CONCRETE MIX DESIGN FOR PERFORMANCE-BASED CONCRETE

V. Vimmr (1), M. Sarkkinen (2), D. Reid (3)

(1) STÚ-K, Prague, Czech Republic
(2) CT Heikkinen, Siilinjärvi, Finland
(3) Ardoran, Hiiumaa, Estonia

Abstract

Potential use of industrial waste is highlighted, together with relevance to performance-based concrete. Research has shown that relevant amounts of environmentally-unfriendly cement can be replaced using suitable industrial wastes such as blast furnace slag, silica fume, fly ash, oil shale ash, rice husk ash and glass. These industrial by-products in the form of fine particles influence the properties of concrete. We discuss how the concrete mix can be optimised to reach the required properties of both fresh and hardened concrete and how the aggregate packing optimisation theory can be applied to predict the behaviour of concrete and properties such as workability, hydration heat, early strength development, shrinkage, thermal characteristics, sulphate resistance or durability. Finally, environmental implications of the use of industrial by-products in concrete and other cement-based materials are discussed.

Key words: concrete mix performance-based requirements, industrial waste, cement replacement, fine particles

1. INTRODUCTION

Performance-based requirements (PBR) for concrete allow contractors and concrete producers to be more innovative in concrete applications, providing an element of sustainability for concrete construction. Essential elements of PBR include

- desired performance characteristics
- sampling and testing procedures to verify required characteristics
- acceptance criteria

The evolution of performance-based specification (PBS) is critical to ensuring that the concrete construction industry effectively competes with alternative building materials and in sustainable construction initiatives. The more the industry moves towards PBS, the more it is necessary to ensure continued and sustainable growth, with associated improvements in the concrete industry. Utilisation of various industrial by-products is particularly useful regarding PBS, since they are successfully used to control properties of both fresh and hardened concrete.

2. INDUSTRIAL WASTES

Certain kinds of industrial wastes can be used to create specially designed microcomposites to be used as additions to concrete (grout, mortar) mixes or directly in cement. European harmonised standard for cement EN 197-1 defines composition, specifications and conformity criteria for common cements across Europe, providing specifications for 27 distinct common cement products and their constituents. Definition of each type of cement includes the requirements and proportions in which the constituents are to be combined to produce these distinct products in six strength classes. The following industrial by-products are listed: blast furnace slag, silica fume, fly ash and burnt shale.

2.1 Blast furnace slag

Slag accrues as a waste product during the smelting of ore in a blast furnace. Depending on the quenching method its appearance can be amorphous (fast quenching/ water) or crystalline (slow quenching/ steam or air). The fundamental components are CaO and SiO_2 (each 30-40%) and Al_2O_3 and MgO_2 (each 5-15%). Blast furnace slag belongs to the group of latent hydraulic additions, but only the granulated amorphous slag shows reactive properties. Reactive means it can react hydraulically but it needs calcium hydroxide as stimulator in order to develop appreciable strengths without necessarily dissipating it.

2.2 Silica fume

Silica fume is a by-product of producing silicon metal or ferrosilicon alloys. Silicon metal and alloys are produced in electric furnaces. The raw materials are quartz, coal, and woodchips. The smoke that results from furnace operation is collected and sold as silica fume. Silica fume consists primarily of amorphous (non-crystalline) silicon dioxide (SiO_2), with average granule diameter of 0.15~0.20 μm, specific surface area 15000~20000 m^2/ kg, and having an extremely strong surface activity. Because of its fine particles, large surface area, and the high SiO_2 content, silica fume is a very reactive pozzolan when used in concrete.

2.3 Fly ash

Fly ash is a waste residue, that results from the burning and segregation processes in incineration- or coal-plants. The particles predominantly have a spherical or cenospherical, glassy, amorphous appearance. Fly ashes consist mainly of SiO_2, Al_2O_3 and Fe_2O_3, however their chemical and morphological configuration varies in large ranges, depending on several aspects of the combustion process and burnt material. Given the enormous margin of deviation in the performance of fly ashes, only the highest quality ashes are used as additives in concrete technology. Generally, only fly ash from stone-coal plants fulfils quality criteria, as the composition of fly ash from brown-coal plants is generally too unstable. However, some exceptions from this rule exist.

2.4 Oil shale ash

Oil shale, an organic-rich fine-grained sedimentary rock, contains significant amounts of kerogen (a solid mixture of organic chemical compounds) from which liquid hydrocarbons can be extracted. Kerogen requires more processing than crude oil, which increases its cost as a crude-oil substitute both financially and in terms of its environmental impact. Industry can burn oil shale directly as a low-grade fuel for power generation and heating purposes and can use it as a raw material in chemical and construction-materials processing. Burning of oil shale creates large quantities of ash that can be used as a replacement of cement in concrete mixtures.

2.5 Rice husk ash

Rice husk ash is a natural pozzolanic agricultural residue which is abundant in many countries. It consists of high amounts of SiO_2 (90 to 97%) and traces of CaO, MgO, K_2O and Na_2O. Rice husk ash occurs in a large range of different qualities, but depending on the processing, rice husk ash can be a highly reactive pozzolan due to the specific surface area. Some producers in India and other Far-Eastern countries have established rice husk ashes with properties comparable to those of silica fume.

2.6 Glass

Crushed or milled waste glass has been tried as micro filler in some European countries (for instance Norway, Sweden, Spain). Tests show pozzolanic properties in super-cooled (uncrystallised) glass, as well as positive influences on the workability - which makes it promising for the production of self compacting concrete. Tests also confirm that glass can easily be crushed or milled to the same fineness as micro silica.

3. REDUCTION OF CEMENT CONTENT

Cement is a rather environmentally unfriendly material responsible for about 7% of the total worldwide CO_2 production and also involves huge energy consumption. Thus any reduction of cement consumption is very important. Industrial by-products listed in the previous section provide pozzolanic properties that enable considerable reduction of cement content of concrete mixes. Furthermore, industrial wastes provide tools for governing concrete properties according to each specific application requirement.

The replacement of cement in concrete mix using industrial by-products is usually in the range of 10 to 30%. When by-products in the form of fine particles are used, they ease the movement of larger particles, thus the amount of water can be reduced. Use of suitable waste materials actually improves the quality and durability of the concrete and reduces cost, quite apart from reducing the environmental impact.

4. FINE PARTICLES

Fine particles play an important role in a concrete mixture. Let us have a closer look on the main features of fine particles and their influence on concrete properties.

4.1 Fine Filler Effect

Use of fines that are below the fineness of cement may improve some properties of both fresh and hardened concrete. The hydration process of Ordinary Portland Cement (OPC) produces two compounds: calcium silicate hydrate (CSH) and calcium hydroxide. Very fine particles, based on materials other than cement, can act as nuclei for the formation of CSH due to their slower dissolving. This results in a denser and more homogenous microstructure and aggregate-paste interfacial zone, thus improving strength. The filler effect in mixes where cement content is relatively low is partly explained by the need of aggregate particles for a certain distance between each other in order to be able to move. If there is not enough space to move, more water is needed to enable the movement. Fine fillers can move in interspaces of aggregates and thus replace part of the water.

4.2 Packing Density

High density is a significant factor for the good quality of concretes and mortars. Properties of fine materials such as grain shape, particle size distribution and maximum particle size have an effect on packing density. In general, spherical shaped particles offer better compaction than angular grains. Very fine fillers can improve the grading curve and thus improve packing. On the other hand, the larger surface areas of very fine particles (<100 μm) can create surface forces, which result in flocculation and lower packing density.

Mathematical packing models justify the use of inert, micron-scale particles in cement-based products and demonstrate that ultra-fine particles fill the empty space between binder materials and aggregates, thus reducing space which is usually filled either with air or water. This is beneficial, especially when there is a desire to minimise the cement content in products. Figure 1 below clearly illustrates the effect of micron scale particles.

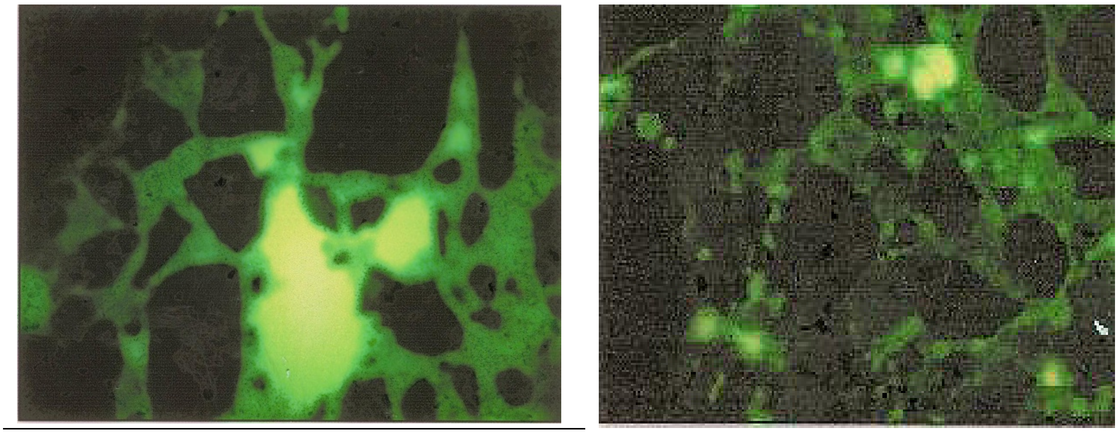

Figure 1: Illustration of the influence of use of microfines in concrete
(left, without/ right, with microfines)

Microfillers can help to optimise grading curves in order to achieve optimal packing and reduce packing problems, like wall-effect and blocking. Wall-effect is a known phenomenon that occurs when smaller particles pack against the surface forming denser packing in the vicinity of the surface. This typically takes place in the interfacial zone (ITZ) located 30 microns around each particle. Disturbance in the ITZ has an effect on strength properties.

4.3 Pore Structure

Concretes and mortars have a porous structure, which is formed on the contact surface between cement paste and aggregate.

The pore structure is based on the size, shape, distribution and the number of pores. Usually finer pores provide better performance compared to larger pores, although they have the same total porosity. A high porosity negatively affects nearly any concrete properties. Micro-fillers can be used for optimizing pore structure through improving packing density and reducing water need.

The durability and longevity of concrete structures are not affected by classical mechanical loading only, but also by non-mechanical processes, such as heat, moisture and chemical influences which need to be taken into account when assessing longevity of concrete structures. The pore structure (distribution and saturation of pores, changes in porosity and quality of pore fluid) of concrete has a significant role in the processes related to moisture movement and physical and chemical reactions affecting durability. For instance, different degradation phenomena change transport and mechanical properties in concrete which have an interaction with pore structure [1].

4.4 Permeability

Density and permeability of cementitious products are related to the pore structure of products. Permeability has a strong influence on durability of concrete. Use of fine fillers can be made in order to achieve optimal packing and thus denser micro-structure which provides higher density and lower permeability. Reduced capillary porosity and lower total porosity usually result in lower permeability and improved physical resistance to the ingress of water, chemical substances and carbon dioxide.

4.5 Durability

The pore structure is one of the core factors determining durability of cementitious products. Calcium silicate hydrate (CSH) is the main component of hardened cement paste. CSH can be defined as a porous structure, including pores starting from nanosize. Thus the properties related to transport, durability and strength are determined at nanometer level.

The property of a concrete surface influences its durability. It determines how easily gases and fluids flow into concrete. Capillary absorption of concrete is one of the main transport mechanisms for water and other fluids and aggressive substances (chlorides, sulphates etc.) that can transfer into concrete along with water. The absorbed water has an influence on the moisture content of concrete, which has an effect, for example, on carbonation and corrosion of steel reinforcements. Gas permeability is one of the parameters that can be used for indicating resistance of concrete against deterioration. The use of fine fillers provides a denser microstructure and thus lowers gas permeability.

4.6 Frost Resistance

The pore structure of concrete and mortar is one of the main factors influencing frost resistance of products. Entrained air voids are particularly important for providing proper frost resistance but the pore structure can also be optimised to have better frost resistance using micronised inert materials.

Frost damage is directly related to the pore structure of concrete and especially to the amount of freezable and non-freezable water and amounts of air and macro-pores. Because moisture uptake of concrete is linked both to internal damage and scaling, the speed of saturation is a very important parameter for durability of concrete. The speed of saturation depends on the pore structure, which is connected to the composition, including use of micro-fines. It can be concluded that a denser microstructure - which can be achieved by use of micro-fines together with use of Air-Entraining Admixtures (AEA) - provides reduced saturation and thus lower risk of internal damage [1].

4.7 Shrinkage and Cracking

From the viewpoint of durability, an objective should always be to minimise shrinkage. Reduced shrinkage is a result of smaller amount of cement and improved microstructure of products, where the empty space between particles - usually filled with water - is now filled with microfines, preventing shrinkage due to the drying of excess water. On the other hand, an excessive amount of microfines can lead to increased water demand and thus increased shrinkage.

4.8 Carbonation and Corrosion of Reinforcement

Corrosion of steel reinforcement is the most significant durability problem of reinforced concrete structures and carbonation is one of the main reasons for it. Research has shown that the distribution of air content and fines content is related to carbonation. Both can be optimised by means of micro-technology and use of micro-fines [2].

4.9 Workability

Workability of cement-based products is a complex issue influenced by several factors, such as paste and water content, aggregate grading, surface area and size, aggregate shape, angularity and surface texture, mineralogy, microfines and absorption and admixtures.

Workability is typically measured as flow or slump. Stability of concrete is measured by bleeding and segregation. When bleeding, the concrete releases free water on the surface and in segregation aggregate particles loose their stability in the mix. Other characteristics defining workability are, e.g., viscosity, cohesion, (self) compactibility, (self) smoothing and (self) leveling which are typical required characteristics of very flowable products like SCC or floor screeds. The tendency for bleeding and segregation increases when the concrete has high flow characteristics without sufficient cohesion.

4.10 Strength

It has been known, for a long time, that pore structure and micro-structure of concrete have a high influence on strength of concrete. The addition of inert fillers to cement paste leads to faster hydration rates and a finer pore-structure. The phenomenon is known as the filler effect. CSH produced from the hydration of C_3S which would otherwise deposit on reacting C_3S particles, in the presence of surfaces of inert fillers, will now deposit on them. This reduction in accumulation of products of these reactive particles increases the reaction rate and causes also a more uniform porosity.

Strength is strongly related to water/ cement ratio of cement-based materials. Reduction of need of water i.e., reduced water-cement ratio thus increases strength. The use of inert mineral quartz powder can reduce need for water and increases strength due to lowering of the w/ b ratio, especially when using crushed aggregate in concrete. This is a result of improved interaction between paste and aggregate, which is explained through chemical and physical factors, such as:

- Fine materials interfere with the formation and orientation of large crystals at the paste-aggregate interface.
- Large amounts of small particles may alter the rheology, reducing internal bleeding at paste-aggregate interfaces.
- The wall-effect does not weaken the contact between the paste and the fine aggregate (FA) particles; thus FA function approaches that of the unreacted cement particle core
- The components (paste and aggregate) are homogenously mixed, lowering the stress peaks [3].

According to Järvenpää [4], aggregate mineralogy (mineral size, texture, mineralogical composition, shape, angularity and surface texture) have an effect on strength properties of aggregate products.

Latent hydraulic properties of fine particles can accelerate strength development, increase hydration temperature, shorten curing time and increase final strength [5].

5. CONCRETE MIX DESIGN OPTIMISATION

Concrete and mortars are composite materials containing cement, aggregates, water, admixtures and additives. The size of the solid aggregate particles can range from millimeters to several centimeters, size of cement and other micro-fines, including micronised materials, in microns and nanometers.

Micro-proportioning means proportioning of material particles, taking into account micron-size particles, besides larger particles. Cement-based mixes have a certain optimum point of solid particles where amount of water and air voids is a minimum and the amount of solid particles, a maximum. Packing density means volume fraction of solid particles and the density increases to a certain extent, with increased dispersion of the particle size distribution. The function of mineral powders derives from their filler and binder effects, which mean that the particles should be, very fine [3].

There are several theoretical models for the proportioning of particles.
The first theoretical models for particle packing or compaction were defined in the early 20th century. The most commonly used particle size distribution model is the Fuller curve defined by Fuller and Thomson [6]:

$$P(x) = \sqrt{\frac{x}{D_{\max}}} \qquad (1)$$

Where *P(x)* is a cumulative particle volume, *x* is the particle diameter and *Dmax* is the maximum particle diameter.

The packing or compaction is optimized by an equation (Andreasen & Andersen [7]) where parameter q has a value between 0 and 1. The equation prescribes a particle size distribution from 0 to Dmax. Lower q-value indicates higher amount of fine particles in a mix, which is usually needed when the particle shape is irregular. According to the model, the optimal particle distribution is achieved with q-value 0,33-0,50 when particles are spherical.

$$P(x) = \left(\frac{x}{D_{\max}}\right)^q \qquad (2)$$

A modified version of the equation developed by Alfred takes into account also the minimum particle diameter d_{min} (Brouwers and Radix [8]), as can be seen in the following:

$$P(x) = \frac{x^q - d_{\min}{}^q}{d_{\max}{}^q - d_{\min}{}^q} \qquad (3)$$

A commonly used packing model is the Linear Packing Density Model (LPDM), developed originally in 1986 by Stovall, de Larrard and Buil, [9] that has been developed further since then. The model takes into account particle shapes, sizes, interference effect and the so-called wall-effect. The case of grain sizes continually distributed is derived.

In 1994 the LPDM model was developed further by de Larrard and Sedran, [10] for example, to include viscosity factor based on Mooney's viscosity model and the name changed to Solid Suspension Model (SSM). SSM model has been used especially in design of ultra high performance concretes (UHPC). There are also several other packing models used internationally.

Effective utilization of waste materials requires expertise in cement chemistry and optimization of mix designs. Variability of materials obtained from different sources requires that each mix design should be optimized and tested. The ECOCRETE project addresses these issues by aiming to provide a comprehensive toolset to facilitate design and testing of concrete optimized for durability and sustainability, utilizing locally available waste materials and aggregates. The knowledge-based expert system furthermore enables users to identify best practice and research results directly relevant to their application.

As an example of the utility of the toolset, the methodologies with be used to design a novel concrete mix utilizing oil shale waste from Estonian power stations.

6 PERFORMANCE-BASED CONCRETE

6.1 Introduction of the performance based approach (PBA)

PBA can be applied to:

- Products, methods and systems
- Components of structures, entire structures and structure complexes
- Services and processes

The performance of a concrete structure has to be considered in terms of its ability to fulfil the requirements set by the owner, by the responsible authorities and, more widely, with respect to societal expectations. Achievement of good performance requires understanding of the many influencing factors, of the inter-relationships between them and how to attain a satisfactory balance between the most significant factors for a particular situation. To do this well requires good design and specification. This should deliver not only effective performance that meets the fundamental objectives, but should do so in an exemplary manner which delivers excellence whilst being cost-effective.

6.2 Environmental performance of construction materials

The Japanese have developed recommendations for environmental performance verification of concrete structures which define environmental performance for concrete structures as follows: "When conducting design, construction, use, maintenance/ management, dismantling, disposal and reuse after dismantling of a concrete structure, environmentality shall be examined by setting environmental performance as a performance requirement" [11]. Environmental performance can be evaluated through life cycle assessment (LCA) method. That concerns also other cement-based and dry premixed products. Environmental performance can be verified using a simple statement R ≤ or ≥ S, where R is the retained performance and S is performance requirement [11].

The performance-based approach, in production of cement-based products, means, for example, that instead of setting up strict quantitative or qualitative limitations, standards and restrictions on used components (prescriptive approach), quality requirements should be defined as performance-related properties of ready products. This would provide more possibilities for the development of, and re-use of, recovered and recycled waste materials and new innovative, interdisciplinary solutions. Figure 2 (adopted from [12]) describes the fundamental difference between a performance-based and a prescriptive approach which has been used traditionally, e.g., in product development and definition of standards and guidelines for such products.

Performance-based approach supports also the ideological and ecological product concept which is based on the idea that the basic economic value is service, not material.

6.3 Environmental implications of use of concrete- and other cement-based materials

The concrete industry has addressed the issues of sustainability issues for decades. In principle, it sustainability design has two mains viewpoints that should be taken into account:

- design of optimal durability; and
- energy-efficient use of raw materials.

In the design of cement-based products, this requires taking into account factors, such as: optimising mix design and composition of raw materials (use of supplementary cementitious materials, industrial by-products, waste materials and minimising use of organic compounds).

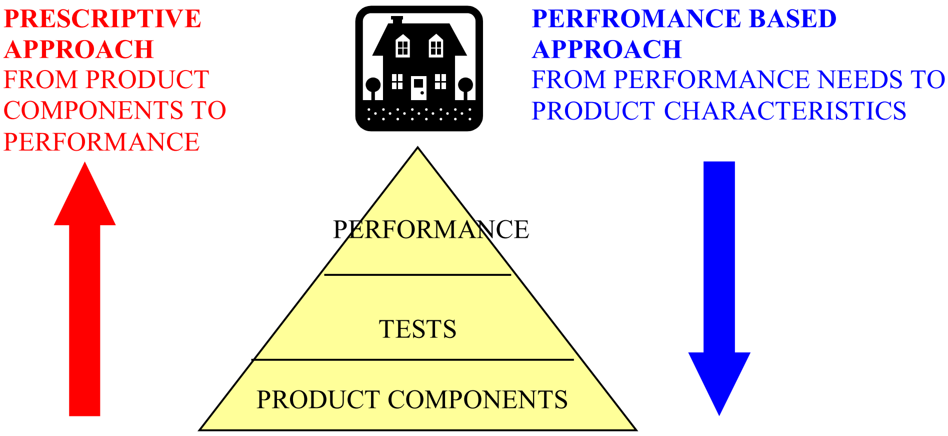

Figure 2: The concept of the performance based approach PBA

Sustainability in cement-based products can be defined as a minimal consumption of natural resources and minimal production of waste with optimal utilisation of raw materials, in order to produce products with optimal performance and life expectancy.

Optimal performance can include aspects such as energy efficiency, safety, aesthetics and durability. Design and production of sustainable cement-based products can be, at the same time, very economical, when based on optimum utilisation of recovered and recycled materials. A significant factor supporting the use of recovered and recycled materials is the increasing prices of cements (including future increasing carbon and fuel taxes), natural aggregates and admixtures. Use of supplementary cementitious materials (SCM), the improvement of efficiency of SCM by micronising, use of recovered and recycled materials as aggregate and the optimisation of mix design using micro-proportioning are significant factors in production of sustainable cementitious products. The use of these materials and methods can reduce the amount of cement (energy, limestone and CO_2) needed to produce concrete.

7. CONCLUSIONS

Several industrial by-products can be used as direct replacement of cement in concrete mixes. Such utilization of wastes is a welcome contribution to improvement of environment contribution in sustainability of concrete structures, by reduction of demand of natural resources. Furthermore, industrial by products, when used as fines, can positively influence the properties of fresh concrete and hardened concrete, including strength, durability and resistance against chemical attack. The knowledge -based expert system, under development within the framework of ECO-INNOVATION ECOCRETE project, will enable users to identify best practice.

ACKNOWLEDGEMENTS

The authors of this paper appreciate the financial support provided by the Eco-innovation funding scheme, part of the EU's CIP, within the project EcoCrete Reducing the Environmental Impact of Concrete by Knowledge-based Design and Utilisation of Industrial Waste Materials.

This publication reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

REFERENCES

[1] Setzer, M.J., et al. 2007. Structure of Pore System Essential for Durability of Cementitious Materials, TRANSCON 07 Transport in Concrete: Nano- to Macrostructure. Proceedings of 5th International Essen Workshop. Editor Max J. Setzer. Aedificatio Publishers, pp. 529-531

[2] Selmo, S.M.S, et al., 2007. Contribution to the Macro and Microstructure Analysis of Repair Mortars for Corroded Reinforced Concrete Structures, 5th Int. Essen Workshop – Transport in Concrete, pp. 241-251.

[3] Kronlöf A., 1997. Filler effect of inert mineral powder in concrete, Technical Research Centre of Finland, VTT Publication 322, Espoo

[4] Järvenpää H. 2001. Quality characteristics of fine aggregates and controlling their effects on concrete. Helsinki University of Technology, pp. 1-20.

[5] Vimmr, V., and Vimmr, T. 2006. D1.State-of-the-art. MICROCON project: New economical and ecological solutions to reduce raw material costs of cement based products by utilizing microtechnology, pp. 6-34.

[6] Fuller, W. and Thompson, S.E. 1907. The laws of proportioning concrete. Transactions of the ASCE. Paper No 1053.

[7] Andreasen, A.H.M. and Andersen, J. 1929. Über die Beziehung zwischen Kornabstufung und Zwischenraum in Produkten ans losen Körnern (mit einigen Experimenten). Kolloid.

[8] Bronwers, H.J.H. and Radix, H.J. 2005. Self-Compacting Concrete. Theoretical and experimental study, Cement and Concrete Research 35. Elsevier. pp 2116-2136

[9] Stovall, T. de Larrard, F. and Buil, M. Linear density model of grain mixtures, Elsevier B.V. 1986

[10] de Larrard, F. and Sedran, T.: Optimization of ultra-high performance concrete by se of a packing model.

[11] Sakai K. 2006. Environmental design of concrete structures – its possibilities. Eco-Serve seminar, pp.29-63.

[12] Mathews, S, Sarkkinen, M. and Morlidge, J. Achieving durable repaired concrete structures. Adopting a performance based intervention strategy. BRE Press 2007.