, modulus of elasticity, poisson ratio) [20, 21].
- Ductility of the concrete is very sensitive to the modulus of elasticity of the concrete (E_c) in ascending and descending portions of the concrete strength-strain diagram, and E_c is a function of the aggregate's modulus of elasticity and the volumetric ratios of the aggregate and the mortar [11, 22,23,24].
- In calculating capacity of high strength concrete columns, factor K in the basic equation $\mathbf{f(\varepsilon_o)= f_1+K\ f_r}$ is taken as 4.1 in the classical approach. However, it is shown through recent experimental research that it is possible to obtain different values of K by changing the aggregate type, i.e. mechanical properties of the aggregate[25].

The discussers wish to make the following contributions to the subject:

- Fig. A depicts the best fit equations showing the porosity-density-uniaxial strength relationships for the aggregate, which are derived by means of regression analysis. In the regression analysis, the untreated data from ref..26 (p.38) was used. Density of aggregates increase with decreasing porosity (Fig.A). In other words, if the linear relationship between the porosity and the water absorption is considered, with decreasing water absorption, density of the aggregate increases.

Therefore, a low degree of water absorption is required of the aggregate for obtaining a high aggregate compressive strength.

- With increasing density, compressive strength of the aggregate increases exponentially (Fig.A). This increase is significant for the aggregate densities larger than 2.5 g/cm^3. For a good quality aggregate of density 2.6 to 2.7 g/cm^3, the corresponding strength of aggregate can be predicted as averaging 100 and 130 MPa, respectively, from the equations given in Fig.A. Additionally, the Popovics equation[27] is depicted in the same figure for comparison. It is interesting to note that the Popovics equation is approximately averaging the equations derived for the lower and upper limit values of aggregates, thus in a reasonable agreement with equations derived in this study. The authors' experimental results are also presented within each graph on a reproduction of the curves. The authors' data can be seen in good agreement with the equations derived in this study.

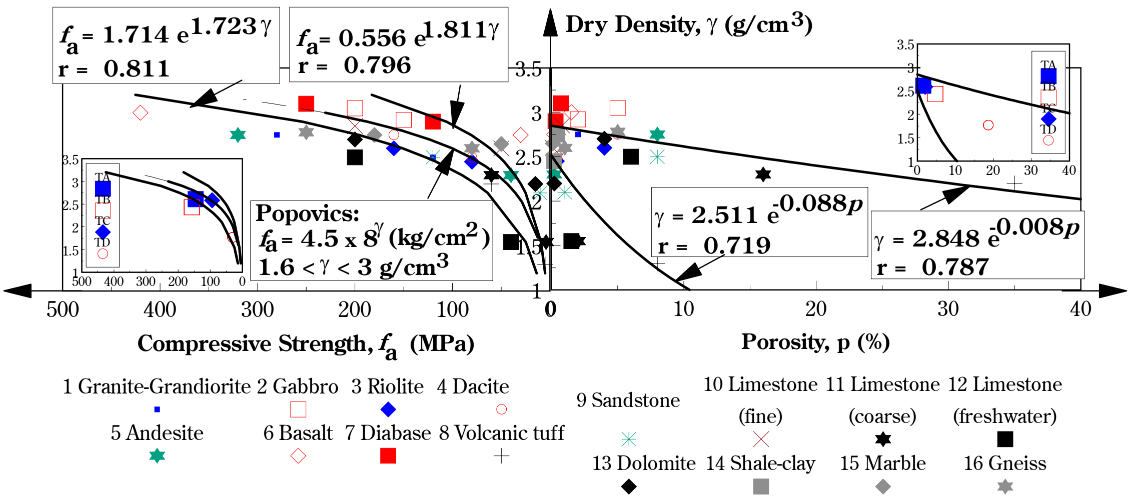
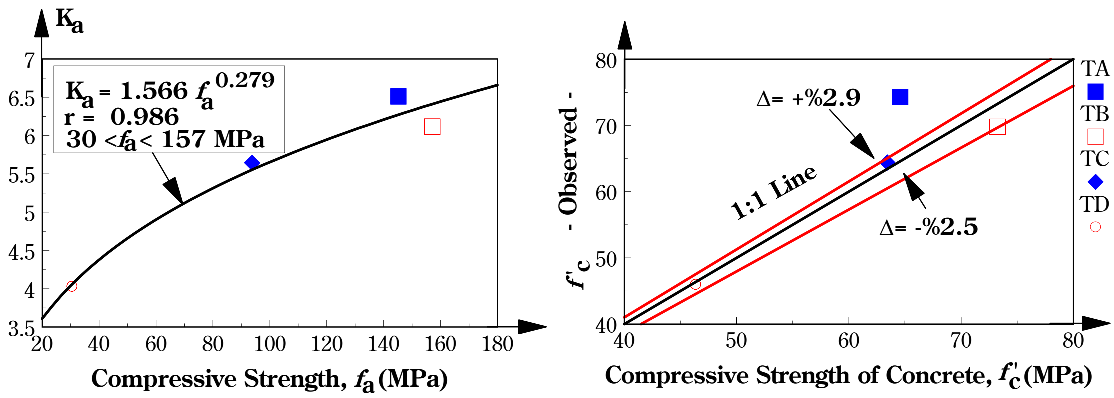


Fig. A–Relationships between the aggregate's physical and mechanical properties

- Effect of aggregate compressive strength on the compressive strength of concrete can be analytically expressed by the De Larrard's equation, which is a modified version of the Féret's equation to be applicable for high strength concrete (Eq.A., Table A). The K factor in the equation is a function of the following factors: strength of cement (chemical composition, fineness modulus), factors peculiar to the -coarse+fine- aggregate used (physical and mechanical properties), compaction type and duration of concrete, curing condition (heat and humidity) and curing age of concrete. Effect of aggregate strength can be numerically determined, when all these factors are kept constant and the aggregate strength is varied. For this, taking the *w/c* ratio as 0.3 and using De Larrard's equation for β=0, K_a factors corresponding to the given 28 day strength data are calculated and plot against the compressive strength as shown in Table A. Thus, using this procedure, keeping the mix composition constant, K_a factors can be calculated for each different type of aggregate. The curve fitted to K_a - $f'_{c,28}$ relation shows that for the 30 to 100 MPa concretes K_a factor increases with a higher rate than for concrete with strength larger than 100 MPa. It is hereby shown that, for a constant *w/c* ratio, it is possible to obtain significant increase of the concrete compressive strength by increasing the aggregate compressive strength. In the high strength concrete production that promotes a potential of achieving higher strength more economically by using aggregates with enhanced physical and mechanical characteristics (low water absorption, low porosity, high density, high strength, high modulus of elasticity).

Table A- De Larrard equation and representation of the aggregate factor K_a in terms of aggregate compressive strength



De Larrard Equation[28]:

$$f'_{c,28} = \frac{K_a 42.5}{\left[1+3.1\frac{w/c}{1+0.15K_{sf}\left[1-\exp(-11\beta)\right]}\right]^2} \qquad \text{(A)}$$

For β=0 and using the regression equation above, Eq.A becomes: (B)

$$f'_{c,28} = \frac{1.566 f_a^{0.279} 42.5}{\left[1+3.1w/c\right]^2}$$

where:

$f'_{c,28}$ = 28 days compressive strength of concrete, MPa

K_a = Aggregate factor

f_a = Aggregate uniaxial strength, MPa

K_{sf} = Silica fume factor

w/c = Water/cement ratio (by weight)

42.5 = Corresponds to 28 -days strength of cement used, MPa

β = Silica Fume/Cement Ratio (by weight)

- It is interesting to note that when the lower limit density of limestone fine of 2.6 g/cm^3 is considered, the lower limit compressive strength is obtained as 62 MPa and the corresponding K_a factor is calculated as 4.95. This value is in close agreement with the K_a factor proposed by De Larrard[29] as 4.92 for limestone.

In passing, De Larrard's equation is successfully used for mix design for high strength concrete in the research project of Yapı Merkezi Inc. for production of 10 cm cube, 28 day strength of 160 MPa concrete (≅138 MPa ϕ15x30 cm cylinder strength -steel molds-). In the aforementioned study[30], Seyhan diabase (γ=2.78 g/cm^3;water absorption=0.96%) was used in the concrete mix (*w/c*=0.25; β =0.25 by weight Σaggregate= 1079 kg/m^3; Σaggregate/c= 1.96). K_a factor was estimated for Seyhan diabase as 7.60 in this previous research[30].

The writers would like to conclude that, development of the K_a concept proposed in this discussion (Table A), through additional empirical research will make a significant contribution to concrete literature.

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