COMPREHENSIVE STRATEGY FOR HSC BEST PERFORMANCE IN EXTENSIVE APPLICATIONS OF LANDMARK WORKS IN ITALY

A. Migliacci[1], P. Ronca[1], P. Crespi[1] and G. Franchi[2]
[1]*Structural Engineering Department, Politecnico of Milan, Milan, Italy*
[2]*AMiS-Structural Engineering Office, Milan, Italy*

Abstract

Centering on worldwidly present urban areas, there have been many high-rise landmark buildings constructed in recent years. It is recognized that reinforced concrete has merit over steel frame construction in high-rise buildings, such as less sway in high winds, better human life protection in case of accidental heavy damage, better noise resistance. The use of high-strength concrete is rising, not only for pillars, in high-rise buildings. The paper points out on the need of classifying the HP-HSC for the different requested characteristic that materials have to exhibit on different structural elements of a complex structure. Among types of concrete, which binds together characteristics of High Strength Concrete (HSC) and High Performance Concrete (HPC), particular reference is made to Limestone Concrete (LSC).

Existing literature provides data on self-levelling, high performance, rapid hardening concrete, able to reach in few days the standard of HPC (Kelham, 1998; Montgomery et al., 1998; Nehdi et al., 1998). In particular the technology here referred for limestone concrete is not the usual one, but it makes reference to a mix design, characterized by an industrially produced limestone aggregates, with total absence of Silica Fume or any other addition of pozzolanic material or accelerating admixture (Cangiano, 2005; Cangiano et al., 2004).

The paper points out the significance of Limestone Concrete, as High Performance Concrete, application, starting from the following key construction requirements: in large public works with characteristic of very high durability, the choice of a technical solution it is not at all dependent on the construction cost only. In fact in this work, life service and safety performances, that slightly increase the construction costs, are of paramount importance. Starting from this key assumption, new materials, and in particular new concretes, may be able to notably cut life service and safety costs, considerably improving the performance/cost ratio of the selected solution, due to the large cut of maintenance costs. The paper wants to briefly explain the state of the art and the today frontier which lead to the material basic choices in structural design of high-rise buildings. In particular the paper refers to a comprehensive campaign of tests, in a starting-up phase, shared among different university and private laboratories in Italy, which aims to draw Guide Lines for different specific uses of Limestone Concrete, as HPC, in different structures typologies and environmental conditions.

Introduction

Italy, like other countries in Europe, has experienced high rise building constructions with significant delay, respect to different countries all over the world. Reasons due to architectural heritage, cultural and educational schools in architecture may be the principal sources of delay. The construction of high rise buildings as new land-mark of our traditional and world-wide known cities is still a debating issue. Nevertheless, or because of that, and due to some episodes unfortunately experienced by important widely known buildings, the today technological background about the best requisites of advanced materials, as well as methods of structural analysis and design, indicates the need of significant and innovative approaches and strategies for achieving the best results for the construction

M. Pandey et al. (eds), Advances in Engineering Structures, Mechanics & Construction, 853–863.

Fig. 1. The sail building phase of the "Dives in Misericordia" Church.

Fig. 2. WTC in San Marino construction site.

of landmark buildings, like the high-rise buildings are (High-Rise Manual, 2003; Simiu et al., 1996; Fairweather, 2004).

The solution of the engineering project of an architecture design has to be the optimal solution among several feasible solutions, often mutually contradictory and conflicting each other. Each different architectural project has own characteristic and demands for the best solution. Recent realizations have been discussed as peculiar examples in Italy, as for example the "Dives in Misericordia" Church in Rome (Figure 1) or the main r.c. structures of the World Trade Center in S. Marino (Figure 2) .

Due to some innovative architectural solutions, the demand due to particular layout of the structural elements or due to geometrical shape and slenderness of the vaulted structure, together with particular demand for the durability of brightness, have stimulate the research toward new technological, engineering and material solutions. The best design of the so called landmark building, as the high-rise buildings mostly are, is today focused, taking advantages from previous experiences, on different main objectives. The objectives to be considered, as far as materials are concerned, are:

(a) mechanical resistance,
(b) stiffness,
(c) ductility and toughness,
(d) durability,
(e) fire resistance.

In addition the objectives to be considered in the construction site are:

(a) simplicity and easiness of the construction processes,
(b) construction immediate costs,
(c) construction time and feasibility to respect the time schedule,
(d) site job environmental impact,
(e) historical and monumental existing constraints.

The new design philosophy for landmark long-lasting architectural buildings has to take account also the objectives for the service life, from which the most significant are:

(a) construction flexibility,
(b) low maintenance costs,
(c) assurance of high safety level (human life safeguards),
(d) environmental sustainability,
(e) urban costs and constraints.

The strategy of choosing the solution has to consider all the costs among the immediate construction, the life service and the safety costs.

As it will be briefly shown in the next section, among different parameters of the optimized solution, the chosen main structural material has a significant role in improving the performances/cost ratio, due to the cut of life service costs and to further advantages, like smaller dimensions of structures, reduction of construction time.

Main Structural Material Performances for New High-Rise Buildings

Some background considerations, from literature and from direct experiences here reported (Namiki, 2005), states that the improved new generation of High Performance Concrete (HPC) may lead the concrete to be highly competitive in respect to different materials, if the material performance is optimized taking account the response of the structure under the following actions:

(a) the structural behavior under wind actions,
(b) the structural behavior under explosion and impact actions,
(c) the behavior under cyclic and/or alternate loadings,
(d) the shrinkage and creep behavior.

Recent investigations comparing the different performances of various building materials can be summarized in Table 1, where the signs +, 0, – indicate respectively good, neutral, bad performance. High Strength Concrete (HSC) shows positive performances respect to the entire spectrum of the chosen criteria (Chew Yit Lin, 2003; High-Rise Manual, 2003; Taranth, 1988).

Table 1. Comparison on different materials frame construction.

Criteria	Reinforced concrete, Normal-strength concrete	Reinforced concrete High-strength concrete	Steel construction	Composite construction method
Construction costs	+	++	0	++
Weight of construction	0	+	++	+
Stiffness	++	++	0	+
Flexibility of plan	0	0	++	+
Behavior in fire	++	++	–	+
Construction time	–	+	++	++
Usable area	–	+	++	+
SCORE	5	9	7	9

Taking moreover a particular look, for example, to the specific criteria identified as "construction cost" and "construction time", Tables 2 and 3 show significative data (High-Rise Manual, 2003). Table 2 indicates sharp favourite performances by using HSC for the structures, not only considering the cost, but even from the point of view of the usable area needed by the structure. Table 3 is self explaining if we consider that HPC, beside improved mechanical properties, have the further relevant feature: formworks can be taken away just 24 hours after the pouring the concrete, while dealing with NSC (Normal Strength Concrete) at least 4–5 days are required. In Table 3 it is easy to observe that, while 13 working days were required to complete the rough work for a standard floor during the construction of the Dresden Bank high-rise in 1974–1979 (obsolete concrete technology + NSC), the same task is currently achieved in mere 4 working days on the Galileo site (modern concrete technology + HPC) (High-Rise Manual, 2003; The Concrete Society, 1997; Fairweather, 2004). The immediate cost construction are primarily related to the time construction. Tough steel structure is traditionally reckoned to be much faster than the concrete structure, but because of significant advantages in concrete technology, this is no more true: in fact, with concrete showing features of self-levelling (SCC), the new pumps equipment assures concrete puring even at heights of 300 m, and also because of modern formwork systems (self-climbing formwork), rapid and safe progress in the rough work is guaranteed.

Research studies carried out, and still in progress, in the field of mix-design of HSC/HPC, and related technology in the construction sites, seem to show favourable results in achieving better performances, i.e. rapid hardening, absence of segregation, better durability (no alcaly-silica reaction), when limestone is used as filler, as it will show in the next section.

It is worth to recall, as mentioned before, due to even the consequences of recent past accidents, that the engineering design of a land-mark buildings can not ignore the possible blast loading effects. As it is well known, the physical action on a wall F, due to a plane shock wave, generates an overpressure Ps and a drag loading P_d, according to the scheme of Figures 3a and 3b.

When an explosion occurs inside a building, then it is the interior surface of the walls and ceiling which are first loaded by the pressure of the shock wave, reflecting therefore and increasing the pressure. The effects on the structure may be devastating, considering in addition that, as consequence of an explosion, even fire may occur. Figure 4 shows the accident occurred in spring 2002 at the Pirelli building, headquarter of the Regional Government in Milan. The explosion of the fuel tanks of the aircraft, among other consequences, caused a permanent deformation of the 26th r.c. floor with a

Table 2. Construction costs and usable area for different structural material.

		Column	Relative Cost
1.		60-MPa (8600-psi) reinforced concrete 840 × 840 6Y24 [33-in^2 6–1-in. bars] AS3600 ties (R10–360)	1.0
2.		120-MPa (17,300-psi) reinforced concrete 600 × 600 8Y24 [24-in^2 8–1-in. bars] crawley (1989) ties (Y32–200)	0.79
3.		120-MPa (17,300-psi) reinforced concrete 660 × 660 8Y24 [26-in^2 8–1-in. bars] AS3600 ties (R10-360)	0.77
4.		60-MPa (8,600-psi) concrete in grade 250 steel tube 740 × 8 CHS [23-in. dia × $\frac{3}{8}$ in. thick]	0.98
5.		120-MPa (17,300-psi) concrete in grade 250 steel tube 570 × 8 CHS (23-in. dia × $\frac{5}{16}$ in. thick)	0.71
6.		steel column grade 350 600 × 40 flanges [24-in. × $1\frac{1}{2}$-in.] 520 × 40 web [21-in. × $1\frac{1}{2}$-in.]	2.21

Usable Area: reduction of column cross section and compressive reinforcement by increasing the grade of concrete

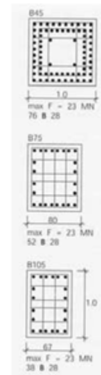


Table 3. Construction time – HPC/HSC versus steel.

Property	Height	Completion	Rough Work per Standard Floor
Business Research Center, Warsaw, Poland	104 m	2000	5 working days
Taunustor Japan Center, Frankfurt, Germany	114 m	1996	4 working days
World Port Center, Rotterdam, The Netherlands	125 m	2001	5 working days
Galileo, Frankfurt, Germany	136 m	2003	4 working days
Dresdner Bank, Frankfurt, Germany	166 m	1979	13 working days
Trianon, Frankfurt, Germany	186 m	1993	5,5 working days
Millennium Tower, Vienna, Austria	202 m	1999	3 working days
Park Tower, Chicago, USA	257 m	2000	3 working days
Trump World Tower, New York, USA	269 m	2001	5 working days
Petronas Tower, Kuala Lumpur, Malaysia	452 m	1998	5 working days

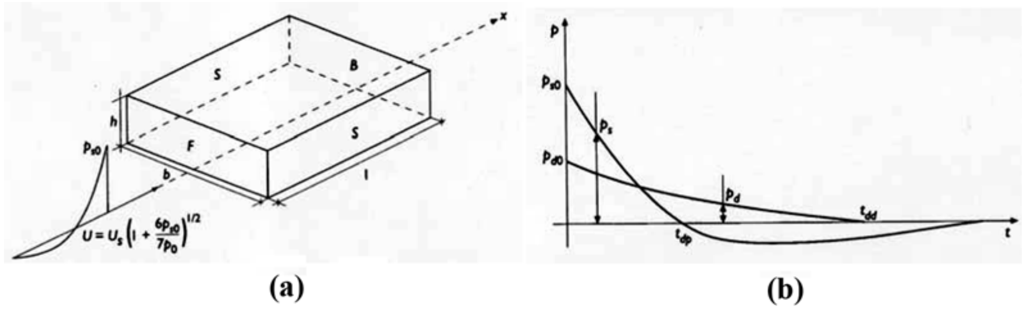


Fig. 3. Overpressure due to plane shock wave action.

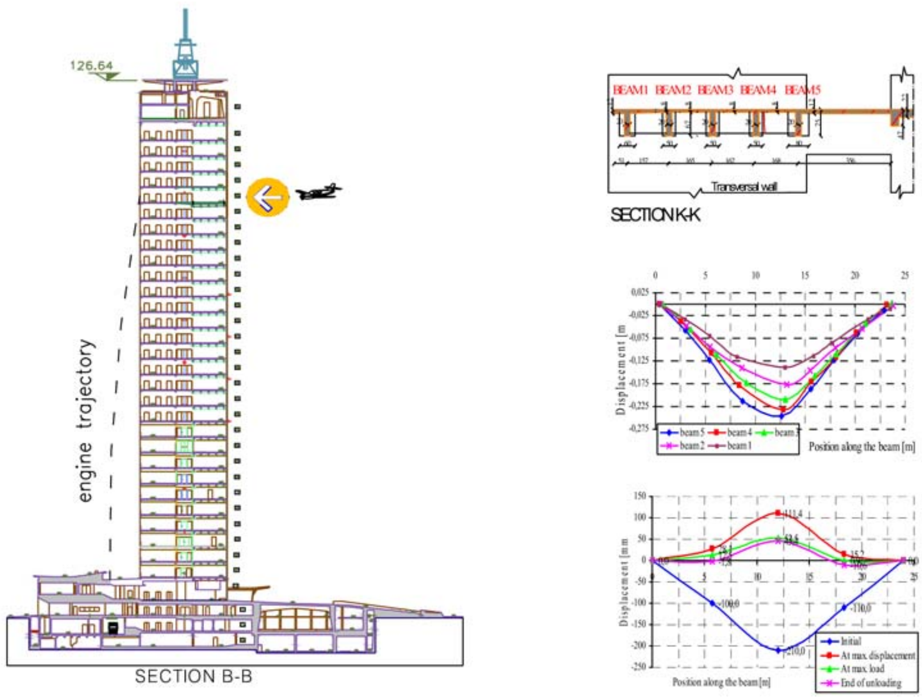


Fig. 4. Draw of the airplane impact and the permanent floor deflection.

deflection of 22 cm, but not the collapse, despite the high temperature due to fire (Migliacci et al., 2005; Kappos, 2002).

The stiffness of the structure is very significant in considering the horizontal loads, i.e. earthquake and wind actions.

- Earthquake effects: stell constructions are highly suitable in areas subjected to earthquake as steel allows the structure to absorb part of the kinetic energy produced by the earthquake in the form of plastic deformation. Technically a similar ductile behaviour can be achieved by using for the structure HSC and reinforcement steel with high strength and ductility.
- Wind effects: reinforced concrete as the merit over steel frame construction in high rise buildings to present a less sway wind. The structural behaviour minimizing the wind effect is at best achieved by concrete displaying a high values of Young modulus.

Fig. 5. Plastic model of "City Life" project in Milan. .

Fig. 6. Plastic model of "Garibaldi-Repubblica" project in Milan.

The points so far briefly recalled seem to highly recommend the choice of using reinforced concrete structure in the engineering design for a high-rise building, with particular attention to the best suitable mix design of HSC/HPC for each different action and structural component of the building.

For these reasons, a comprehensive study on best performing HPC mix design, with particular reference to Limestone Concrete, have been requested, with the purpose to draw Guidelines for use, in the oncoming starting up design phase of two important land mark interventions in the city of Milano. Figures 5 and 6 show the plastic model of the two projects, respectively the so-called "City Life" in the former trade fair area, and the so-called "Garibaldi-Repubblica" area, both in the central part of the town.

Mechanical Characterization of HPC with Limestone Filler

Technical literature on new generation of HS/HPC is available since a decade or more, with several examples of structural applications (Aitcin, 1999; Rols et al., 1999; Person, 1998; Toutanji et al., 1995; Rosati, 1999; Guerrini et al., 1999; Namiki, 2005; Nawy, 2001). The most significant mechanical parameters of the today well known HPC, refer to strength giving less attention to elastic modulus, or other characteristics related more to workability and durability. Because many characteristics of high performance concretes are interrelated, a change in one usually results in changes in one or more of the other characteristics. Consequently, if several characteristics have to be taken into account in producing a concrete for the intended application, each of these characteristics must be clearly specified in the contract documents. That is why the design documents of the two mentioned interventions should refer to a Guideline documents based on experimental investigations

Table 4. some significant figures of Limestone Concrete samples.

Time (Days)	Compressive strength (MPa)	Flexural tensile strength (MPa)	Dynamic elastic modulus (MPa)
1	80	10.8	43,491
2	91	15.2	44,900
7	103	18.9	46,000
28	118	20.6	48,100

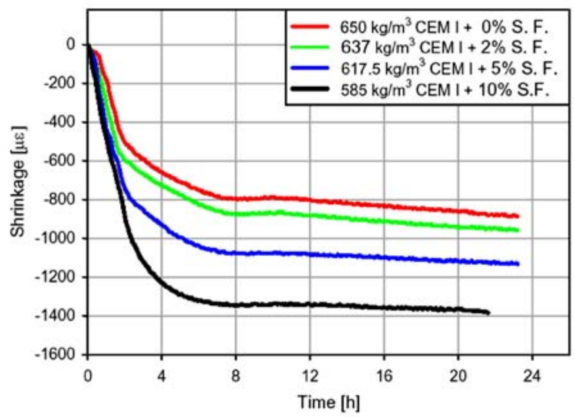
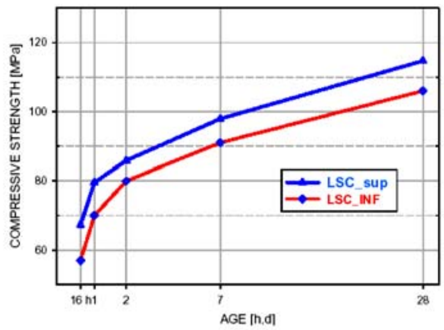


Fig. 7. Technical problems related to silica fume utilisation: plastic shrinkage (constant water/binder ratio) (Cangiano, 2005).

on different mix design best suited for different structural elements of a complex whole building, like are, for examples, underground retaining elements, underground elements in presence of water, floor slab elements, linear horizontal elements, vertical "core" elements. In particular the paper wants to introduce, as mentioned before, the campaign of tests aiming to produce large and well defined spectrum of mix design for particular HS/HPC based on fine aggregate of limestone. LSC's are classified as HS-HP concretes, with the advantages of being characterized by the complete absence of pozzolanic addition, i.e. silica fume, generally present as filling material in practically all type of HPC (De Larrard, 1993; Toutanji, 1995). Table 4 shows some first results of the mean significant mechanical characteristics of Limestone Concrete, and allows us to include Limestone Concrete in the range of HS/HPC, with advantages of being Self-Levelling and Rapid Hardening Concrete (Plizzari et al., 2003).

It is however recognized that the following problems are related to silica fume utilization: (a) the high cost (about 4–5 times the cost of cement), (b) the total shrinkage (plastic and hydraulic) of HPC containing silica fume (10%) may be greater than other HSC based on other mineral admixtures, (c) HPC with silica fume may exhibit a high tendency to desiccation and hence to early micro-cracking, as a consequence the long term durability may suffer, (d) several researchers found a loss of compressive strength between 90 days and 4 years of concrete with silica fume. Figure 7 underline the problems related to shrinkage behaviour when utilizing silica fume and concrete mix designs according to European Code (EN No. 197).

The main task of the experimental research on new generation of HSC using limestone (without any content of silica fume), is to identify a size distribution curve of the system composed by cement and aggregates in order to produce HPC's characterized by: (a) very good rheological properties and



Age	Compressive strength [MPa]	
	LSC_SUP	LSC_INF
16 h	67,3	57,5
1 d	79,6	70,3
2 d	85,8	82,7
7 d	97,9	92,4
28 d	114,7	105,2

Fig. 8. Strength development of two different mix of LSC.

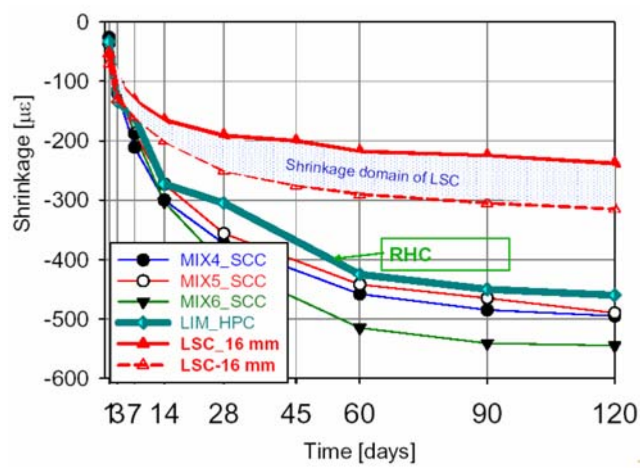


Fig. 9. The favourable performance of LSC respect to hydraulic shrinkage.

(b) rapid development of mechanical performances. In this starting-up phase of the experimental research, just few mix have been proposed and tested with the primar goal to prove the sensibility of the mechanical characteristic to small variations of size aggregates in the early stage.

The graphs and table of Figure 8 show the upper and lower bound of the strength development performance due to slightly different mix, where it is clearly show the rapid hardening characteristic of Limestone Concrete mix.

The favorable performance of LSC respect to shrinkage behavior is summarized in the graphs of Figure 9 where LSC is compaired with different mixes of SCC.

Further development of the research will be focused on obtaining LSC with specific characteristic for the specific used, identified as follows:

– for beams, pillars and floor-slabs → LSC with properties of HSC and RHC;
– for "core" structure → LSC with high resistance to temperature and with high toughness;
– for conteining walls → LSC with properties of durability against salts, very low permeability, low hygrometric shrinkage.

In any case Limestone Concretes, also fiber added, should develop creep characteristics as good as those of SCC.

Conclusions

The paper starts from the assumption that the use of high-strength, high-performance concrete (HS-HPC) is rising up, not only for pillars, in high-rise buildings. The research program undertaken by Politecnico di Milano-Universities of Bergamo and Brescia, which starting-up phase results are here reported, is primarily focused on Limestone Concrete samples tests, to state the mechanical characteristics requested not only by new codes, but also by new building design philosophy in case of high-rise buildings. As a matter of fact, the research on the scaled structural elements (wind test), or/and on numerical models simulating structural elements under impact or blast loading condition will be a necessary completion in the overall knowledge for the optimization of strength and performance capacity of the new HPCŠs and their selected use. The complete range of knowledge may produce a material highly competitive for the bearing structure of the high-rise buildings.

Acknowledgements

The authors acknowledge the researcher team of CTG-Italcementi Group, with particular reference to dott. L. Cassar and eng. S. Cangiano, for their comments regarding this paper.

References

Aitcin, P.C., 1999, *High Performance Concrete*, E&FN SPON.

Cangiano, S., 2005, "The LimeStone Concrete-LSC", CTG Italcementi Group-Scientific Committee, Bergamo, Italy, 14 April.

Cangiano, S. and Plizzari, G., 2004, "The rapid hardening concrete: a new perspective in bridge construction", *Concrete Bridge Conference*, North Carolina, 17–18 May.;

Chew Yit Lin, M., 2003, *Construction Technology for Tall Building*, Singapore University Press.

Concrete Society, 1997, *Proceedings of the Third International Conference "Conquest of Vertical Space in the 21th Century"*, organized by the Concrete Society, London, 7–10 October.

de Larrard, F. and C. Aitcin, P.C., 1993, "Apparent strength retrogression of silica-fume concrete", *ACI Materials Journal*, 90(6).

Eisele, J. and Kloft, E. (eds), 2003, *High-Rise Manual – Typology and Design, Construction and Technology*.

Fairweather, V., 2004, *Expressing Structure – The Technology of Large-Scale Buildings*, Birkhäuser – Publisher for Architecture.

Guerrini, G., Biolzi, L., Cassar, L. and Rosati, G., 1999, "Production and mechanical characterization of very high fibre-reinforced concrete beams", *International Conference "Creating with Concrete"*, Dundee, Scotland, UK, 6–10 September.

Kappos, A.J., 2002, *Dynamic Loading and Design of Structures*, Spon Press.

Kelham, S., 1998, "Portland Limestone Cements", *Concrete (London)*, 32(5), May.

Migliacci, A., Franchi, A., Acito, M. and Crespi, P., 2005, "Analytical and experimental procedures for the realigning of the 26th floor of the 'Pirelli' tall building after the airplane crash on April 2002", presented at the *IASBE Conference*, Lisbon, 14–16 September.

Montgomery, D.G., Van, B.K., Hinczak, I. and Turner, K., 1998, "Limestone modified cement for high-performance concretes", *Fly Ash, Silica Fume, Slag and Natural Pozzolanans in Concrete, Sixth CANMET/ACI/JCI Conference*, Bangkok.

Namiki, S., 2005, "State of the art and future of high-strength concrete technology", *Cement and Concrete*, 69j, January.

Nawy, E.G., 2001, *Fundamentals of High-Performance Concrete*, John Wiley.

Nehdi, M., Mindness S. and Aitcin, P.C., 1998, "Rheology of high-performance concrete: Effect of ultrafine particles", *Cement and Concrete Research*, 28 May 1998.

Person, B., 1998, "Seven-year study on the effect of silica fume in concrete", *Advanced Cement Based Materials*, 7.

Plizzari, G. and Cangiano, S., 2003, "HPC in structural applications and in building codes", *Celebrating Concrete: People and Practice*, Dundee, Scotland, UK, 3–4 September.

Rols, S. et al., 1999, "High performance concrete", in *Proceedings Second CANMET/ACI International Conference*, Gramado, Brazil.

Rosati, G., 1999, "High performance concrete applications in precast and prestressed concrete bridge slabs", *HPFRCC*, Mainz, Germany, 16–19 May.

Simiu, E. and Scanlan, R.H., 1996, *Wind Effects on Structures – Fundamentals and Applications to Design*, John Wiley & Sons.

Taranth, B.S., 1988, *Steel, Concrete and Composite Design of Tall Building*, McGraw-Hill.

Toutanji, H.A. and El Korki, T., 1996, "The influence of silica fume on the compressive strength of cement paste and mortar", *Cement and Concrete Research*, 25.