STUDY OF MACROPORES AND CRACKS IN STRUCTURAL LIGHTWEIGHT CONCRETE

[1]A. Goldman,[2]G. Fishman, [3]V. Toporet, [3]A. Rashcovoi
[1]Academic College in Ariel, and Technion – IIT in Haifa, Israel
[2]Academic College in Ariel, Israel
Technical University of Moldova in Chişinău

1. INTRODUCTION

One may characterize the GFC as Lightweight High Performance Concrete, as it combines superior properties of High Performance Concrete (HPC) such as very high density with substantially reduced bulk unit weight [2]. Unlike other known lightweight concretes, GFC does not contain any lightweight aggregate. It incorporates HPC as matrix, containing normal aggregate of course, that is, "HPC matrix". Light unit weight of GFC is achieved by introduction of polymer macrofiller grains.

The HPC itself is known since early eighties. The worldwide "HPC boom" in concrete science and technology took place as a result of two major developments. One of them was Condensed Silica Fume, or microsilica, first introduced into concrete technology as early as fifty six years ago. The other development (High Range Water Reducing Admixtures HRWRA, or super plasticizers) took place some twenty years later. Today, the HPC covers a wide range of cement-based products, offering very-to-ultra high strength, very high density, and substantially improved durability in aggressive environments. Its compressive strength is 80-160 MPa, and it can be as high as 800 MPa [3, 4]. The HPC is often considered as more fragile than conventional 20-60 MPa concrete. Consequently, the field of HPC applications is not as wide as one might predict two decades ago. The mechanisms of the HPC fracture remain unclear in some of their aspects [5, 6].

Being relatively fragile, the HPC is known for possessing the "true composite" behavior [3, 4, 7, 8], which resembles that of some natural rocks [7]. Fiber reinforcement can make it less fragile and can significantly improve its fracture toughness. This method is efficient, and thus it is widely accepted. However, the use of fibers actually did not yet widen the range of HPC applications, and in several aspects it is not intended to.

From this point of view, the application of HPC as the matrix to produce its lightweight version, that is GFC, is expected to improve the fracture toughness, much like it is achieved by introducing fibers. Steel fibers can take tensile stresses while cracks propagate in concrete under external loads. Lightweight polymer macrofillers that produce voids in GFC are also intended to partially arrest the crack propagation [9, 17]. The fracture toughness can therefore be improved, and so one can see the incorporation of voids into the HPC matrix as another possibility of improving the fracture behavior of the HPC. Several studies have shown the possibility of controlling stress concentrations, and crack propagation by changing the size and the content of voids [10, 11, 12, 13].

Computerized Tomography (CT) in medicine is known for years. Yet, one may qualify its application in concrete research as relatively new, whereas the CT has been used for studying mainly crack patterns [15] and void distributions [16, 19]. In this study, the CT serves for studying the distribution of polymer macrofiller grains and their impact on crack propagation in the mass of the HPC matrix. Some observations on crack patterns by this technique, and by Scanning Electron Microscopy (SEM), are represented as well.

2. SCOPE OF INVESTIGATION

Beside fibers, introduction of some water-soluble polymers can also produce an impact on the elasticity of cementations matrix, thus improving the fracture behavior. The price shall be certain, although limited, reduction of strength [6, 8]. Use of lightweight polymer grains as macrofillers, which can actually serve as voids of given sizes in hardened HPC is another possibility. Their presence shall affect the mechanisms of crack development, possibly reducing stress concentrations and speed of crack propagation [9, 12]. The polymer is chemically inert in cementations systems, while its grain size varies between approximately 2 and 6 mm. The unit weight of such grains shall be low enough to be negligible when compared to that of cementations components.

The influence of thus created voids on the macrostructure and crack distribution in GFC is being investigated. We have suggested that proper introduction of voids by means of macrofiller grains is beneficial for controlling strength and fracture behavior. This is aimed at developing various lightweight structural elements of buildings.

3. RESULTS AND DISCUSSION

The trial GFC mix, aimed at checking its feasibility, was first prepared in 2001. It was based on a typical HPC mix design containing microsilica and commercially available super plasticizer. This mix served as the matrix for the GFC, as well as for the reference.

Another series of testing was conducted in 2003 as an introductory part of the Ph.D. research. It has included (a) an HPC mix with Portland cement of EN type 52.5, microsilica (10% by weight of cement), and a commercial super plasticizer; and (b) three GFC mixes, containing polymer macrofiller grains (13%, 23%, and 41% of total mix volume). Properties of fresh mixes were defined according to Israeli Standard (IS) 26, part 2. Compressive strength was measured following IS 26, part 4. Mechanical testing was conducted using the "Sercomp 7" system manufactured by Controls Group Ltd. in Italy. The results are shown below it Table1.

Significant reduction of compressive strength and modulus of elasticity, which fits the increase of the macrofiller content, is observed. The bulk unit weight is also reduced, although to a smaller degree. Yet, mechanical properties of GFC remain satisfactory at all levels of the macrofiller content [18, 19].

The experiment was aimed also at evaluating the influence of the macrofiller content on major properties of fresh and hardened HPC, while no changes are introduced into its own mix design. The results indicate that one can achieve a significant reduction of bulk unit weight, however on the account of mechanical properties. On one hand, the bulk unit weight can be as low as roughly 2000 kg/m^3, and even 1600 kg/m^3, while keeping satisfactory level of compressive strength [18, 19]. On the other hand, the reduction of compressive strength, and probably of other mechanical properties, can be very significant. One shall take into account the dependence of these results on the initial strength of the HPC matrix.

Table 1. Results of mechanical testing.

Properties	Reference HPC 2001	GFC 2001	Reference HPC 2003	GFC 1 2003	GFC 2 2003	GFC 3 2003
Compressive strength, MPa, at:						
1 day	-	-	34.7	29.0	20.4	-
7 days	59.8	34.0	71.3	45.8	33.1	17.0
28 days	78.0	47.2	84.7	54.7	38.8	21.8
Modulus of elasticity, MPa	46,000	35,000	-	-	-	-
Bulk unit weight, kg/m^3	2426	2018	2445	2223	2074	1614
Standard slump, mm	-	-	110	90	170	170
Filler content, volume %	-	≈25	-	13	23	41
Percentage of bulk unit weight reduction	-	16.8	-	9.1	15.2	34.0
Percentage of 28 days compressive strength reduction	-	39.5	-	35.4	54.2	74.2

These tests have clearly confirmed the feasibility of achieving structural lightweight concrete without lightweight aggregate, while controlling its mechanical properties and weight by means of a lightweight polymer macrofiller.

The whole idea of GFC is viable only if proper distribution of macrofiller grains in the concrete volume is achieved (fig. 1). According to the observations, several factors shall have an effect on movement and positioning of macrofiller grains in the mass of fresh concrete.

It is believed, that these factors can be divided between two groups, representing separately the influence of aggregate and paste. The most

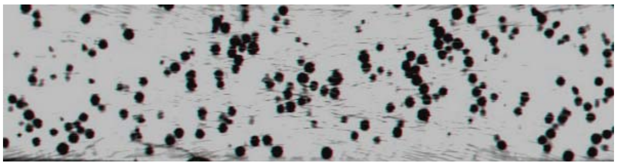

Figure 1. Typical distribution of macrofiller grains in the 70x280 mm cross section (x-ray CT image).

influential group of factors is introduced by the aggregates, namely by their grain size, grading, and volume content.

One should therefore expect a correlation to exist between the maximal size $\mathbf{D_a}$, fineness modulus **FM**, and volume $\mathbf{V_a}$ of aggregate, and correspondent parameters of the macrofiller, such as average size $\mathbf{D_f}$, and volume $\mathbf{V_f}$. Assuming that unit volume of concrete consists of paste and aggregate, and taking into account the volume of paste $\mathbf{V_p}$, one may express the content of macrofiller as follows:

$$V_f = (1 - V_a - V_p) \cdot D_f / D_a, \qquad (1)$$

where the constituent $\mathbf{D_f/D_a}$ is macrofiller - to-aggregate size ratio. Somewhat alike aggregate-to–paste volume ratio, this one is believed to influence the workability of fresh concrete. The major impact it produces is however on distribution of macrofiller introduced into concrete**.** Regarding the distribution, the fineness modulus **FM** shall be taken into account as well. The above ratio can thus be given as $\mathbf{FM_f/FM_a}$. The influence of aggregate parameters on the macrofiller distribution is shown in fig. 2 and in fig. 3.

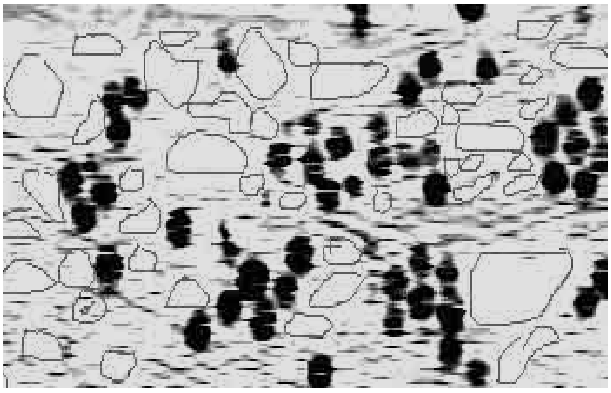

Figure 2. Positioning of macrofiller particles and coarse aggregate grains (reconstruction of X-rays CT image).

The distribution in fig.3 was obtained in an HPC mix whereas the aggregate-to-paste ratio is relatively high. This is typical for the "traditional" HPC. One can see that coarse aggregate grains can form zones where groups of macrofiller particles are entrapped. From this point of view, the aggregate size and volume content, as given by expression (1) seem to play the major role. It has been suggested, that the optimal aggregate size is roughly similar to that of macrofiller, as well as their grading, that is, $\mathbf{FM_f/FM_a \approx 1}$ [14]. As to the aggregate content, it shall vary, thus allowing variability of the macrofiller content, which in its turn leads to controlling the unit weight and other related properties of Lightweight High Performance Concrete (GFC).

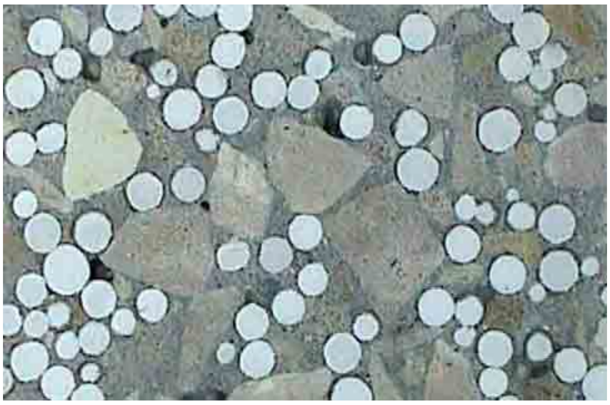

Figure 3. Typical distribution of macrofiller particles between coarse aggregate grains.

Under these conditions, and providing the paste content $\mathbf{V_p}$ in a fresh mix is constant, one can describe the mechanism of controlling the properties of GFC as follows:

$$V_f = k(1 - V_a), \qquad (2)$$

The lower is the aggregate content, the larger amount of the macrofiller can be introduced. The coefficient **k** is a constant depending on paste content $\mathbf{V_p}$, if $\mathbf{FM_f/FM_a \approx 1}$ as given above.

Another group of factors is induced by paste. As long as the aggregate content is relatively high, it can provide proper distribution of macrofiller as shown in fig. 2 and fig. 3 above. The role of paste becomes significant in two cases: (a) when lowering the aggregate content in order to increase the amount of macrofiller, and (b) when the aggregate size is smaller than that of macrofiller ($\mathbf{FM_f/FM_a<1}$). Paste of composition typically found in High Performance Concrete contains very efficient super plasticizers (HRWRA). Under certain conditions, such paste can by itself provide proper distribution of macrofiller particles by well known dispersion mechanisms, induced by HRWRA [14].

The system of voids created by the lightweight macrofiller is believed to have two major effects on mechanical properties of concrete. It may increase the potential of absorbing fracture energy, thus improving fracture behavior of the HPC matrix [6, 14]. Consequently, it shall be able of arresting the crack propagation [9, 12]. The latter effect has been observed by multiple X-rays CT scanning (fig. 4), and it has been verified by SEM investigation (fig. 5).

Figure 4. Fragments of X-rays CT scans showing cracks ending at macrofiller spheres.

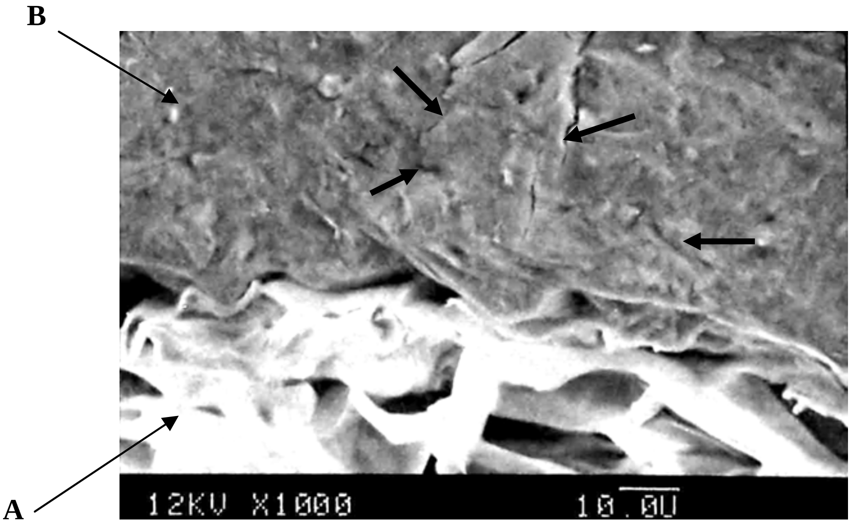

Figure 5. SEM image of boundary zone between polymer macrofiller particles (A) and HPC matrix (B): arrows show crack patterns in the HPC matrix.

4. CONCLUSIONS

1. Proper distribution of lightweight polymer macrofiller in the mass of concrete can be achieved mainly by adjusting aggregate volume content, if its average size is similar to that of macrofiller particles.

2. Paste can be of significance for proper distribution of macrofiller when aggregate size and/or volume content are lowered. Paste may influence macrofiller distribution through dispersion mechanisms induced by super plasticizers.

3. Crack propagation in HPC containing polymer macrofiller can be controlled. Spherical macrofiller particles can serve for arresting crack development, which has been confirmed by combined X-rays CT and SEM study.

ACKNOWLEDGMENTS

Authors are thankful to the Technical University of Moldova for making possible and coordinating this study. We are grateful to the Academic College in Ariel, where the experimental work has been carried out, for providing laboratory facilities.

Bibliography

1. Pruteanu N., Fishman G., Goldman A. *Composition for Preparation of Lightweight High Strength Concrete, Patent MD 2772 C2 2005.05.31, Chişinăy, Moldova, 2005.*

2. Goldman A. *Properties of Concretes and Pastes with Microsilica, M.Sc. Thesis, Technion IIT , Haifa , 1987.*

3. Goldman A., Bentur A. *Bond Effects in High Strength Silica Fume Concretes, ACI Materials Journal, 1989, vol. 86, pp. 440-447.*

4. Shah S. P. *Materials Aspects of High Performance Concrete, First Int. Conf. on High Strength Concrete (UEF), Kona, Hawaii, 1997, pp. 504-511.*

5. Ali M. A. , White R.N. *On expending ACT 318 to High Strength Concrete, First Int. Conf. on High Strength Concrete (UEF), Kona, Hawaii, 1997, pp.554-567 .*

6. Goldman A. *Mechanisms of Strengthening in Cementitious Systems Containing Microsilica, D.Sc. seminar, National Building Research Institute, Technion IIT, Haifa, 1988.*

7. Aitcin P.-C. *High-Performance Concrete, E and FN SPON, London & New York, pp. 442-445.*

8. Goldman A. *High Performance Concrete: From Late Seventies to Nowadays, 2005 (in progress).*

9. Fishman G. *Private Communication, Netanya, Israel, July 200 .*

10. Broek, D, et. al., *Applicability of fracture toughness data to surface flaws and to corner cracks at holes, Nat. Aerospace Inst. Amsterdam, Report TR 71033 (1971).*

11. Bowie, O. L. *Analysis of an infinite plate containing radial cracks originating at the boundary of an internal circular hole, Journal of Math, and Physic., 25 (1956) pp. 60-71.*

12. Fishman G. *Stress Concentration Examples. Part 1., Meridian Ingineresc, Journal of Moldavian Engineering Association and TUM in Chişinăy, No. 3, 2004, pp. 46-48.*

13. Fishman G. *Stress Concentration Examples. Part 2, Elliptical Hole, Meridian Ingineresc, Journal of Moldavian Engineering Association and TUM in Chişinăy, No. 3, 2005, pp. 79-82.*

14. Goldman A. *Private Communication, Haifa, Israel, March, 2003.*

15. Saleh H. H. and Livingston R. *The Use of X-Ray Computed Tomography (CT) Techniques to Study the Internal Structures of Concrete, NDT.net, 2nd MENDT Proceedings, vol. 9, No. 06, pp. 01-06.*

16. Garboczi E. J. *Three-Dimensional Mathematical Analysis of Particle Shape Using X-Ray Tomography and Spherical Harmonics: Application to Aggregates Used in Concrete, Cement and Concrete Research, vol. 32, No. 10, October 2002, pp. 1621-1638.*

17. Fishman G. *On Controlling Pore System in Lightweight Concrete, Seminar, Technical University of Moldova, October 10, 2004.*

18. Fishman G. *Technology for High Resistance Easy Concrete Bearing Elements, Ph. D. dissertation, Technical University of Moldova, May, 2006.*

19. Fishman G. and Goldman A. *Technology of Lightweight Concrete with Controllable Pore Formation, Meridian Ingineresc, Journal of Moldavian Engineering Association and TUM in Chişinăy, No. 4, 2005, pp. 82-85.*

Recomandat spre publicare: 11.01.2013