TECHNICAL TRANSACTIONS | CZASOPISMO TECHNICZNE
ARCHITECTURE | ARCHITEKTURA
8-A/2014

TERESA ZYCH*

NEW GENERATION CEMENTITIOUS COMPOSITES WITH FIBRES – PROPERTIES AND APPLICATION

FIBROKOMPOZYTY CEMENTOWE NOWEJ GENERACJI – WŁAŚCIWOŚCI I ZASTOSOWANIA

Abstract

The paper presents the properties of new generation cementitious composites with fibres, such as "bendable concrete" (ECC, Engineered Cementitious Composites) (plastic, not brittle but resistant to cracking material) with the addition of polyvinyl alcohol (PVA) fibres, high performance concrete (HPC) with glass fibres, reactive powder concrete (RPC) (characterized by ultra-high compressive strength, above 200 MPa) with short steel fibres. The detailed characteristics of the composition of the cement matrix and the role of fibres in the formation of the composite properties are described. Various applications of the composites as structural and architectural materials are also given.

Keywords: polyvinyl alcohol (PVA) fibres, glass fibres, steel fibres, bendable concrete (ECC – Engineered Cementitious Composites), reactive powder concrete (RPC), high performance concrete, ultra-high performance concrete, architectural concrete, concrete durability, cracks

Streszczenie

W artykule przedstawiono właściwości najnowszej generacji kompozytów cementowych z dodatkiem włókien, m.in. „betonów zginalnych" (ECC) (plastycznych, a nie kruchych przy zginaniu, odpornych na pękanie) z włóknami polialkoholowinylowymi (PVA), wysokowartościowych betonów (HPC) z włóknami szklanymi, betonów z proszków reaktywnych (RPC) (cechujących się ultrawysoką wytrzymałością na ściskanie – powyżej 200 MPa) z krótkimi włóknami stalowymi. Szczegółowo scharakteryzowano skład matrycy cementowej oraz opisano rolę, jaką spełniają włókna w kształtowaniu właściwości kompozytu. Pokazano możliwości zastosowania kompozytów jako materiałów konstrukcyjnych oraz architektonicznych.

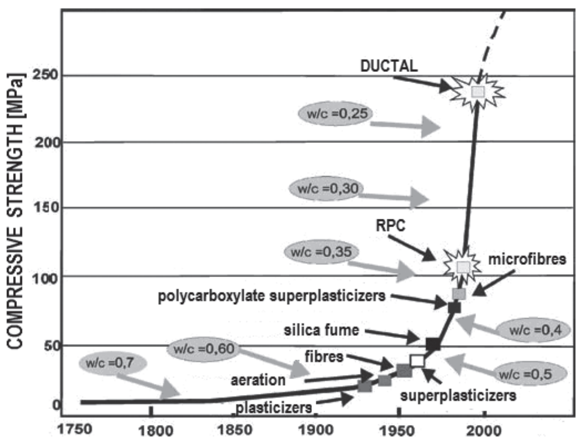
Słowa kluczowe: włókna polialkoholowinylowe (PVA), włókna szklane, włókna stalowe, beton zginalny (ECC), beton z proszków reaktywnych (RPC), beton wysokowartościowy, beton ultrawysokowartościowy, beton architektoniczny, trwałość betonu, rysy

* Ph.D. Teresa Zych, Institute of Building Materials and Structures, Faculty of Civil Engineering, Cracow University of Technology.

1. Introduction

The requirements given for concrete technologists by architects and constructors lead to the development of new types of concrete. The new generation **high performance fibre reinforced cement composites** (HPFRCC) presented in the paper: **reactive powder concrete** (RPC) with short steel fibres, **bendable concrete = engineered cementitious composite** (ECC) with **p**olyvinyl **a**lcohol (PVA) fibres, **high performance concrete** (HPC) with glass fibres are the effect of the modification of plain (conventional) cement concrete throughout many years.

During the past thirty years there has been considerable progress in concrete technology. Through the reduction of typical drawbacks of plain concrete (cement matrix microcracks resulting from shrinkage or excessive loading, destruction of the material in a brittle manner, as well as high open porosity, and thus high penetration of water and aggressive agents, low frost resistance) new types of cement composites have been obtained [9, 24]. The following changes in the composition of concrete have been introduced to provide better mechanical properties and durability: the significant reduction of water-cement (w/c) ratio, the application of cement binder with the highest strength, the filling of the intergranular space with small particles (e.g. silica fume) to obtain low porosity, the limitation of the size of inclusion grains (e.g. not applying coarse aggregate) in order to obtain a material of much higher homogeneity, as well as the addition of new generation admixtures (e.g., highly effective superplasticizers – polycarboxylates) to achieve good workability of composites [6, 24]. Furthermore, various types of fibres have been used in order to strengthen the matrix by the reduction of all kinds of cracks and the improvement of strength properties due to the interaction of fibres in the transfer of tensile stresses [4, 7, 11] (Ill. 1).



Ill. 1. Generalized curve of concrete development [9]

In the eighties of the 20th century, the following types of concrete were invented: **self compacted concrete** (SCC) characterized by very good workability and the lack of necessity of intentional concrete mixture compaction (due to new generation superplasticizers), **high performance concrete** (HPC) having not only high compressive strength (classes above C50/60 according to PN-EN 206-1 standard [46]), but also other properties of higher level (mainly low permeability for liquid and gaseous environmental media, high resistance to abrasion due to low value of water-cement ratio, the application of silica fume and new generation superplasticizers etc.) [3, 9].

The search for new types of high-performance concretes led to the determination of the composition of **reactive powder concrete** (RPC) and **bendable concrete = engineered cementitious composite** (ECC) in the 90s of the twentieth century. RPC with short steel fibres and ECC with polyvinyl alcohol (PVA) fibres constitute a group of **high-performance fibrous cementitious composites**, characterized by, apart from high durability, ultra-high compressive strength in the case of RPC (e.g., of 200 MPa) and ultra-high ductility in the case of ECC [18, 39]. Experimental studies concerning these composites are still carried out by research centres and universities from different countries around the world, and the latest research achievements are presented at international conferences: “International Symposium on **Ultra-High Performance** Fibre Reinforced **Concrete**” – “**UHPC**” (2009, 2013 – Marseille, France) [39], “International RILEM Conference on **Strain Hardening Cementitious Composites**” – “**SHCC**” (2009 – Stellenbosch, South Africa, 2011 – Rio de Janeiro, Brazil, 2014 – Dordrecht, the Netherlands), etc. In the case of **RPC** (**UHPC**) the leading countries in the world, both in research work and implementations are the USA, Canada, France, etc. [5, 15, 49, 52, 56], and in the case of **ECC** (**SHCC**), the USA, Japan, South Africa, Czech Republic, the Netherlands, etc. [17, 22, 55].

The paper contains up-to-date information on new generation high-performance fibre reinforced cementitious concretes, their composition, properties and the range of application as structural and architectural materials.

2. Reactive powder concrete

Reactive powder concrete (**RPC**) is one of the most advanced mineral building materials. The composite belongs to the group of **ultra-high performance concretes** (**UHPC**), i.e., concretes with 28-day compressive strength of above 150 MPa (typically 200 MPa) (high-performance concretes of lower strength: High-Performance Concrete /HPC/ with compressive strength of 60–120 MPa, Very High Performance Concrete /VHPC/ with compressive strength of 120–150 MPa) [7, 13, 17].

The composition of reactive powder concrete was developed in the early 90s of the 20th century, after a decade of research in the laboratory of **Bouygues** (a French company, which designs and constructs structures) [33, 34]. Concrete with a compressive strength of 200 MPa and flexural strength of 40 MPa was then obtained. The result of further research, carried out since 1994 by Bouygues together with the French companies: **Lafarge** (the manufacturer of concrete) and **Rhodia** (the manufacturer of building chemistry), was a patent for RPC. The innovative material was called **Ductal®** to emphasise in its name that the material is characterized not only by ultra high strength, but also by **ductility** [13, 24, 31, 32, 35, 38].

Nowadays, apart from Ductal®, RPC-type composites, offered as commercial products are: **BSI/Ceracem®** (**B**éton **S**pécial **I**ndustriel), produced by **Eiffage** (France)/**Sika**

(Switzerland), **BCV®** (**B**éton **C**omposite **V**icat), produced by **Vinci/Vicat** (France), etc. [35, 39]. Ductal® is most commonly used in the United States, Australia and Asian countries.

Reactive powder concrete is a fibre reinforced cementitious composite made from powders: the highest class of Portland cement (CEM I 52.5 R), silica fume, powdered quartz (0/0.1 mm), quartz sand (0/0.6 mm) as well as water, superplasticizer and the fibrous reinforcement in the form of short and very thin steel fibres (Ill. 2). RPC does not contain coarse aggregate and the average size of coarse particles is 200 µm (sand grains). Determining the composition of the composite is a complex problem, which involves not only the assumption of the appropriate ratio between the components with different grain size (in order to get possible maximal packing of the granular component), but also in their appropriate selection as to their physical and chemical properties [3, 7, 38]. The example of the proportion of the components (by mass) is as follows [6, 43]: cement: silica fume: ground quartz: sand: water = 1:0.2:0.34:0.81:0.24. A superplasticizer is used in the amount of about 2% of the weight of the cement. RPC is a self-leveling concrete, which does not require compaction. RPC is mostly manufactured in a concrete plant and is transported to the construction site.

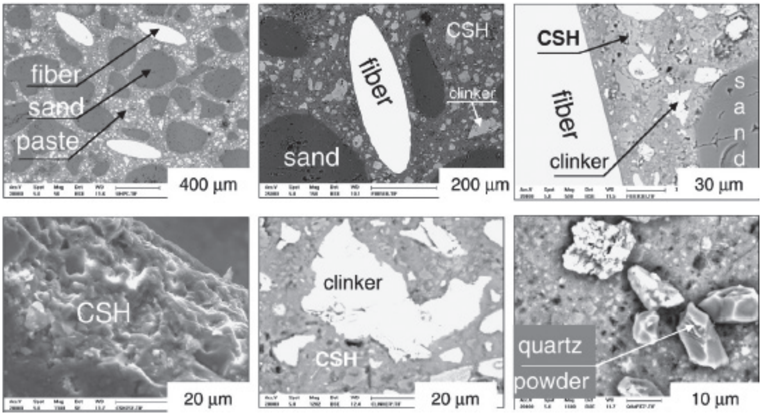
CEM I 52.5R Portland **Cement** (with the particle diameter /size/ of **1–100 µm**) is used in the amount of about 700 kg/m^3, which is more than double than in the case of ordinary concrete.

Silica fume (a by-product obtained in the metallurgical process during the production of metal silicon, ferro-silicon and other alloys) is a component of concrete of the smallest size. Microscopic grains of spherical shape, which are almost pure, amorphous **SiO_2**, have a diameter of less than 1 µm (**0.1–1 µm**). The average grain size is **0.2 µm** (cement particles are 100 times greater) [13, 28, 29]. Silica fume is characterized by an enormous surface area (from 130 000 to 200 000 cm^2/g measured by the BET method) [29]. A very large surface area of silica fume particles enables the adsorption of water and concrete mixture containing this additive hardens very quickly, thus the mix cannot be used without superplasticizers. Silica fume creates the microstructure of the cement matrix by physical (as a microfiller) and chemical interaction. The essential role of silica, due to its granulation, is to fill the empty spaces between the larger grains of cement and aggregate. In order to get the maximum possible packing of granular components, silica fume is applied in the amount of 20% of the weight of the cement. Silica fume results not only in sealing, but also in strengthening the cement matrix. As a result of the chemical reaction of silica fume (SiO_2) with calcium hydroxide $Ca(OH)_2$ (contained in cement paste) hydrated calcium silicates (**C**aO–**S**iO_2–**H**$_2$O) are formed, i.e. the additional amount of **C–S–H** (**C**alcium – **S**ilicate – **H**ydrate) phase [43].

Quartz flour=Ground quartz (=Quartz powder=Silica flour) (with the particle diameter of **0.1–100 µm**) complements the fine sand fractions and therefore the granulation of the ground quartz should be close to the cement's granulation. When the quartz grains are very fine (smaller than 5µm), the quartz (known for its low reactivity to $Ca(OH)_2$) may react with Ca^{2+} ions. The amorphous silica (silica fume)/crystalline silica (ground quartz) ratio should be selected in such a way that the forming of the C–S–H phase would take place by the C/S mole ratio within the range of 0.83 to 1.0 [37, 38].

Quartz sand (Silica sand) (with the particle diameter of **150–600 µm**) plays the role of a micro-aggregate [3, 37]. Granulation of quartz sand ought to be continuous to provide the tightness of the stack of particles when the micro-aggregate is mixed with ground quartz. Quartz sand is added in almost the same amount as the cement fraction.

Water/cement ratio is very low and is usually about 0.2 (lower than 0.28). Such a low amount of water (in particular at high temperatures of curing) reacts completely with the cement, which limits the possibility of formation of capillary pores effected by the evaporation of non-reacted water. The use of such low w/c ratio is possible by the application of new generation polycarboxylate superplasticizers (Ill. 1). The cement particles that are not totally hydrated serve as microfillers (Ill. 2) [7].



Ill. 2. RPC – microstructure (SEM images) [37]

Superplasticizer is added both because of the very low water-cement ratio and the presence of a fibrous inclusion that worsens workability.

Steel fibres (fibrous reinforcement of concrete), typically having a diameter of **0.2 mm** and a length of 12 mm (with dimensions not exceeding these values to ensure the homogeneity of the composite) are used in the amount of **2%** by volume (150 kg/m^3). Fibre properties are given in Table 1. The presence of fibres (taking over the tensile stresses) is intended to improve resistance to cracking of reactive powder concrete, which is a very brittle material [10, 45, 52].

Heat-moisture treatment of concrete (curing in a water vapour environment at higher temperatures) is applied for improvement of the microstructure of the cement matrix. The process, conducted in atmospheric pressure conditions (low-pressure treatment) or in autoclave (high-pressure treatment) affects the improvement of strength properties of the composite [1, 3, 6, 21, 37, 38]. The low-pressure heat treatment at the temperature of 90°C (in water vapour) [24] is specific in the acceleration of the cement hydration process and induction of pozzolanic reactivity of residual components, and then the amount of the C–S–H phase formed. It also affects positively the limitation of autogeneous shrinkage of the material which contains a substantial amount of binder [3, 6, 21]. The high-pressure heat treatment (steaming in the autoclave, e.g. for 2 days), conducted at the temperature of 250°C, may lead to the formation of crystalline hydrated calcium silicates (e.g. tobermoryte $C_5S_6H_5$ and ksonotlite C_6S_6H), which improve the mechanical properties of RPC [3, 38].

Table 1

Properties of fibres [7, 10, 23, 41, 53, 55]

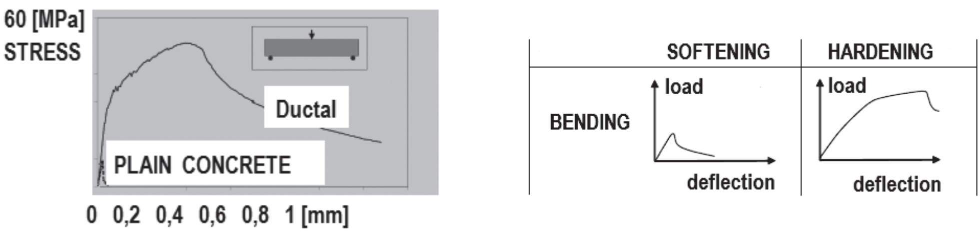
Type of fibre	Diameter [mm]	Density [g/cm³]	Tensile strength [GPa]	Modulus of elasticity [GPa]	Elongation [%]
Steel	0.20	7.8	2.2	210	3–4
Polyvinyl alcohol (PVA)	0.04	1.3	0.9	26	6–10
Glass (AR-Alkali Resistant)	0.01	2.8	2.2	70–80	0.5–4.0
Cement paste	–	2.0–2.2	0.003–0.006	10–30	–

RPC is characterized not only by ultra-high compressive strength (200 MPa), but also by other advantageous mechanical properties: flexural strength – above 20 MPa (Ill. 3), tensile strength – about 10 MPa (see Table 2), high resistance to impact and abrasion [39, 40, 47]. The research on the behaviour of RPC during tension has shown the formation of a large number of tiny cracks, but not big ones. Moreover, in RPC subjected to bending, no single, wide cracks have been observed (which do occur in the case of brittle composites), but many dispersed microcracks. Tiny cracks do not adversely affect the durability of the composite [10, 13]. RPC shows the increase in load capacity after the first crack during bending, i.e. hardening after cracking and therefore it belongs to the group of "deflection-hardening" composites (compare Chapter 3, Ill. 3, 16) [13].

Table 2

Properties of plain concrete, RPC, ECC, HPGRC [20, 21, 34, 35, 39, 40, 41, 47, 52, 53]

Property	Plain concrete	RPC	ECC	HPGRC
Compressive strength [MPa]	till 50	150–200	60–70	70
Tensile strength [MPa]	1–3	5–10	4–6	9
Strain during tension [%]	0.01	0.02–0.06	3–5	0.6
Modulus of elasticity [GPa]	15–40	50–60	20	17



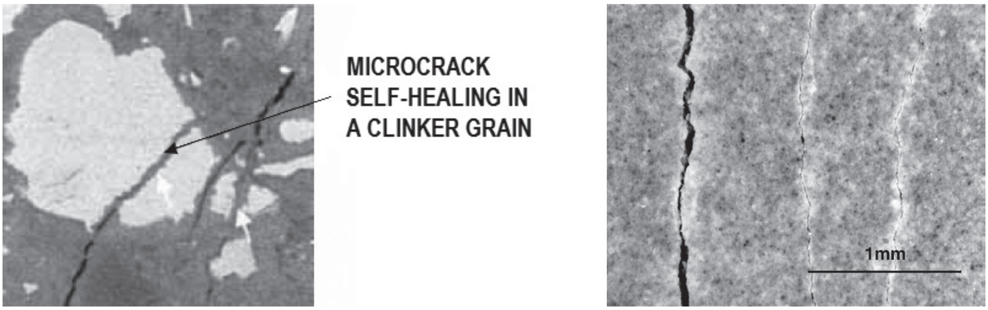
Ill. 3. Behaviour of RPC during flexion – hardening after cracking ("deflection-hardening") seen on the "stress-deflection" diagram [3]

Tight microstructure of RPC (open porosity: RPC: 1.5–6%, plain concrete: 12–16%; oxygen permeability: RPC < 10^{-19} m², plain concrete: 10^{-15}–10^{-16} m²; portlandite content:

RPC: none, plain concrete: 76 kg/m^3 [34]) prevents the penetration of any corrosive agents (harmful liquid and gaseous media) into concrete, and thus provides durability of the material. Reactive powder concrete, combining **ultra-high strength properties with durability**, may be suitable for buildings exposed to various aggressive environmental conditions.

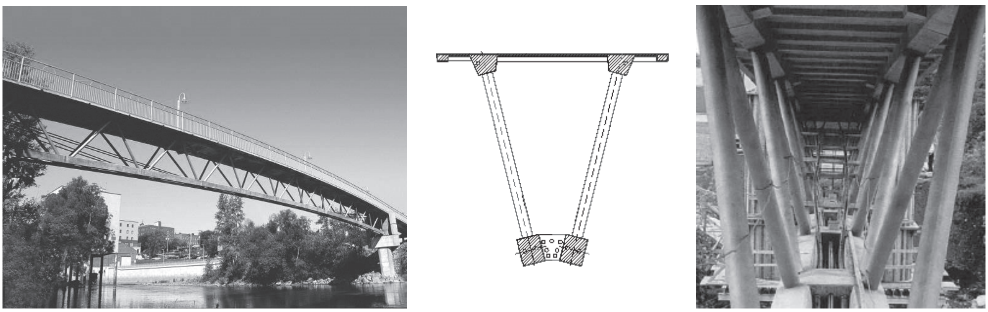
Moreover, the structure of concrete is constantly being sealed. In RPC **self-healing (self-sealing)** of microcracks has been observed. The particles of cement, which are not totally hydrated because of the use of a small quantity of water (w/c ratio of about 0.2), significantly improve material durability as they may potentially continue the hydration process whenever any micro-cracks appear (at the appropriate ambient humidity) [24]. The image of self-healing of microcracks is presented in Ill. 4a.

a) b)

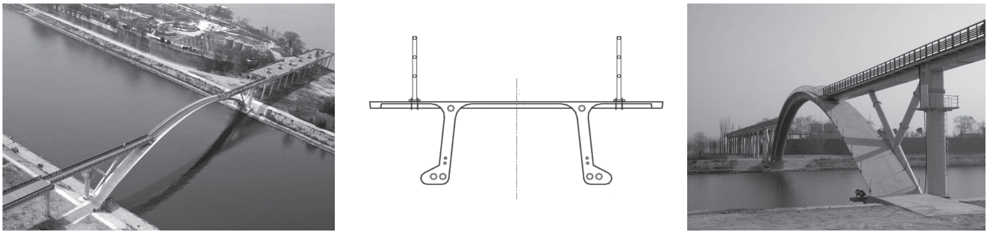


Ill. 4. Self-sealing of microcracks: a – RPC composite, b – ECC composite [23, 42]

Advantageous properties of reactive powder concrete have determined its application as a **structural** material from which are made:
– prefabricated structural elements (beams, girders, slabs, columns etc.), e.g. elements of footbridges (Ill. 5, 6) [31, 39] (these elements are slender and light as opposed to previously applied large, massive and heavy elements made of other materials),



Ill. 5. Application of RPC (Reactive Powder Concrete) – "Ductal®": "Sherbrooke footbridge" – the first structure in the world made of RPC (span: 60 m) (3 cm thick RPC slab, steel-concrete composite elements – RPC confined in steel tubes) – prestressed concrete structure, Sherbrooke, Canada, 1997 [24, 52]



Ill. 6. Application of RPC (Reactive Powder Concrete) – “Ductal®”: “Seonyu footbridge” (“Footbridge of Peace”) – the longest footbridge in the world made of RPC (span: 120 m) (3 cm thick slab, π-shaped cross-section of the arch) – prestressed concrete structure, Seoul, South Korea, 2002 [24, 52]

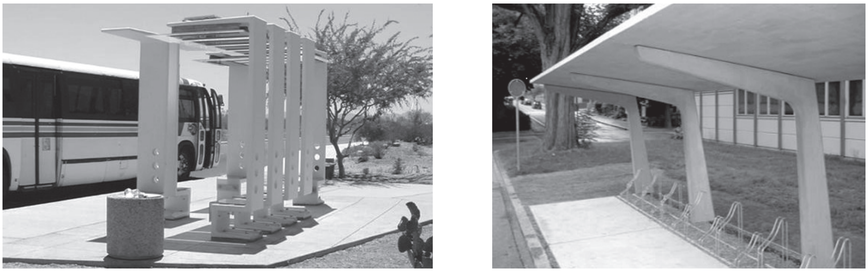
– elements of marine structures, hydraulic structures, etc., exploited in harsh environmental conditions, exposed to abrasion [31],
– roof shells (also with a complicated geometrical shape) such as railway (Ill. 7), car (Ill. 8), bus and cycling (Ill. 9) sheds,
– pipes [24].

Ill. 7. Application of RPC (Reactive Powder Concrete) – “Ductal®”: Shawnessy Light Rail Train (LRT) Station (RPC precast elements: ultra-thin (2 cm) curved roof shell, columns), Calgary, Canada, 2004 [40]

Ill. 8. Application of RPC (Reactive Powder Concrete) – “BSI/CERACEM®”: shed: Millau Viaduct Toll Gate, Millau, France, 2004 [49, 56]

The world’s first structure made of RPC (Ductal®) is a footbridge in Sherbrooke in Canada, built in 1997 (Ill. 5) [1, 5, 13]. The footbridge is a prestressed structure with the

a) b)



Ill. 9. Application of RPC (Reactive Powder Concrete): sheds: a – bus shelters, Tucson, Arizona, USA (“Ductal®”) [52], b – bicycle shed, Bern, Switzerland (“BCV®”) [47]

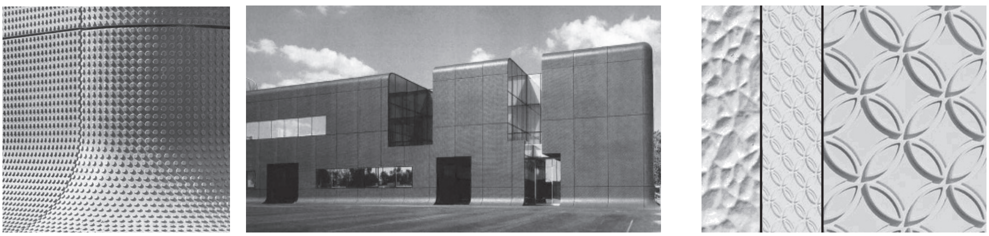
span of 60 m, made of prefabricated elements. RPC was used as a filler of steel tubes and to construct the bridge deck bottom which was 3 cm thick [53]. Nowadays the world’s thinnest coating made of RPC (2 cm thick) is a part of the roof (designed as Catalan surface) at Shawnessy Boulevard railway stadion in Calgary, Alberta, Canada (Ill. 7).

Reactive powder concrete is also applied as an **architectural** material from which are constructed:

– prefabricated cladding panels and façade sun-shades (with various textures – Ill. 11b), e.g. façade elements of bus station buildings (Ill. 11a), airport buildings (Ill. 12b), apartment and office buildings (Ill. 10, 12a), etc. [24],

Ill. 10. Application of RPC (Reactive Powder Concrete) – “Ductal®”: façade panels (curtain wall system) (ultra-thin), “The Atrium”, Victoria, Canada, 2010 [12, 52]

a) b)



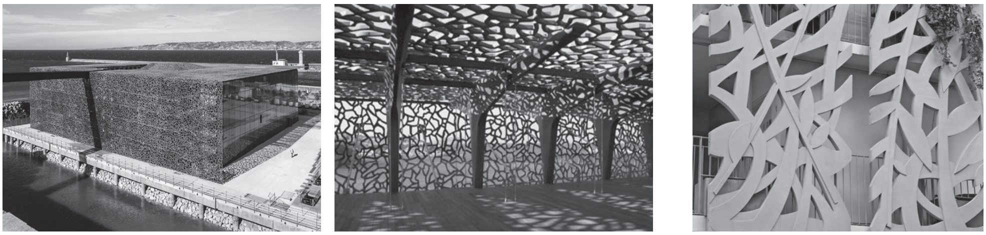
Ill. 11. Application of RPC (Reactive Powder Concrete) – “Ductal®”: a – façade panels (“LEGO® style” texture), Thiais RATP (Régie Autonome des Transports Parisiens) Bus Centre building, Thiais (near Paris), France, 2007 [12, 32, 50, 52], b – various textures of cladding panels [52]

a) b)

Ill. 12. Application of RPC (Reactive Powder Concrete) – “Ductal®”: façade panels – sun-shades (“double-skin façade”=“building envelope”), a – Plescop City Hall, Plescop, France, 2010, b – Rabat-Salé Airport building, Rabat, Marocco, 2011 [52]

– prefabricated façade elements with complicated shapes (Ill. 13) [32, 51, 52],
– pathways (Ill. 14),
– elements of interior furnishings: benches, tables (Ill. 15b), floor tiles, etc.,
– elements of parks and gardens “small architecture”: plant pots (Ill. 15a), urban and garden furniture, etc. [32],
– repair layers.

a) b)



Ill. 13. Application of RPC (Reactive Powder Concrete) – “Ductal®”: cladding (façade) elements, a – Museum of the Civilisations of Europe and the Mediterranean (MuCEM), Marseille, France, 2013 [51], b – housing block, ZAC Paris Rive Gauche, Paris, France, 2007 [52]

Ill. 14. Application of RPC (Reactive Powder Concrete) – “Ductal®”: pathway – “Flying Carpet”, Tomi Ungerer Museum – International Centre for Illustration, Strasbourg, France, 2007 [52]

a) b) c)

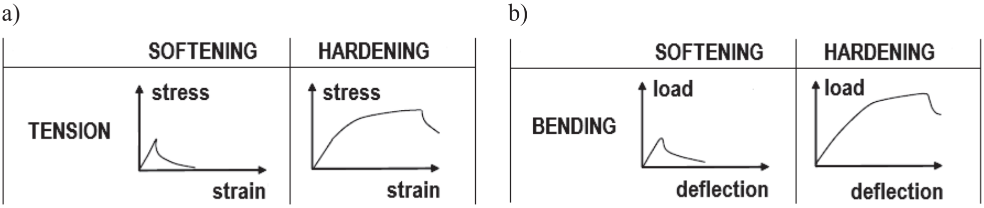
Fig. 15. Application of RPC (Reactive Powder Concrete) for "small architecture" elements: a – plant pots ("BSI/Ceram®"), Marseille, France, 2006 [49], b – litter-bin ("Ductal®") [52], interior elements: c – benches ("Ductal®") [30]

3. Bendable concrete

Bendable concrete - ECC (**E**ngineered **C**ementitious **C**omposite) belongs to the group of HPFRC (**High Performance** Fibre Reinforced Cement Composite) because of the **very high plasticity** of the material. As a fibrous material, ECC does not destruct in a brittle manner. The first publications about this material appeared in the 90s of the twentieth century. ECC is the effect of the research conducted by Professor Victor C. Li from the University of Michigan in the USA [33, 34].

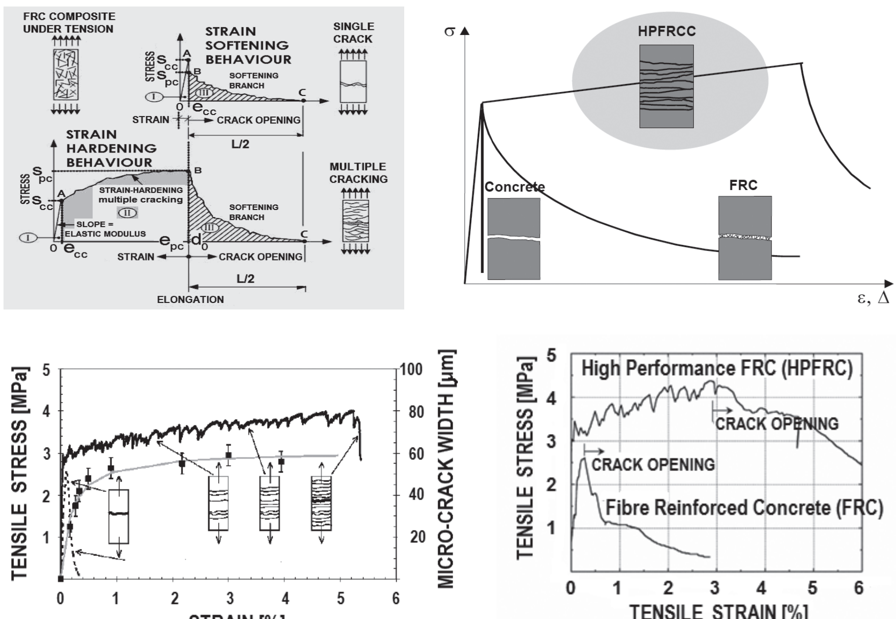
ECC is made from CEM I 42,5R Portland cement, siliceous fly ash, quartz sand, water, superplasticizer and fibrous reinforcement in the form of short polyvinyl alcohol (PVA) fibres. ECC does not contain coarse aggregate. The particle size (diameter) of composite components does not exceed 200 μm: **1–100 μm** (cement), **1-45 μm** (fly ash), up to **200 μm** (sand). The example of the proportion of the components (by mass) is as follows [42]: cement: fly ash: sand: water = 1:1.2:0.8:0.55. Superplasticizer is used in the amount of about 3% of the weight of the cement [42]. **PVA** (**P**oly**v**inyl **a**lcohol) fibres with a length of 12 mm and diameter of 39 μm (Tab. 1) are added in the amount of 2% by volume (26 kg/m^3) [7, 19, 20, 23, 42]. Siliceous fly ash should contain a minimum of 70% SiO_2+Al_2O_3+Fe_2O_3, a maximum of 5% sulphates calculated as SO_3 and the fineness should not exceed 34% (class F according to ASTM C618) [21]. A very high amount of fly ash, whose particles are smaller than cement grains, provides the uniformity of the cement matrix. The addition of fibres increases ductility (plasticity) of the composite.

New generation high performance fibrous composite ECC differs from plain **FRC** (**F**ibre **R**einforced **C**oncrete, known and widely used for several decades, see [4, 8, 11, 45]) in behaviour during **tension**. ECC is a ductile material. Strain during tension in the case of ECC is 3–5% (in comparison to **0.01%** for plain concrete, **0.02–0.06%** for RPC) [16, 17, 19] (Fig. 17). ECC shows **hardening** after cracking during tension and therefore it belongs to the group of "strain-hardening" composites (according to Naaman's classification from 2006 [27]); however, plain fibre reinforced concrete demonstrates softening after cracking, seen on the "stress-strain" curve (stress decreases after cracking) and belongs to the group of "strain-softening" composites (Ill. 16a).

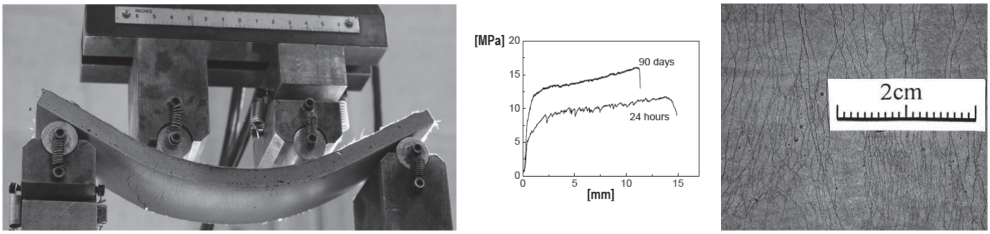


Ill. 16. Behaviour of composites during tension (a) and flexion (b): a – tension: softening after cracking (“strain-softening”), hardening after cracking (“strain-hardening”), b – flexion: softening after cracking (“deflection-softening”), hardening after cracking (“deflection-hardening”) [4, 7, 15, 20, 27]

In ECC subjected to tension, scattered microcracks with a width of less than 60 µm (about the size of half the diameter of a human hair) and ductile behaviour of material can be observed (see Ill. 17) [20, 42]. In the case of plain fibre reinforced concretes, the addition of fibres causes only the increase in concrete resistance to cracking (fibres take over tensile stresses and prevent the formation of cracks), but without visible changes in ductility. Contrarily, plain concrete destructs in a brittle manner (single cracks are formed, which may broaden very quickly and lead to the destruction of material). The presence of only micro-cracks, in the case of ECC, allows for **high durability** of this material because the transport of environmental media into the concrete takes place through the cracks with a width above 0.1 mm [7].



Ill. 17. Behaviour of ECC during tension – hardening after cracking (“strain-hardening”) seen on “stress-strain” diagram; the width of microcracks (s_{cc}/s_{pc} – first cracking /postcracking stress, e_{cc}/e_{pc} – first cracking /postcracking elongation) [16, 20, 21, 23, 27, 41, 44]



Ill. 18. Behaviour of ECC during flexion – hardening after cracking (“deflection-hardening”) seen on “stress-deflection” diagram and microcracks [20, 41]

Not only during tension, but also during bending, a large number of distributed microcracks and the lack of single, wide cracks are observed in ECC [20, 41] (Ill. 18).

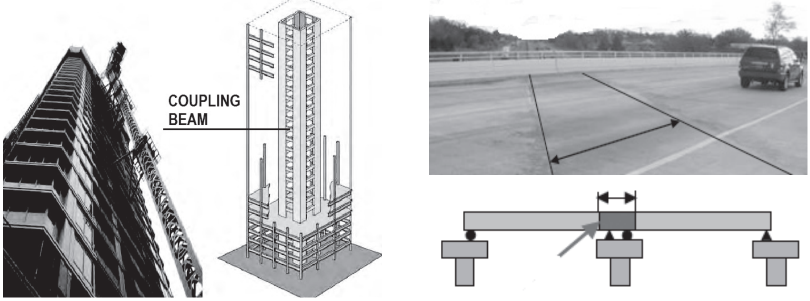
ECC shows plastic behaviour during bending, reaching a 28-day flexural strength of about 15 MPa. Bendable concrete is characterized by **hardening** after cracking during bending. Thus, it belongs to the group of “deflection-hardening” composites (according to Naaman’s classification [27]) (see Ill. 16). ECC has also high shear strength, impact, fatigue and abrasion resistance [18, 22, 44].

In ECC, similar to RPC, the phenomenon of **self-healing (self-sealing)** of microcracks has been observed. The continuation of the hydration process whenever any micro-cracks appear (at the appropriate ambient humidity) can result from the high content of fly ash in ECC [23, 42]. The image of self-healing of microcracks is presented in Ill. 4b.

Advantageous strength and durability properties of ECC (bendable concrete) have determined its application as a **structural** and **architectural** material from which are constructed:

- structural elements to protect against hurricane winds, earthquakes and other natural disasters (by the absorption of the energy by the material), e.g., coupling beams (Ill. 19a),
- other structural elements: bridge deck link-slabs (Ill. 19b), elements of road pavements, floor panels, etc.,
- pipes (produced by extrusion method),

a) b)

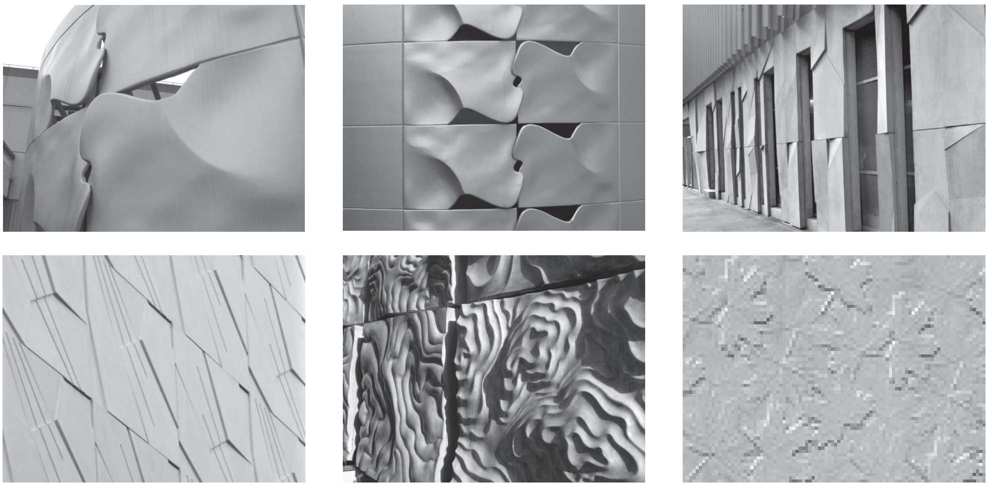


Ill. 19. Application of ECC: a – coupling beams, 41-storey building Nabeaure Yokohama Tower, Yokohama, Japan, 2010, b – bridge deck link-slab [18]

- architectural elements (prefabricated): cladding panels, façade sun-shades, elements of "small architecture" (e.g., benches, flower pots), etc.,
- protective coatings (as a corrosion protection), repair layers of e.g. bridge decks, strengthening of slopes with the application of spraying methods, etc. [17–20, 22].

4. High performance cementitious composite with glass fibres

Fibre reinforced cement composite with glass fibres (**GRC**, **GFRC** – **G**lass **F**ibre **R**einforced **C**oncrete), which belongs to the group of High Performance Concretes (**HPC**, see Chapter 1), is fibre reinforced mortar with a compressive strength of 50–80 MPa from which external cladding panels are obtained (Ill. 20) [48, 53, 54]. The example of the composition of fibre reinforced mortar (for the implementation of elements by spraying method) is as follows [53]: 50kg of CEMI 42.5R Portland cement, 50 kg of sand 0/2 mm, 5 kg of polymer, 13.5 kg of water, 0.5 kg of superplasticizer and 5% (by volume) of AR (**A**lkali **R**esistant) glass fibres (with the properties given in Table 1). High-performance cement-polymer mortar, having a tensile strength of about 9 MPa, shear strength of 8–11 MPa and modulus of elasticity of 10–20 GPa, is also characterized by high durability resulting from the tight structure of the composite [53].



Ill. 20. Application of HPGRC (High Performance Glass Fibre Reinforced Concrete): cladding panels [48, 53, 54]

5. Conclusions

New generation fibre reinforced cementitious composites are characterized in the paper. The possibility of the application of the latest advances in concrete technology for architects and constructors are presented. The high-performance cementitious fibrous composites of high strength and/or plasticity (ductility) as well as durability and aesthetics allow for designing "new cubature and shapes". By decreasing of the dimensions of construction elements (due to the high strength of the composites) and thus reducing the weight of the construction, it is possible to obtain slender and light construction elements (e.g. slabs of the thickness of 2 cm of RPC). Plastic composites (RPC, ECC) enable the formation of architectural elements of complicated shape with a smooth and non-cracked surface.

The article presents the possibility of the application of fibre reinforced composites as structural materials (to construct e.g. elements of footbridges, offshore and hydraulic structures, roof shells /RPC/, elements to protect against seismic actions /ECC/, road pavements) and as architectural materials /RPC, ECC, HPGFRC/ (to perform façade panels, elements with complicated shapes, e.g. elements of "small architecture", etc.). The application of new generation high performance concretes fits well with the strategy of sustainable development because of the durability of composites [1, 3, 9] and also in the case of ECC due to the use of a waste material: siliceous fly ash.

Despite the still high price (the cost of 1 m^3 of RPC from which the world's first building: the footbridge in Sherbrooke, Canada was made (Ill. 5) was around 1000US $ in 1997 [1]), the current price is below half of this amount, depends on the country and has varied considerably [52]; the cost of ECC is related to the high price of polyvinyl alcohol (PVA) fibres: 20 Euro/kg [55]; the cost of 1 m^2 of HPGFRC cladding panels is about 80-100 Euros [48, 54]) new generation fibre cementitious composites are the "concretes of tomorrow" because they allow architects and designers to fulfill the eternal principles of design as contained in an ancient work of Vitruvius (first century BC) "The ten books on architecture" ("De Architectura" Libri Decem): "Architecture is to keep the three principles: durability (firmitas), utility (utilitas), beauty (venustas)".

References

[1] Aïtcin P.-C., *Cements of yesterday and today. Concrete of tomorrow*, Cement and Concrete Research, 30, 2000, 1349-1359.

[2] Aïtcin P.-C., *High-Performance Concrete*, E&FN Spon, 1998.

[3] Aïtcin P.-C., *The art and science of durable high-performance concrete*, Conference "Concrete Days", Szczyrk, 8–10.10.2002, 7-36 (in Polish).

[4] Bentur A., Mindess S., *Fibre reinforced cementitious composites*, Taylor&Francis, 2007.

[5] Blais P.Y., Couture M., *Precast, prestressed pedestrian bridge – world's first reactive powder concrete structure*, PCI (Precast/Prestressed Concrete Institute) Journal, September–October 1999, 60-71.

[6] Brandt A.M., *Cement based composites: materials, mechanical properties and performance*, Taylor&Francis, 2009.

[7] Brandt A.M., *New generations of structural concrete*, Building Materials, 9, 2001, 182-188 (in Polish).

[8] Chawla K.K., *Fibrous materials*, Cambridge University Press, 2005.

[9] Czarnecki L., Kurdowski W., *Tendencies shaping the future of concrete*, Conference "Concrete Days", Wisła, 9–11.10.2006, 47-64 (in Polish).

[10] Glinicki M.A., *Concrete with structural reinforcement*, 25th Workshop for Structural Designers (“WPPK’2010”), Szczyrk, 10–13.03.2010, 279-308 (in Polish).

[11] Hannant D.J., *Fibre-reinforced concrete*, [in:] J. Newman, B.S. Choo (Eds.), *Advanced Concrete Technology. Processes*, Elsevier Ltd., 2003, Chapter 6.

[12] Henry K.A., Seibert P.J., *Manufacturing UHPC architectural products*, CPI (Concrete Plant International), Special Print: Concrete Technology, October 2011.

[13] Kaszyńska M., *HPC: opportunities, properties, applications*, 17th Workshop for Structural Designers (“WPPK’2002”), Ustroń, 20–23.02.2002 (in Polish).

[14] Kurdowski W., *Chemistry of cement and concrete*, Association of Cement Manufacturers / Polish Scientific Publisher, 2010 (in Polish).

[15] Lappa E.S., *High Strength Fibre Reinforced Concrete. Static and fatigue behaviour in bending*, PhD Thesis, Deft University of Technology, Deft, The Netherlands, 28.06.2007.

[16] Lepech M.D., Li V.C., *Long term durability performance of engineered cementitious composites*, International Journal for Restoration of Buildings and Monuments, Vol. 12, No. 2, 2006, 119-132.

[17] Li V.C., *Advances in ECC research*, ACI (American Concrete Institute), SP 206-23, 2002, 373-400.

[18] Li V.C., *Bendable composites. Ductile concrete for structures*, Structure, July 2006, 45-48.

[19] Li V.C., *Durable overlay systems with Engineered Cementitious Composites (ECC)*, International Journal for Restoration of Buildings and Monuments, Vol. 9, No. 2, 2003, 1-20.

[20] Li V.C., *Engineered Cementitious Composites (ECC) – material, structural and durability performance*, Concrete Construction Engineering Handbook, Taylor&Francis, 2008, Chapter 24.

[21] Li V.C., *High Performance Fiber Reinforced Cementitious Composites as durable material for concrete structure repair*, International Journal for Restoration of Buildings and Monuments, Vol. 10, No. 2, 2004, 163-180.

[22] Li V.C., Kanda T., *Engineered Cementitious Composites for structural applications*, Journal of Materials in Civil Engineering, Vol. 10, No. 2, 1998, 66-69.

[23] Li V.C., Yang E., *Self healing in concrete materials*, van der Zwaag S., Self Healing Materials. An Alternative Approach to 20 Centuries of Materials Science, Springer, 2007, 161-193.

[24] Łukasik U., J., Acker P., Vernet Ch., Behloul M., *Ductal®: ultrahigh-performance concrete with ductility*, Conference “Concrete Days”, Wisła, 11–13.10.2004, 111-124 (in Polish).

[25] Maeder U., Lallemant-Gamboa I., Chaignon J., Lombard J.P., *CERACEM – a new high performance concrete: characterization and applications*, International Symposium “Ultra High Performance Concrete” (“UHPC”), Kassel, Germany, 13–15.09.2004, 67-76.

[26] Mindess S., *High performance concrete: recent developments in material design*, International Seminar “Design and Application of High Performance Cement Based Materials”, IPPT PAN, Warszawa, 16–18.10.2003.

[27] Naaman A.E., *High performance fiber reinforced cement composites: classification and applications*, International Workshop “Cement Based Materials and Civil Infrastructure” (“CBM-CI”), Karachi, Pakistan, 10–11.12.2007, 389-401.

[28] Neville A.M., *Properties of concrete*, Association of Cement Manufacturers, Cracow, 2012 (in Polish).

[29] Nocuń-Wczelik W., *Application of silica fume in concrete technology*, Ceramic Materials, 2, 2007, 68-71 (in Polish).

[30] Perry V.H., Seibert P.J., *Manufacturing UHPC artisan products*, CPI (Concrete Plant International), Special Print: Concrete Technology, August 2011.

[31] Perry V.H., Seibert P.J., *Manufacturing Ultra-High Performance Concrete structural products*, CPI (Concrete Plant International), Special Print: Concrete Technology, June 2011.

[32] Perry V.H., Seibert P.J., *Working with Ductal Ultra-High Performance Concrete*, CPI (Concrete Plant International), Special Print: Concrete Technology, February 2011.

[33] Richard P., Cheyrezy M., *Composition of reactive powder concrete*, Cement and Concrete Research, Vol. 25, No. 7, 1995, 1501-1511.

[34] Richard P., Cheyrezy M., *Reactive Powder Concrete with high ductility and 200–800 MPa compressive strength*, ACI (American Concrete Institute), SP 144-24, 1994, 507-518.

[35] Russell H.G., Graybeal B.A., *Ultra-High Performance Concrete: a state-of-the-art Report for the Bridge Community*, Report No. FHWA-HRT-13-060, Federal Highway Administration, McLean (VA), USA, June 2013.

[36] Shah S.P., *High Performance Concrete: strength vs. ductility and durability*, International Symposium on Non-Traditional Cement & Concrete, Brno, Czech Republic, 11–13 June 2002, 347-358.

[37] Sorelli L., Constantinides G., Ulm F.J., Toutlemonde F., *The nano-mechanical signature of Ultra High Performance Concrete by statistical nanoindentation techniques*, Cement and Concrete Research, 38, 2008, 1447-1456.

[38] Śliwiński J., Zdeb T. *Reactive Powder Concrete (RPC) as ultra high strength cement-based composite*, New Generation Cement Concretes (NGCC) − Ideas, Design, Technology and Applications, LLP-ERASMUS-IP 9203-0574, Kraków 2010, 108-122.

[39] Toutlemonde F., Resplendino J. (editors), *Designing and building with UHPFRC: state-of-the-art and development*, John Wiley&Sons, 2011.

[40] Vicenzino E., Culham G., Perry V.H., Zakariasen D., Chow T.S., *First use of UHPFRC in thin precast concrete roof shell for Canadian LRT Station*, PCI (Precast/Prestressed Concrete Institute) Journal, Vol. 50, September-October 2005, 50-67.

[41] Wang S., Li V.C., *Polyvinyl alcohol fiber reinforced engineered cementitious composites: material design and performances*, International RILEM Workshop “High Performance Fiber Reinforced Cementitious Composites (HPFRCC) in Structural Applications”, Honolulu, Hawaje, 23–26.05.2005, 65-73.

[42] Yang Y., Lepech M.D., Yang E.-H., Li V.C., *Autogenous healing of engineered cementitious composites under wet-dry cycle*, Cement and Concrete Research, 39, 2009, 382-390.

[43] Zdeb T., Śliwiński J., *The influence of steel fibre content and curing conditions on mechanical properties and deformability of Reactive Powder Concrete in bending*, 9th International Symposium “Brittle Matrix Composites” (BMC 9), Warszawa, 25–28 October 2009, 33-42.

[44] van Zijl G.P.A.G., Wittman F.H., *Durability of strain-hardening fibre-reinforced cement-based composites (SHCC)*, RILEM State-of-the-Art Reports, Vol. 4, Springer, 2011.

[45] Zych T., *Contemporary fibre reinforced concrete – possibility of forming of structural elements and architectural forms*, Czasopismo Techniczne (Technical Transactions), 8-A, Issue 18, 2010, 371-386 (in Polish).
[46] PN-EN 206-1:2003 Concrete–Part 1: Specification, properties, production and conformity (in Polish).
[47] http://f2fcontinuum.wordpress.com/notes-on-materials-and-techniques; access: 15.09.2013.
[48] http://www.architecturalmaterials.com/gfrc-high-performance-cement-cladding; access: 15.09.2013.
[49] http://www.bsieiffage.com; access: 15.09.2013.
[50] http://www.dezeen.com/2007/12/03/thiais-bus-centre-by-ecdm-architects; access: 15.09.2013.
[51] http://www.designboom.com/architecture/mucem-by-rudy-riccioti-sports-a-delicate-concrete-filigree; access: 15.09.2013.
[52] http://www.ductal-lafarge.com; access: 15.09.2013.
[53] http://www.grcenvironments.com.au; access: 15.09.2013.
[54] http://www.grcuk.com; access: 15.09.2013.
[55] http://www.kuraray.eu; access: 15.09.2013.
[56] http://www.nxtbook.fr/newpress/Sika/ceracem; access: 15.09.2013.
[57] http://www.theconcreteportal.com/reac_pow.html; access: 15.09.2013.