Studia Geotechnica et Mechanica, Vol. XXIX, No. 3–4, 2007

EFFECT OF STANDARDIZED AGGREGATE SIZE ON THE PARAMETERS OF CONCRETE IN VARIOUS WATER-SATURATION STATES

MICHAŁ SZCZEŚNIAK

Institute of Civil Engineering, Wrocław University of Technology,
50-370 Wrocław, Wybrzeże Wyspiańskiego 27, Poland.

NICOLAS BURLION, JIAN FU SHAO

Laboratoire de Mécanique de Lille, UMR CNRS 8107, Polytech'Lille, France.

Abstract: The strength of cement-based composites is influenced by several factors. The three chosen for the study are: water saturation of cement matrix, aggregate diameter and volume fraction of particles. It is assumed that in cement-based composites, where water violently reacts with cement powder during hydratation process, different water saturation of composites can be achieved by their drying or saturating under moderate conditions, which changes free water content. Particle diameter influences the strength of the composites tested. This is attributed to stress concentration around the particles. In the case of smaller particles, better distribution of stresses is observed and in the case of relatively big particles, serious cracks are locally distributed. As a result, after exceeding a certain value of the parameter $L1/L3$ (the minimum sample length to the particle diameter ratio), no further strength loss is observed. On the other hand, at a smaller diameter, strength continues to grow but no exact limit of this growth is identified. The third parameter, i.e., the volume fraction of the particles, is fixed macroscopically at 35% and 59%.

Streszczenie: Wytrzymałość kompozytów z cementową matrycą zależy od wielu czynników (m.in. termicznych, hydrologicznych i mechanicznych). Spośród głównych z nich do analizy wybrano stopień nasycenia wodą matrycy cementowej, średnicę kruszywa oraz jego zawartość objętościową. Założono, że w kompozytach cementowych, w których woda reaguje z cementem, kolejne stany hydratacji kompozytu osiąga się, susząc go lub nasycając wodą w warunkach umiarkowanych. Znajduje to odzwierciedlenie w zmianie zawartości m.in. wody wolnej w matrycy cementowej. Średnica cząstek kruszywa wpływa na wytrzymałość kompozytu. Jest to związane z koncentracją naprężeń wokół kruszywa i w nim. W przypadku mniejszych cząstek występuje lepsza redystrybucja naprężeń. W przypadku większych cząstek dochodzi do intensyfikacji i lokalizacji uszkodzenia. Po przekroczeniu pewnej wartości parametru $L1/L3$, czyli proporcji najmniejszego wymiaru próbki do średnicy kruszywa, nie obserwuje się dalszego zmniejszania wytrzymałości w funkcji średnicy kruszywa. Gdy $L1/L3$ maleje, obserwuje się ciągły wzrost wytrzymałości; w pracy nie wyznaczono ograniczenia tego wzrostu. Trzecim analizowanym parametrem jest udział objętości kruszywa, który makroskopowo wynosił 35% i 59%.

Резюме: Устойчивость композитов с цементной матрицей зависит от многих факторов (м.др. термических, гидрологических и механических). Из главных из них для анализа были выбраны степень насыщения водой цементной матрицы, диаметр заполнителя, а также его объемное содержание. Было предположено, что в цементных композитах, в которых вода реагирует с цементом, очередные состояния гидратации композита достигаются посредством его сушки или насыщения водой в умеренных условиях. Это отражается в изменении содержания м.др. свободной воды в цементной матрице. Диаметр частиц заполнителя влияет на устойчивость композита. Это связано с концентрацией напряжений вокруг заполнителя и в нем. В случае меньших частиц выступает лучшее перераспределение напряжений. В случае больших частиц доходит к интенсификации и размещению повреждения. После прекращения некоторого значения параметра $L1/L3$, т.е. пропорции наименьшего размера пробы к диаметру заполнителя, не наблюдается дальнейшее понижение устойчивости в функции диаметра заполнителя. Когда $L1/L3$ понижается, наблюдается непрерывное повышение устойчивости; в настоящей работе не были определены ограничения этого повыщения. Третим анализируемым параметром является участие объема заполнителя, который макроскопически составлял 35% и 59%.

1. INTRODUCTION

Notable advances in the understanding of mechanical behaviour of cement-based materials like concrete, mortar, cement allow for better and more efficient usage of limited material resources. Nowadays a considerably large number of aggregate types are used for concrete preparation. Of the industrial wastes most frequently appearing in the region of structure construction, we can mention recycled glass [3] or partially hydrated old concrete [4]. All of aggregates differ in physical properties. Their most important feature being considered on the level of material designing is the ability to react with cement paste which constitutes the concrete matrix [7]. Its reactivity can be understood not only in a chemical sense, but also as the aggregate ability to adsorb water from cement paste, which weakens the bond strength and creates the so-called intertransition contact zone (ITZ) [5], [6], [8]. Because the influence of aggregate diameter on mechanical behaviour of cement-based composites is often clouded by other factors, spherical glass aggregate was used. With such an aggregate the problem of water inflow and outflow is avoided. Bond strength is reduced to minimum. There is no significant chemical reaction between the aggregate and cement matrix.

The mechanism of hydro-mechanical reactions for mono-diameter aggregate is of a practical importance, thus it should be proven. First, during concrete mixing it is common and obligatory, in some national standards or regulations, to plot granulometric curves. Based on these curves and the aggregate size effect, it is possible to assess the future durability and performance of material [2].

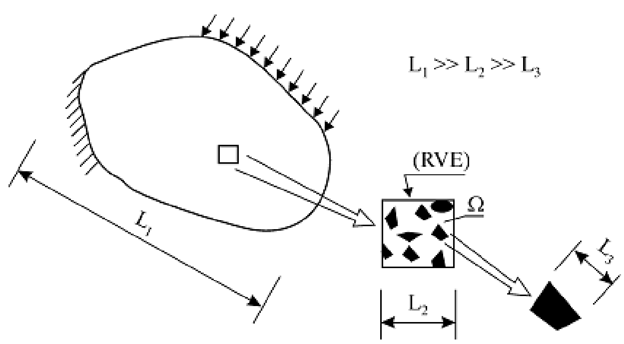


Fig. 1. Basic scales of composites tested

Second, when pouring fresh concrete into the mould and choosing wrong vibration time or technique, segregation of aggregate particles can appear. This leads to greater concentration of larger aggregate in lower areas of construction elements and the appearance of cement "milk" on the surface. This is inconvenient, because on the level of modelling, we suppose that the material is homogeneous. Moreover, in the absence of decorative surface finish, cement paste "milk" on the surface will shrink for lack of restraining aggregate. Finally, bigger aggregates are involved in bleeding mechanism, which is responsible for macroscopic porosity and lower densities of cement paste below the aggregate. We consider beam element with its common steel reinforcement mostly concentrated in lower tensile areas, which allows easier access of moisture leading to corrosion.

The effect of ground glass particle size on the performance of concrete was explained in [3]. Crashed, ground particles with the maximum sizes of 38 μm, 75 μm, 150 μm were tested. A smaller size of the particle of ground glass resulted in a higher reactivity of glass with lime, a higher compressive strength of concrete as well as a slighter expansion.

2. EXPERIMENTAL

The cement-based composites used at present consist of such materials that allow a considerably high level of shrinkage [1]. For the uniaxial and triaxial compression studies, cylindrical samples in the moulds of stainless steel were prepared. Initially, each sample was 36 mm in diameter and 100 mm in height. After 24 hours, it was demouled and placed in water for 28 days. After this time the height of samples was reduced to 72 mm which meets French standards set for height/diameter ratio of cylinders ($d/h = 1/2$). In order to test a total and autogeneous shrinkage (figures 2, 3), prismatic samples were prepared in steel moulds. Initially each sample was 40×40 mm^2 in cross section and 160 mm in height. After 24 hours the samples were demouled and placed in water for 28 days.

For each series of composites, six samples were dried at 90 ± 1 °C, under 20 ± 5RH conditions. Final mass is taken as reference m_{90} (g). Then in order to calculate final mass loss (ml_{90}), greater final mass (m_{90}) is used.

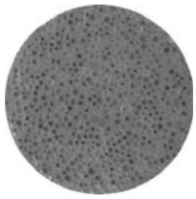
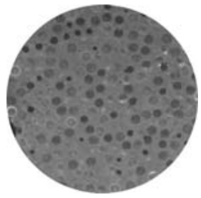
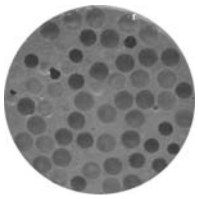
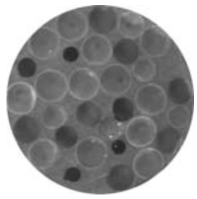
If we assume that m_0 is an initial mass of the samples and m_i a current mass, final water saturation can be obtained as

$$Sw = 100 - 100\frac{m_0 - m_i}{ml_{90}m_0} \quad [\%],$$

$$ml_{90} = \frac{m_0 - m_{90}}{m_0} \quad [-].$$

Table 1

Representative composite cross-sections. Mass and volume ratios of composite components for:
(a) 35% of aggregate volumetrically, (b) 59% of aggregate volumetrically

1 mm 	2 mm 
4 mm 	6 mm 
Glass spheres 638.75 kg/m^3 Cem I 52.5 N CP2 800.00 kg/m^3 Water 400.00 kg/m^3 Water/cement ratio 0.5 Volume fraction of aggregate 35% Glass aggregate diameters 1, 2, 4, 6 mm (a)	Glass spheres 638.75 kg/m^3 Cem I 52.5 N CP2 504.62 kg/m^3 Water 252.31 kg/m^3 Water/cement ratio 0.5 Volume fraction of aggregate 59% Diameters of the aggregate used: 1, 2, 4, 6 mm (b)

The series of the samples of various water saturation (roughly 100%, 66%, 33% and 0%) previewed for compression were systematically mechanically tested. Because of the specific character of saturating and drying cement-based materials, we adopt the testing procedure that allows the samples to be at first saturated and then dried. This prevents restarting hydration process for 0 to 100% saturation testing procedure. On the other hand, we should be aware of a subtle difference between what is an effect of a direct influence of various water saturation, what is a result of cracks, which are the derivatives of hydriation gradients, and finally we couple what is direct with what is indirect. Glass is similar to natural aggregate, since their ratios of Young's modulus to the Poissons ratio are equal. It should be noted that such a material does not permit water adsorption by aggregate. The second major difference is an almost zero roughness of the contact zone of intercomponents (called further ICZ).

It is advisable to provide some additional information on water saturation level. According to the experimental procedures adopted the water-saturation degrees of the samples were consecutively tested from fully saturated sample to those in equilibrium with ambient conditions. This means that saturation has dropped in parallel with maturing process. Initially unknown influence of saturation degree could be clouded by commonly known positive effect of maturing (higher hydratation level). In order to make the interpretation of the results correct and valid, some additional “witness” samples were kept saturated and tested in parallel with all the tests under the drying regime.

Table 2

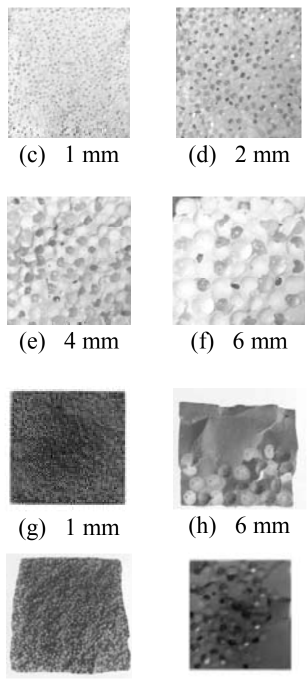
Representative composite cross-sections. Mass to volume ratios for the samples of: 35% of aggregate volumetrically (a), 59% of aggregate volumetrically (b), representative cross-sections of the composite (c, d, e, f), presentation of humid and carbonized regions (g, i), aggregate segregation making the samples useless (h, j)

(a)

Diam. of particle	Surface of particle	Volume of particle	Number of particles	Total ICZ surface T_{icz}	T_{icz}/V_s
mm	mm^2	mm^3		mm^2	mm^2/mm^3
1	3.14	0.52	48989	153903	2.10
2	12.57	4.19	6124	76951	1.05
4	50.27	33.51	765	38476	0.53
6	113.10	113.10	227	25650	0.35
Mix	–	–	–	73745	1.01
Sample volume (V_s), 73287 mm^3					

(b)

Diam. of particle	Surface of particle	Volume of particle	Number of particles	Total ICZ surface T_{icz}	T_{icz}/V_s
mm	mm^2	mm^3		mm^2	mm^2/mm^3
1	3.14	0.52	82581	259436	3.54
2	12.57	4.19	10323	129718	1.77
4	50.27	33.51	1290	64859	0.89
6	113.10	113.10	382	43239	0.59
Sample volume (V_s), 73287 mm^3					

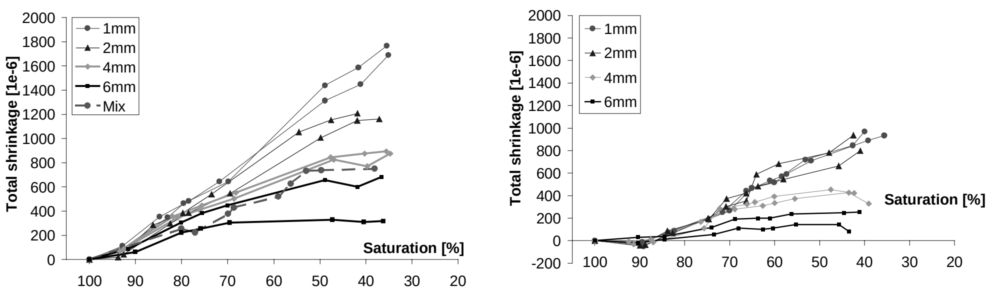


(c) 1 mm (d) 2 mm (e) 4 mm (f) 6 mm (g) 1 mm (h) 6 mm (i) 1 mm (j) 6 mm

3. RESULTS AND DISCUSSION

In figure 2, the total deformation of composite versus its saturation is presented. Total shrinkage is a sum of three basic processes affecting the cement paste. These processes are complex in their physicochemical nature [2], [8]. The first one is chemical shrinkage. This phenomenon is related to the hydration of cement and to the progressive hardening of its mineral skeleton. As is generally known, in mature samples protected from drying, the progressive desaturation of their pores generates compressive stresses high enough to cause volume changes called the autogenous shrinkage. These forces are particularly great in cement-based matrices with low *W*/*C* ratio. This ratio for working composites is equal to 0.5.

Figure 2 presents the results of total shrinkage at 35% and 59% aggregate content, additional "Mix" series has the same volume ratio of the aggregate added, but in this case, we deal with the aggregates of four diameters used in equal (¼) proportions.



(a) (b)

Fig. 2. Total shrinkage during drying at 30 °C ± 5 °C, 30RH ± 5RH in the function of saturation of composites with glass aggregate, (a) 35% of aggregate volumetrically, the diameters of 1, 2, 4, 6 mm compared with the mixture comprising the aggregates of all diameters, (b) 59% of aggregate volumetrically, the diameters of 1, 2, 4, 6 mm

The results for both volume ratios of aggregate testify to the influence of the aggregate diameter on a material shrinkage capacity. The smaller the aggregate diameter, the higher the load bearing of the composite. In other words, the relaxation, connected with meso- and macrocracking, appears much faster for a 6 mm diameter (L_3/L_1 = 1/6) than for 1 mm one (L_3/L_1 = 1/36). If we consider the negative effect of the biggest particle inside the composite, figure 2a seems to show it clearly. In figure 2, we see that "Mix" series behaviour corresponds to the results between the biggest aggregate diameters, i.e., 4 and 6 mm.

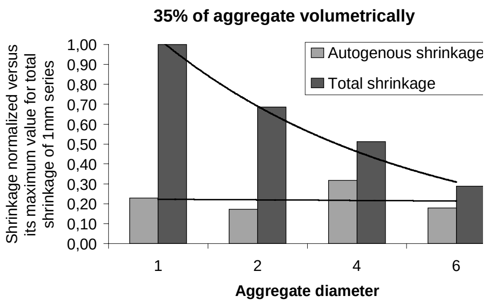
Comparing the behaviour of 35% and 59% series (figure 2) we gain the insight into the difference between them expressed as the change in weight versus the change in height. It seems that the ability of the two composites (35%, 59%) to deform during drying depends upon the aggregate diameter, i.e.:

- Only in the first period of drying the composites with all aggregate diameters behave exactly the same (see also [2]). At the starting point for the second period of drying the final mass loss of composites approaches 10%.
- The composites' (35% and 59% series) behaviour changes with the aggregate diameter. The change is continuous. For L_3/L_1 = 1/36, the composite (59% series) shrinks

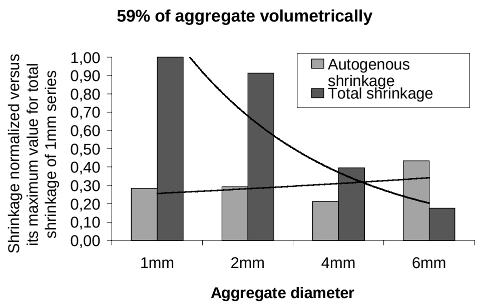
more than that of 35% series. For L_3/L_1 = 1/18 this difference diminishes and for L_3/L_1 = 1/9 the curves that almost match each other are obtained. Finally, for L_3/L_1 = 1/6 the tendency is reversed and in 35% series the change is twice as much as that in 59% series.

The results obtained show the influence of aggregate diameter on certain characteristics of cement-based composites.

Drying shrinkage and the resulting total shrinkage are strongly dependent on aggregate diameter (figure 2a, b). The smaller the aggregate, the bigger the shrinkage.



(a)



(b)

Fig. 3. Shrinkage normalized to maximum value obtained for all diameters, i.e., 1 mm total shrinkage for 35% (a) and 59% (b) of aggregates volumetrically

Table 3

Rate of change in strength during drying from 100% to about 0% saturation level

Type of test	Aggregate diameters			
	1 mm	2 mm	4 mm	6 mm
Uniaxial	+8.5%	+15.6%	–6.0%	–6.0%
	(4 MPa)	(4.9 MPa)	(–7.8MPa)	(–7.6 MPa)
Uniaxial “witness”	+10.0%	+15.6%	+18.0%	–6.0%
	(4.5 MPa)	(4.9 MPa)	(4.3 MPa)	(–7.6 MPa)
Triaxial, 5 MPa	+12.5%	+10.5%	+13.0%	+30.6%
	(9.4 MPa)	(5.7 MPa)	(7.6 MPa)	(19.3 MPa)
Triaxial, 15 MPa	+20.7%	+4.7%	+20%	+38.2%
	(20.9 MPa)	(3.3 MPa)	(16.8 MPa)	(34.1 MPa)

Some characteristics of the composites tested are not affected by the aggregate diameter. One of them is autogenous shrinkage, which keeps constant value for all the diameters tested and for all the volume ratios of aggregate. We should be aware, however, that the values under consideration are relatively small (for example, in comparison with total shrinkage) and the measuring error of deformations can play a major role.

Table 3 summarizes the results of uniaxial and triaxial loadings for the composites with different aggregate diameters and for 35% of aggregate volume ratio. The difference between the relative and absolute strength is positive when the dried composite has greater strength than the saturated one.

4. SUMMARY AND CONCLUSIONS

The results of investigating the influence of water saturation degree on material behaviour under different loading conditions allow the following conclusions to be drawn:

• Drying increases internal friction in cement paste, but at the same time a decrease in cohesion is observed. This information alone does not explain, which of those two mechanisms is dominant on the consecutive saturation levels.

• Autogenous shrinkage values, which are not connected with saturation level but with the class of composite only, are constant for all the diameters tested and for all the volume ratios of aggregate. We should be aware, however, that the values under consideration are relatively small (for example, in comparison with total shrinkage) and the measuring error of the deformations can play a major role. If we normalize this type of shrinkage in the function of the aggregate diameter, once again diversification in the function of aggregate diameter will occur. But at that time we must be aware that this is intrinsic value instead of absolute comparison (figure 3).

• Uniaxial compression tests performed on the composite samples in different stages of drying and on the samples protected from water evaporation show similar variation in their resistance. For the samples initially confined by hydrostatic compression, the influence of desaturation level becomes considerable if the confining pressure increases. In composite with 1 mm aggregate diameter, an increase in resistance due to a decrease in saturation level becomes more important for higher initial hydrostatic compression values. At the hydrostatic compression of 15 MPa an increase in strength due to desaturation exceeds that due to maturing process (table 3).

• These changes can be explained if one takes account of two phenomena which control the failure process. The first phenomenon is the mechanical microcracking induced by the external loading. This cracking will propagate all the more because the material is initially damaged by microcrackings caused by water. The second phenomenon, concomitant with the first, is the effect of the capillary pressure which will lead, during the desiccation, to an increase in mortar prestressing. This prestressing will induce an increase in multiaxial compression strength of material. According to the preponderance of these two phenomena, the process of failure arising is different. The changes of the strength of the samples subjected and not subjected to drying are almost the same. On the other hand, in multiaxial compression, the capillary pressure plays an important role due to the fact that mechanical microcracking is limited by confinement.

• The composite resistance to damage decreases with drying (or remains quasi-stable) when mechanical microcracking can propagate, therefore in uniaxial compression. The sample resistance increases with its drying in triaxial compression because of the effect of capillary pressure. The more important the microcracking caused by water, the greater the influence of the failure process on mechanical damage. The more dried the material, the higher the capillary pressure and the greater its resistance (in the absence of microcracks).

• The analysis performed in this study mostly concerns the composites with one-diameter inclusions (aggregate). In the case of normal and high-performance concrete, we always deal with the set of diameters, represented by granulometric curves of normalized volumetric fractions. This fact should be accounted for the further study.

Negative, damaging effect of the biggest, irregularly shaped aggregate particles is well known and explained in the literature. However, no extensive study has been performed on the geometries of particular samples of several monosized particle sets in order to quantify the limits of the problem. In all the tests performed, general conclusion is that the smaller the aggregate used, the bigger the strength obtained. This phenomenon is connected with the fact that smaller aggregate seems to distribute the stress inside the composite more evenly. If the stress is not localized, less cracks occur during maturing, drying and finally mechanical loading.

REFERENCES

[1] BISSCHOP J., PEL L., van MIER J.G.M., *Effect of aggregate size and paste volume on drying shrinkage microcracking in cement-based composites*, Creep, Shrinkage & Durability Mechanics of Concrete and other Quasi-Brittle Materials, Proc. of CONCREEP-6@MIT, F. Ulm, Z.P. Bažant and F.H. Wittmann (editors), MIT, Boston, USA, 2001, 75–80.

[2] YURTDAS I., BURLION N., SKOCZYLAS F., *Experimental characterisation of the drying effect on uniaxial mechanical behaviour of mortar*, Mater. Struct., 37 (267), 170–176.

[3] SHAO Y. et al., *Studies on concrete containing ground waste glass*, Cement and Concrete Research, 2000, 30, 91–100.

[4] KATZ A., *Properties of concrete made with recycled aggregate from partially hydrated old concrete*, Cement and Concrete Research, 2003, 33, 703–711.

[5] TAM V.W.Y. et al., *New approach in measuring water absorption of recycled aggregates*, Constr. and Building Mater., 2006, di:10.1016/j.conbuildmat.2006.08.009.

[6] RAMYAR K. et al., *Effects of aggregate size and angularity on alkali–silica reaction*, Cement and Concrete Research, 2005, 35, 2165–2169.

[7] TASONG W.A. et al., *Aggregate–cement paste interface. II: Influence of aggregate physical properties*, Cement and Concrete Research, 1998, Vol. 28, No. 10, 1453–1465.

[8] WESTERHOLM M. et al., *Influence of fine aggregate characteristics on the rheological properties of mortars*, Cement Concrete Comp., 2007, doi:10.1016/j.cemconcomp.2007.08.008.