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Innovation and Application of Ultra High Performance Concrete

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Abstract—*Regards on its strength, durability, resistance, shape versatility, low maintenance, and cheap price; concrete is the most used construction material. Thus, the existing building stock throughout the world widely constructed of RC (reinforced concrete) structures in which either NSC (Normal Strength Concrete) or HSC (High Strength Concrete) are used. However, increasing demand of structures having remarkable varieties in size and shape has led to the necessity of utilizing advanced construction materials. In order to response this demand, since the last two decades, a very high strength and ductility cement based composite named RPC (Reactive Powder Concrete) had been developed. Intensive research and development in this field worldwide now enables the use of concrete with extremely high strength, ductility, and durability called UHPC (Ultra High Performance Concrete). UHPC can be applied and used in a wide variety of structural applications, including those built in severe environment. UHPC suits to be used in structures which require less weight, greater spans and durability. Considering the important outstanding properties of UHPC, this paper reports the innovation and current applications of UHPC.*

Keywords — *RPC, Ultra High Strength Concrete, UHPC*

I. INTRODUCTION

Indonesia is an archipelago country which lays among three active and unstable tectonic plates (Indian, Indo-Australian and Pacific plate); and passed by the Ring of Fire, a giant curve where a rapid volcanic mountains laid, that causes lots tectonic earthquakes (80% earthquakes happen in the world have epicentre in this area). Therefore, as a country that very critical to disaster (i.e.: earthquake, tsunami, flood, landslide, etc), Indonesia is in the need to have high resistant buildings and infrastructures in order to minimize victims, reduce loss and damage. Besides that, the survived building and infrastructure facilities could be alternative places to survive and take shelter, when and after disaster. Unfortunately, most of building and infrastructure facilities in Indonesia, even the important ones (i.e.: public, government and other critical facilities) are not built as disaster resistant structures; consequently when disaster happen, there are many victims, loss and damage (for example: Aceh (2004) and Yogyakarta (2006) earthquakes which caused death and displacement of thousands people).

Concrete is considering as the most widely used material for constructing a wide range of buildings and infrastructures, due to its high strength, durability, resistance, shape versatility, low maintenance, and low price. However, the current available types of concrete either NSC (Normal Strength Concrete) or HSC (High Strength Concrete) have not answered the increase demand of structures having remarkable strength, and varieties in size and shape. Thus, these have led to the necessity of utilizing advanced construction material.

In order to increase public safety and protect public property from the destructive effects caused by overload loadings, since the last two decades, a very high strength and ductility cement based composite named RPC (Reactive Powder Concrete) had been invented. The further intensive research and development of RPC worldwide enables the use of concrete with extremely high strength, ductility, and durability named UHPC (Ultra High Performance Concrete) to be applied in a wide variety of structural applications, including those built in severe environment. The superiority material of UHPC allows this type of concrete to be used in structures which require less weight, greater spans and durability. In this paper, attention is focused into the innovation and current applications of UHPC worldwide.

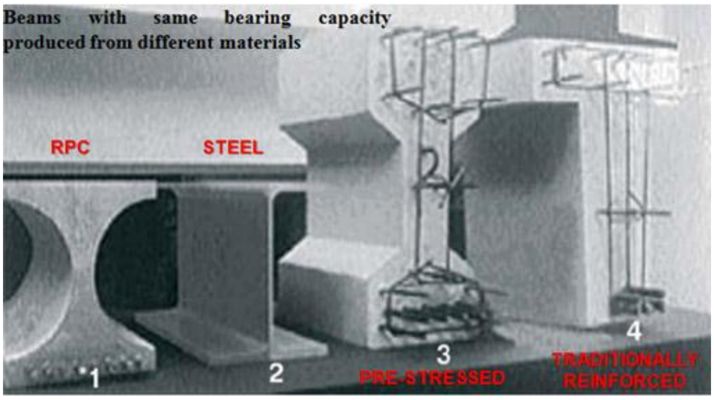
II. REACTIVE OF POWDER CONCRETE (RPC)

At the present time, HSC is not the strongest and most high performance concrete on earth; because after years of carefully thinking and efforts, researchers have found a remarkable technological breakthrough named RPC, a natural extension of the existing HSC which has many enhancements in its material properties.

RPC is a super plasticized and silica fume-cement based mixture material which has a very low water cement ratio (w/c) characterized by the presence of very fine quartz sand instead of ordinary coarse aggregate. The absence of coarse aggregate is considered to be a key aspect for the microstructure and performance of RPC, in order to reduce the heterogeneity between its cement matrixes and aggregate [1-2]. RPC provides improved seismic performance of concrete structure by reducing inertia loads with lighter members, allows larger elastic deflection by reducing cross sections, provides higher energy absorption, and improves concrete confinement [3-7].

A comparison of sections depth and weight of beam cross sections made from variety materials, but having equal moment capacities are shown in Fig. 1. Next, a comparison of stress-strain curves among NSC (Normal Strength Concrete), HSC and RPC is illustrated by Dallaire *et al.* as in Fig. 2. It can be seen here, that the presence of fibers and confinements can significantly enhance the strength of RPC.

Between the year of 1990 and 1995, RPC was first investigated by Bouygues [8]. Following that, in 1997, the first world's engineering structure made by RPC was built by Ductal® in Sherbrooke, Quebec, Canada; namely the Sherbrooke Pedestrian Bridge.



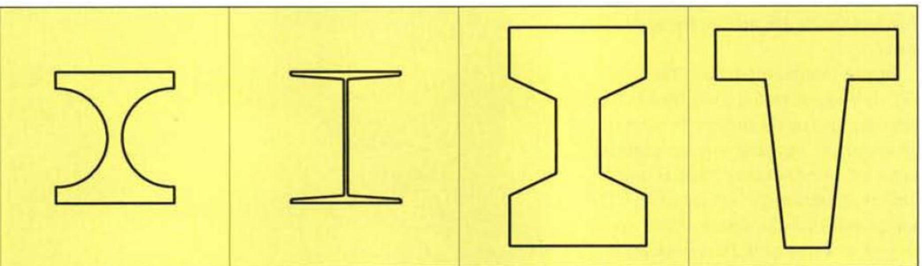
Cross Section Schematic (Reinforcing bars and tendons are omitted)								
Type of beam	Reactive powder concrete, X-shaped		Steel wide flange		Prestressed concrete		Reinforced concrete	
Section depth	360 mm	14 in.	360 mm	14 in.	700 mm	27.6 in.	700 mm	27.6 in.
Weight	130 kg/m	87 lbs per ft	110 kg/m	74 lbs per ft	470 kg/m	316 lbs per ft	530 kg/m	356 lbs per ft

Figure 1. Comparison of sections depth and weight of beam cross section made from variety materials, but having equal moment capacities [9].

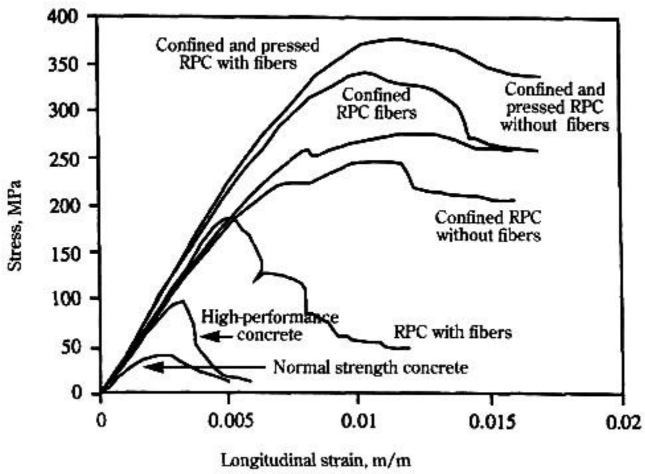


Figure 2. Stress-strain curves of NSC, HSC and RPC, 1998 [10].

III. ULTRA HIGH PERFORMANCE CONCRETE (UHPC)

1. Fundamental principles

The development of UHPC (henceforward RPC is written as UHPC) is made possible regards on the utilization of fundamental principles of the composition, mixing, casting and post-set heat curing of concrete [8]; as following:

1) Enhancement in homogeneity
   For reducing the mechanical effects of heterogeneity between cement matrixes and aggregates in UHPC, the use of very fine quartz sand is important to gain better microstructure, hence better performance of UHPC. Large aggregates are avoided to eliminate large stress concentrations, as it would reduce the strength.
2) Enhancement in compacted density
   For optimizing granular mix in the mixture of UHPC, silica fume is added to act both as filler and pozzolanic material. Silica fume behaves as micro filler in space (thus reduce porosity), whilst provides a lubrication effect. As a pozzolanic material, silica fume reacts chemically with CH, forming compounds with cementitious properties (C-S-H or Calcium Silicate Hydrate), thus improves the mechanical properties of cement paste. For maintaining a very small space within cement grains and interfacial zone, the use of a very low water-cement ratio is also applied. The amount of water is kept as lowest as possible, and water is managed to be used only for hydration purpose; while the non-hydrated cement particles behave as fillers. For achieving sufficient workability of fresh paste of UHPC within a very low water-cement ratio condition, a superplasticizer is needed.
3) Enhancement in microstructure
   For enhancing the UHPC performance, optionally the microstructure of UHPC can be improved through production processes such as the application of pressure or heat curing. However, the difficulties of these technologies and its cost must be considered.
4) Enhancement in ductility
   Not only for increasing the ductility, tension and flexural capacities; but also for toughening; fine fibers can be added in the UHPC mixture. Henceforward, the new form of UHPC namely UHPFRC (Ultra High Performance Concrete Fiber-Reinforced Concrete) is made.

The first three principles will produce a very high compressive strength of concrete; however its ductility is not much better than that of HSC. Therefore, the addition of fiber in the mixture of UHPC is significant for obtaining higher value of ductility. Maintaining mixing and casting procedures as close as possible to existing practice, is also another principle of making UHPC.

2. Constituents

The UHPC constituents can be described as following:

1) Fine and coarse aggregates
   Firstly, the aggregate sizes used in UHPC was limited to a maximum size of 1 mm (i.e.: RPC used a maximum aggregate size of 0.5 mm), however later UHPC can be made with a larger diameter of aggregates. Schmidt and Fehling *et.al* [11] demonstrated that UHPC having a compressive strength of 150 N/mm^2 can be reached by using maximum diameter aggregates of 8 and 16 mm.
   However, the Japan Draft Recommendation of UHSFRCS [12] recommends that the aggregates used in UHPC should have the maximum particle size less than 2.5 mm. The use of quartz sand is also proposed, as it employs high hardness and offers good interface between pastes and aggregates [13]. Nevertheless, a slightly difference of term is made between fine and coarse aggregates in UHPC; whereas aggregates having diameter <1 mm is called fine grained aggregates, while >1 mm is called coarse grained aggregates.
   In order to obtain high compactness with a very low permeability, the grain size distribution among aggregates, silica fume and cement have to be optimized. While to obtain workable mixture with a water/cement ratio <0.20, fine aggregates having a low water demand in combination with suitable cement and appropriate additives should be used. However, unfavorable shapes of aggregate can negatively influence the water demand of fresh mortar.

2) Cement
   Portland cement with a low C3A content is desirable to be used in a UHPC mixture, as it requires a relatively lower water demand and less superplasticizers within similar strength and workability among others.
   High-silica-modulus cement is the best cement to be used in a UHPC mixture, regards on its rheological characteristics and mechanical performance; however this type of cement has a very slow setting rate. On the other hand, quick-setting high performance cements provide similar mechanical performance, despite its high water demand. Schachinger *et al.* [14] shows that the use of Blast Furnace cements of CEM III/B 42.5 NW/HS contained 12% of silicafume and storaged at 20^0C, will produce a 28 days compressive strength of 160 N/mm^2. However, in one day heat treatment at 90^0C, starting at the first day of the age, a compressive strength of 180-215 N/mm^2 can be obtained.
   Regards on the low level of water/cement ratio in the UHPC mixture, cement contents between 100-600 kg/m^3 are essentially used. Cement contents as low as 500 kg/m^3 leads to a successful of UHPC mixture.

3) Silica fume
   The preferable silica fume used is the non-compacted ones, totally disaggregated and free of impurities. Silica fume in the form of slurry must be avoided as its water quantity will exceed the total required water in the UHPC mixture. The best result of silica fume can be gained from the zirconium industries.
   The silica fume/cement ratio used in the UHPC mixture is 0.25, as it responds to the optimum filling performance and is close to the required dosage for a complete lime consumption of the total cement hydration. However, as in UHPC its cement hydration is incomplete, consequently the quantity need of silica fume is often more than the required of cement reaction.

4) Quartz powder
   Quartz powder is an inert material, which does not chemically react with cement or water. It is used to produce an optimized high packing density of UHPC mixture. The use of quartz powder in the UHPC mixture will effect in a 20% increase of compressive strength without a reduction in the equivalent water/cement ratio. The 20% of cement in the UHPC mixture can be replaced by quartz powder, without a forced reduction of the equivalent water/cement ratio [15-18]. The particle size of quartz powder which can be used in the UHPC mixture is in the range of 5-12µm, with the mean of 10µm [19].

5) Superplasticizers
   The most sufficient superplasticizers can be used in the UHPC mixture, are those having polyacrylate-based dispersing agents (i.e.: PCE or Polycarboxylatether), however problem in practical applications may occur as it exhibits a retarding characteristic. The consequence of a low level of water/cement ratio in the UHPC mixture is the high optimum ratio of superplasticizers is required (1.6% solid content of cement content).

6) Fibers
   Fibers are added in the UHPC mixture in order to improve ductility, tension and flexural capacities of the UHPC. The dimensions of fibers used are: length in the range of 8-16 mm, diameter in the range of 0.08-0.5

mm (the best mean diameter to be used is in the range of 0.1-0.2 mm). For optimizing the effectiveness use of fibers in the UHPC mixture, the ratio between fiber length and maximum aggregate size used in the UHPC mixture should be at least 10.

Schmidt *et al.* [20, 21] demonstrated that steel fibers are best suited to improve ductility in the post-cracking stage of UHPC. The polypropylene fibers 0.3-0.6% of volume will increase the fire resistance of UHPC structures; however special attention is required in term of its workability.

UHPC using short fiber, which is heat-treated at >250°C will experience the enhancement in its mechanical performance both in compressive and tensile strengths, as its fracture energies are reduced. Steel fibers having a length of 13 mm, diameter of 0.15 mm, and with an amount of 2-2.5% of volume exhibits a ductile behavior to UHPC structures [19].

A precise combination of aggregates, cement, silica fume, quartz powder, superplasticizers and fibers in a UHPC mixture will develop UHPC structures which have outstanding properties as follows:

- Have a very high compressive strength (exceeding 200 MPa); resulting a significant save in the dead load of overall structures, due to the reduce cross section areas in structural members.
- Have a very high tensile strength (over 40 MPa); may eliminating the need of steel reinforcement.
- Have a very high flexural strength (over 50 MPa); tolerating the expand range of structural shapes and forms needed by architects for aesthetic possibilities.
- Have a very high durability to freeze-thaw cycles, chloride penetration, abrasion resistance, and carbonation; contributing to the overall structural performance, improving construction safety, providing longer service life, and lowering maintenance cost.
- Have a very high ductility; providing greater reliability under overload conditions.

Next, Table 1 illustrates the typical compositions and material properties among NSC, HSC and UHPC [22].

Table 1. Typical compositions and material properties among NSC (ordinary concrete), HSC and UHPC

		Ordinary concrete	HSC [1]	UHPC [2]
matrix composition	Component:	[kg/m^3]	[kg/m^3]	[kg/m^3]
	Portland cement	< 400	410	700 - 1000
	Coarse aggregate	≈ 1000	920	0 - 200
	Fine aggregate, sand	≈ 700	620	1000 - 2000
	Silica fume	-	40	200 - 300
	Superplasticizers	-	5	10 - 40
	Water	> 200	100 - 150	110 - 200
	Water-cement ratio	> 0.35	0.28 - 0.38	< 0.24
	Water/binder ratio		< 0.38	< 0.22
	Reinforcement / Fibres [kg/m^3]	designed	designed	> 150
properties	Density [kg/m^3]	2000 - 2800	2000 - 2800	> 2500
	Compressive strength [MPa]	< 60	60 - 100	> 150
	Tensile strength [MPa]	< 3	< 5	> 8
	Initial modulus of elasticity [GPa]	≈ 30	< 45	50 - 70
	Fracture energy [J/m^2]	30 - 200 [3]	< 150 [4]	< 90 without fibres [4] > 10 000 with fibres

[1] [Larrard, Sedran 2002], [2] [Graybeal, Hartmann 2003], [Reda et al. 1999], [Graybeal 2006], [3] [CEB 1993], [4] [Wittmann 2002]

IV. APPLICATION OF UHPC

Since the invention of RPC by Bouygues in 1997, the world's first UHPC structure was successfully constructed in the form of a 60 m (190 ft) span lightweight prestressed space-truss bridge named the Sherbrooke Pedestrian Bridge, in Quebec, Canada by Ductal® (see Fig. 3.a). Besides, having no passive reinforcements on its entire structure, this bridge has a deck thickness of 3 cm (1.25 in) which able to withstand 200 MPa compression strengths, while the RPC filled inside the 2 mm thick-wall stainless steel tubes can withstand 350 MPa compression strenghts [23].

In 2002, the world's first UHPFRC (Ultra High Performance Fiber-Reinforced Concrete) structure was also successfully constructed in the form of a slender arc pedestrian bridge crossing Han River named the Seonyu Footbridge, in Seoul, South Korea by Bouygues Construction [24]. The bridge has a 120 m span of arc consists of six voussoirs, whereas each has a length of 20 m and a deep of 1.3 m, and is supported by 3 cm thick deck (see Fig. 3.b).

In the same year, a 50 m (164 ft) span box girder pedestrian bridge named the Sakata Mirai Bridge was built by Taisei Construction, as the first structural application of UHPC in Japan (see Fig. 3.c). The decks of Sakata Mirai Bridge consist of 2.4 m (8 ft) wide simple beams having circular web holes. Its entire structure is longitudinally prestressed by an external prestressing and has no passive reinforcement.

Next, the bridge over Shepherds Creek in New South Wales, Australia was claimed as the first highway traffic UHPC bridge in the world. The construction of the Shepherd's Creek Bridge was carried out by VSL Australia. Having a span of 15 meters, a width of 21 meters, and an in-situ 170 mm thick reinforced concrete deck slab; this bridge serves four traffic lanes and a footway [25]. The bridge's reinforced concrete slabs placed onto thin precast UHPC permanent formwork panels (Fig. 3.d).

Another project is the Papatoetoe Station Footbridge in Auckland, New Zealand; it is also the first of its kind in the region. The Papatoetoe Bridge has a total length of 265 meters, and it consists of 15 simply supported spans of 20 meters long. Its deck is 50 mm thick with no ordinary reinforcement, and it has two symmetrical legs having large circular holes for responding into architectural interest and weights reduce (Fig. 3.e). The bridge's major upgrade was completed in August 2007 by VSL Australia [25].

In 2007, the first European composite bridge made with UHPC was constructed across the Fulda River, in Kassel [26]. The Gärtnerplatz Bridge which has a deck thickness of 8-12 cm, is a 140 m span space frame steel and UHPC composites pedestrian bridge that had been planned to hold a designed load of 60 kN (Fig. 3.f).

a. Sherbrooke Pedestrian Bridge, in Quebec, Canada[27].

b. Seonyu Footbridge, in Seoul, South Korea [24].

c. Sakata Mirai Bridge, in Yamagata, Japan [28].

d. Shepherd's Creek Bridge, in NSW, Australia [25].

e. Papatoetoe Station Footbridge, in Auckland, New Zealand [25].

f. Gärtnerplatz Bridge, in Kassel, Germany [26].

Figure 3. UHPC infrastructures worldwide

V. CONCLUSION

This paper has reported the current innovation of UHPC and its application worldwide. The beginning invention of RPC; the fundamental principles of UHPC in its composition, mixing, casting and post-set heat curing; and the UHPC constituents have also been described. However, this paper has not scoped everything of UHPC. Intensive investigations relate of UHPC worldwide currently is developing in order to apply an advanced type of concrete having superior characteristics in more structural applications effectively and efficiently.

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REFERENCES

[1] Acker P., and Behloul M. 2004. *Ductal Technology: A Large Spectrum of Properties, A Wide Range of Applications.* Proceedings of the International Symposium on Ultra High Performance Concrete, Kassel, Germany.

[2] Buitelaar P. 2004. *Heavy Reinforced Ultra High Performanc Concrete.* Proceedings of the International Symposium on Ultra High Performance Concrete, Kassel, Germany.

[3] Cadoni E., Caverzan A., and di Prisco M. 2008. *Dynamic Behavior of HPFR Cementitious Composites.* Proceedings of the Second International Symposium on Ultra High Performance Concrete, Kassel, Germany.

[4] Habel K., Denarie E., and Bruhwiler E. 2007. *Experimental Investigation of Composite Ultra-High-Performance Fiber-Reinforced Concrete and Conventional Concrete Members.* ACI Structural Journal, Vol. 104, No. 1, pp. 93-101.

[5] Noldgen M., Riedel W., Fehling E., and Thoma K. 2008. *Impact on Structural Ultra High Performance Concrete (UHPC) Elements in High Rise Buildings.* Proceedings of the Second International Symposium on Ultra High Performance Concrete, Kassel, Germany.

[6] Shaheen E, and Shrive N.G. 2006. *Optimization of Mechanical Properties and Ductility of Reactive Powder Concrete.* ACI Materials Journal, Vol. 103, No. 6, pp. 444-451.

[7] Vogel H., Davoudi S., Noel M., and Svecova D. 2008. *Evaluation of Properties of High Strength Concrete for Prestressed Concrete.* Proceedings of the Second International Symposium on Ultra High Performance Concrete, Kassel, Germany.

[8] Richard P., and Cheyrezy M. 1995. *Composition of Reactive Powder Concrete.* Cement and Concrete Research, Vol. 25, No. 7, pp. 1501-1511.

[9] Blais P.Y., and Couture M. 1999. *Precast, Prestressed Pedestrian Bridge: World's First Reactive Powder Concrete Structure.* PCI Journal.

[10] Dallaire E., Aitcin, P.C., and Lachemi M. 1998. *High Performance Powder*. Civil Engineering, ABI/INFORM Global, pp. 48.

[11] Schmidt, M., Fehling, E., Teichmann, T., Bunje, K., Bornemann, R. 2003. *Ultra-Hochfester Beton – Perspektiven für die Betonfertigteilindustrie.* Beton- und Fertigteil- Technik (BFT). H. 3, s. 16-29.

[12] JSCE Guidelines for Concrete, Recommendation for Design and Construction of Ultra High Strength Fiber Reinforced Concrete Structures (Draft), Research of Ultra High Strength Fiber Reinforced Concrete, Japan Society of Civil Engineers, No. 9, 2006.

[13] Richard, P., 1996. *Reactive Powder Concrete: A new ultra-high-strength cementitious material.* Proceedings of the 4th International Symposium on Utilization of High-strength/ High-performance Concrete. Paris, s.1343-1349.

[14] Schachinger, I., Schmidt, K., und Heinz, D. 2003. *Zeitabhänginges Verformungsverhalten von UHFB*. Ultrahochfester Beton Innovationen im Bauwesen – Beiträge aus Praxis und Wissenschaft. König, G., Holschemacher, K., Dehn, K. (Hrsg.), Berlin.

[15] Bornemann, R., and Schmidt, M. 2002. *The Role of Powders in Concrete*. 6th International Symposium on High-strength/ High-performance Concrete. Leipzig, pp. 863-872.

[16] Bornemann, R., Schmidt, M., Fehling, E., und Middendorf, B. 2001. *Ultra-Hochleistungsbeton UHPC – Herstellung, Eigenschaften und Anwendungsmöglichkeiten.* Sonderdruck aus: Beton- und Stahlbetonbau 96, H. 7, s. 458-467.

[17] Schmidt, M., und Bornemann, R. 2002. *Ultrahochfester Beton (UHPC) - Herstellung und Anwendung.* Betonwerk + Fertigteil-Technik (BFT), H. 2, s. 10-12.

[18] Schmidt, M., und Fehling, E. 2003. *Ultra-hochfester Beton.* 3. Kasseler Baustoff- und Massivbautage, Schriftenreihe Baustoffe und Massivbau, Kassel University Press.

[19] Reinhardt, H.W., Jooß, M. 2003. *Wasserspeicher aus UHFB-Technologie.* Ultrahochfester Beton. Innovationen im Bauwesen – Beiträge aus Praxis und Wissenschaft. Bauwerk Verlag GmbH. Berlin. S. 239-255.

[20] Schmidt, M., Bunje, K., Fehling, E., und Teichmann, T. 2006. *Brückenfamilie aus Ultra-Hochfestern Beton in Niesetal und Kassel*, Beton- und Stahlbetonbau 101, H. 6, s. 198-204.

[21] Schmidt, M., and Teichmann, T. 2006. *New Developments in Ultra-High-Performance-Concrete – Non corrosive PVA-fibers and gluing of structural elements*. Proceedings fib-congress. Napies.

[22] Spasojevic A. 2008. *Structural Implications of Ultra-High Performance Fibre-Reinforced Concrete in Bridge Design*. Doctoral Theses. Ecole Polytechnique Federale de Lausanne. Suisse.

[23] Adeline, R., Lachemi, M. and Blais, P. 1998. *Design of Behaviour of the Sherbrooke Bridge.* International Symposium on High-Performance and Reactive Powder Concretes. Sherbrooke, Quebec, Canada, August 16-20, pp. 89-98.

[24] Williams, R. 2002. *A First for Ductal® - the Concrete of the Future,* Press Releases. Accessed 20/12/2010. http://www.infotechfrance.com/cgi-local/affichage_signet_secteur.pl?UNI_ID=8&RUB_ID=54&SS_ID=4152&SEC_ID=26

[25] Rebentrost, M. and Wight, G. 2009. *UHPC Perspective from a Specialist Construction Company*. Proceedings of Ultra High Performance Fibre Reinforced Concrete (UHPFRC). Marseille, France.

[26] Gärtnerplatz Bridge. 2008. Accessed 20/12/2010. http://www.gaertnerplatzbruecke.de/

[27] Lafarge North America. 2007. Accessed 20/12/2010. http://www.lafargenorthamerica.com/wps/portal/lna/products/datasheet?WCM_PORTLET=3_0_FM&WCM_GLOBAL_CONTEXT=/wps/wcm/connect/LNA/Library/Project/Product/Ductal/Sherbrook_Bridge/Sherbrook%20Bridge

[28] Resplendino, J. and Petitjean, J. 2003. *Ultra High Performance Concrete: First Recommendation and Examples of Applications.* Proceedings of 5th International Symposium – ISHPC.