Towards Greener Concrete: The Challenges of SUS-CON Project

Agnese Attanasio[1(✉)], Alessandro Largo[1], Raffaele Vinai[2], Marios Soutsos[2], Jeanette Visser[3], René van Gijlswijk[3], Chrysanthi Panagiotopoulou[4], Maria Taxiarchou[4], Francesco Sonzogni[5], Marco Preda[5], and Massimo Pugliese[6]

[1] Materials and Structure Engineering Department, CETMA – Technologies Design and Materials European Research Centre, Brindisi, Italy
{agnese.attanasio,alessandro.largo}@cetma.it

[2] School of Natural and Built Environment, QUB – Queen's University of Belfast, Belfast, UK
{r.vinai,m.soutsos}@qub.ac.uk

[3] Civil Engineering Department, TNO – Built Environment and Geosciences, The Hague, The Netherlands
{jeanette.visser,rene.vangijlswijk}@tno.nl

[4] School of Mining and Metallurgical Engineering, NTUA – Technical University of Athens, Athens, Greece
{chrysapanag,taxiarh}@metal.ntua.gr

[5] Magnetti Building, Carvico, Italy
{f.sonzogni,m.preda}@magnetti.it

[6] Business Unit Real Estate, Industry Service Division, TUV Italia, Sesto San Giovanni, Italy
massimo.pugliese@tuv.it

Abstract. Portland cement production is an energy-intensive process responsible for a significant share of the total CO_2 production. Its replacement with low carbon binders from by-products of industrial processes is a sustainable alternative for innovative construction materials. In addition, the combination of low carbon binders with recycled aggregates results in a more sustainable concrete, also contributing to reduce waste amounts sent to landfills or incinerators. SUS-CON (*SUStainable, innovative and energy-efficient CONcrete, based on the integration of all-waste materials*) project (Funded by EC under FP7 (call EeB-NMP.2011-1/3, grant agreement no. 285463).), aimed at developing new concepts and technologies to integrate secondary raw materials in the concrete production cycle, resulting in cost-effective, lightweight and insulating concretes with reduced embodied energy and CO_2 footprint. This paper presents a comprehensive overview of the technical work carried out during the Project. The work was structured in three major phases: 1. *material research*, leading to set-up and assess eco-sustainable concretes with recycled aggregates (e.g. waste polyurethane foams, mixed plastic scraps, end-of-life tyres and plastics from electrical and electronic equipment) and low carbon alkali activated binders (e.g. pulverized fly ash from power stations and blast furnace slags from steel plants); 2. *industrial implementation*, validating the developed technologies in

D.A. Hordijk and M. Luković (eds.), *High Tech Concrete: Where Technology and Engineering Meet*, DOI 10.1007/978-3-319-59471-2_270

industrially relevant environment through pre-cast components and ready-mixed concrete production and pilot buildings construction; 3. *industrial uptake*, creating the bases for transferring results and methodologies by environmental and economical assessments (LCA, LCC, HSE) and certification issues. Mechanical, insulation and fire resistance properties of SUS-CON components were tested; energy efficiency performances of SUS-CON pilot buildings were also monitored.

Keywords: Secondary raw materials (SRM) · Sustainable concrete · Recycled aggregates · Alkali activated binders · Industrial scale up

1 Introduction

Concrete is the most widely used construction material. Ordinary Portland cement (OPC) (traditionally used as concrete binder) manufacturing is high energy consuming and results in significant CO_2 emissions[1]. On the other hand, aggregates represent major constituents of concrete and related quarrying activities have significant environmental impacts. The current trend in the construction sector gives major attention on the potential of post-consumer waste and industrial by-products to reduce environmental impacts, energy consumption and costs, limit the utilization of non-renewable raw materials and also prevent waste disposal (Baikerikar 2014; Petrillo et al. 2016; Gayathri et al. 2016). Replacing traditional constituents with secondary materials (SRM), is considered necessary to develop more sustainable production technologies, being also an opportunity for cost savings (Baikerikar 2014; Suhendro 2014). A considerable attention is currently paid to alternative green cements such as alkali activated materials (AAM) (e.g. fly ash from power plants, slag from metallurgical plants). Blending such green binders with aggregates also coming from waste materials (e.g. post-consumer plastics) represents a further step towards the development of more sustainable concrete (Dave et al. 2015).

SUS-CON (*SUStainable, innovative and energy-efficient CONcrete, based on the integration of all-waste materials*) project[2] aimed at developing innovative technologies to integrate SRM from industrial waste and by-products (e.g. plastic recycling plants, power stations, steel plants), in the production cycle of lightweight (LW) concretes, for both ready-mixed and precast applications. The overall target was the development of LW thermal insulating concrete with reduced CO_2 footprint and embodied energy. This paper presents a comprehensive overview of the technical work and the promising results achieved by SUS-CON project. The *material research phase*, on the lab level, aimed at developing eco-sustainable concretes incorporating recycled LW aggregates and low carbon alkali activated binders. The *industrial implementation phase*, supported by industrial producers, aimed at validating the developed technologies, through the production of precast concrete components (i.e. panels, blocks) and ready-mixed solutions, and relevant installation on real scale buildings. The

[1] About 0.9 ton of CO_2 for 1 ton of cement produced.

[2] https://www.sus-con.eu/.

industrial uptake phase, in support of the previous ones, carried out LCA (Life Cycle Assessment), LCC (Life Cycle Cost) and HSE (Health Safety and Environment) evaluations and analyzed certification issues with the aim of creating the bases for an effective transfer of results and methodologies.

2 Material Research Phase

SUS-CON aggregates: A range of post-consumer plastics, selected among industrial waste streams, were investigated to assess their suitability as LW aggregates for concretes. Plastics such as rigid polyurethane foams (PU), mixed plastics scraps rejected from recycling plants (referred to as "Remix"- RX), exhaust rubber tyres (TR), waste plastics from electrical and electronic equipment (EP) were processed to allow their use as aggregates for non-structural concretes. The aggregates were tested in terms of physical (e.g. particle size distribution, particle density, water absorption), mechanical and chemical properties according to relevant standards. The compliance of the aggregates with HSE requirements was also ensured. The compatibility degree between these LW aggregates and traditional cementitious binders was evaluated. A broad characterization campaign was performed to investigate how they can influence the final performance of the concrete in terms of density, consistency, mechanical and insulation performance. The use of recycled plastic aggregates resulted in LW concretes (density 1050–1130 kg/m^3) and low thermal conductivity (λ-values 0.20–0.33 W/mK), compressive strength was also satisfactory (2.6–9.3 MPa). A comparison with similar commercial products was performed resulting in better thermal insulation performances. The outcomes of these investigations led to identify three types of recycled plastic aggregates (PU, RX and TR) to be further investigated and used in combination with SUS-CON binders (Attanasio et al. 2015).

SUS-CON binders: A range of potential aluminosilicate precursors, selected among industrial waste streams or by-products, were investigated with analytical techniques (XRF, XRD, FTIR, laser grain size distribution, SEM coupled with energy dispersive X-ray analysis) for a preliminary screening, assessing properties such as Si and Al content, amorphous content, maximum and average particle size, particle shape. Materials showing potential for activation were then selected for further analysis: pulverized fuel ash (PFA), ground granulated blast furnace slag (GGBS) and perlite tailings were used for an extensive investigation on binder development. Variables such as dosages of alkali, water content, curing conditions and binder composition were studied and their effects on fresh (consistency, setting time) and hardened (compressive strength, thermal parameters, density) properties of mortar were assessed. Activation dosages were determined according to two parameters: alkali dosage M+ (the mass ratio Na_2O/binder), and alkali modulus AM (the mass ratio Na_2O/SiO_2 in the activating solution). Three binders showing satisfactory compressive strength (>20 MPa), consistency, initial setting time and density were selected for the production step: 100% PFA, activated with sodium silicate and NaOH solutions, a PFA/GGBS mix with a 30%–70% blend activated with sodium silicate and NaOH solutions and a cyclones (perlite tailings)/μ-silica mix with a 90%–10% blend activated either with sodium silicate or with NaOH solution only. Conformity tests were carried out by replicating existing concrete products substituting OPC with the SUS-CON developed binders. Products such as building blocks, LW concrete and panels were obtained both at laboratory and industrial scale, verifying the achievement of target values for key performance indicators (e.g. compressive strength, thermal properties, durability). Results were successful as SUS-CON binder-based products showed properties equal or even superior to OPC-based products (Vinai et al. 2015).

SUS-CON concretes: Selected sustainable LW aggregates and binders were combined for producing an environmental friendly LW, high insulating, sustainable concrete made of 100% SRM (Fig. 1). Preliminary results allowed to target four applications: floor screed, floor screed underlay, panel for facades and blocks. For each application, required workability, density and compressive strength were determined from the standards and prescribed by industrial partners. The initial design was based on the (theoretical) density of concrete.

Fig. 1. SUS-CON concrete specimens made of 100% SRM.

Most of the SUS-CON LW aggregates were found to reduce the workability, therefore a compromise between conflicting factors (e.g. lightweight and workability). Adding natural sand was found to be successful for the PFA-based binders but not for the PFA/GGBS-based binders as the concrete density exceeded the target. PU aggregates were found to be suitable for all targeted applications. Together with PFA-based binder, PU aggregates were applicable for blocks, whereas with PFA/GGBS-based binder panels and floor screed (underlay) applications were possible (Visser et al. 2015). Based on the application requirements and the test results, eight successful mixes compliant with the prescriptions for the selected applications were identified (Table 1).

Measured mechanical properties were on average satisfactory for all tested mixes with the exception of the concrete with TR aggregates. The measured low compressive

Table 1. Compliance of the hardened concrete with performance demands.

Mix selected			Compliance with application				
Label	Aggregate	Binder	Target density (kg/m^3)	Measured density (kg/m^3)	Target *fc* (MPa)	Measured *fc* (MPa)	Application
GEOblock_P-31	PU	PFA	1000–1400	1250	≥ 5	8.3 ± 0.0	Block
GEOblock_P-16	PU	PFA	1000–1400	950	≥ 5	5.6 ± 0.2	Block
GEOblock_T-32	TR	PFA	1000–1400	1500	≥ 5	4.2 ± 0.1	Block
GEOblock_P-21	PU	PFA/GGBS	1000–1400	1200	≥ 5	15.1 ± 0.0	Block
GEOblock_R-27	RX	PFA/GGBS	1000–1400	1500	≥ 5	18.2 ± 0.0	Block
GEOpanel_R-34	RX	PFA	<1500	1450	5–20	6.8 ± 0.3	Panels
GEOpanel_P-17	PU	PFA/GGBS	<1500	1050	5–20	6.4 ± 0.1	Panels
GEOscreed underlay_P-18	PU	PFA/GGBS	<1100	1150	≥ 8	11.6 ± 0.1	Floor screed (underlay)

strength was attributed to the low aggregates-matrix bonding. Thermal conductivity was low, as could be expected from the low thermal conductivity values of the aggregates and the (relative) high volume fractions used. Results on thermal conductivity showed λ-values from 0.16 W/mK (PU/PFA) to 0.34 W/mK (RX/PFA). The addition of sand (λ-value approximately 4.8 W/mK) adversely affected the thermal insulation capacity. According to the results obtained from freeze-thaw tests, materials were classified in three classes: low, medium and high resistance. Results of durability tests seemed to correlate with the binder blend and initial water content of the binder systems: higher GGBS contents and lower water contents improved the durability as these factors reduced the (open) porosity of the materials. Six satisfactory formulations were therefore identified for the production of prototypes and building elements required for the demonstration phase: GEO block_P-16, GEO block_P-21, GEO block_R-27, GEO panel_P-17, GEO panel_R-34 and GEO screed_P-18.

3 Industrial Implementation Phase

Process design: The scaling up feasibility of SUS-CON concrete solutions in technical, economic and material terms was evaluated. The compatibility of the innovative SUS-CON concretes production process with the currently used practices was investigated. Three different pilot production lines, one for each type of SUS-CON product (panels, building blocks and ready-mixed concrete) were designed, including equipment pre-selection and dimensioning, mass balance calculations, design of suitable spaces and processes for an efficient production of the pre-fabricated components as well as proposed modification to traditional concretes production lines. The HSE study on the production process was also performed and the resulting recommendations were incorporated into the detailed design. The most important conclusion was that it is possible to use the existing concrete production lines with minor modifications (slightly different manufacturing process in comparison with traditional concrete processing).

Demonstrators: The concrete solutions optimized at laboratory scale were validated through scaling up in real production plants. Pre-cast components (panels, building blocks) and ready-mixed concrete based on formulations with PU, RX aggregates and PFA, GGBS binders were produced (Fig. 2). In total 50 panels and around 1000 LW blocks were successfully produced, some for further characterization tests and others to be installed on real scale demo buildings. The components complied with the specifications for the target applications. SUS-CON products were produced with equipment typically used for OPC products and minimum equipment investments were necessary; such compatibility means good opportunities for technological transfer of SUS-CON solutions in existing concrete plants. Some prototypes were produced using binders from different sources, thus demonstrating the high results replicability and the adaptability of developed technologies. Mechanical performance (flexural tests on panels), thermal transmittance and fire resistance (on blocks and panels) were assessed; thermographic inspections were also carried out. For a full validation of the produced components, the resulting performance were compared with those of traditional components typically produced in the facility.

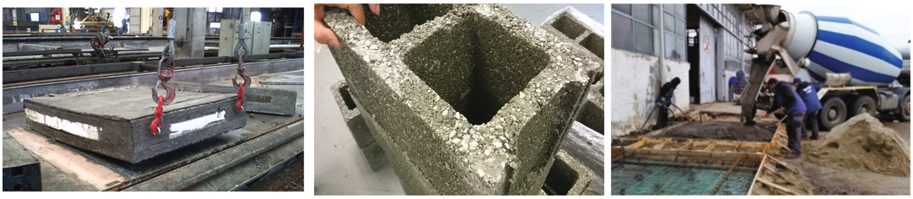

Fig. 2. SUS-CON pre-fabricated components (panels, building blocks) and ready-mixed concrete.

As result of this analysis, the thermal transmittance of SUS-CON blocks was found to be half than traditional blocks (due to their reduced density), while in terms of fire behavior SUS-CON panels were classified as EI 240 (4 times better than reference panels, which are EI 60). These results are very promising in the view of a full-scale industrialization of SUS-CON outcomes. In order to fully demonstrate the applicability of SUS-CON solutions on real scale, pre-fabricated components and ready-mixed concretes were installed on demo buildings (Fig. 3) located in three EU sites (Spain, Turkey and Romania). For comparison purposes, similar demonstrators built with traditional reference components were also completed. SUS-CON demo buildings, when compared with the reference ones, showed better insulation performance.

Fig. 3. Demo buildings installed in EU sites (Spain, Turkey, Romania) using SUS-CON prefabricated components and ready-mixed concretes.

Industrial uptake phase: SUS-CON products were also analyzed in terms of Life Cycle Analysis (LCA), Life Cycle Cost (LCC) and Health, Safety and Environmental (HSE) assessments. LCA and LCC evaluations of SUS-CON products were compared with those of commercial products like LW concrete based on OPC, polystyrene or expanded clay. A significant reduction especially in terms of Global Warming Potential (GWP, in kg CO_2 eq/m^3) was shown (above 50% for panels, blocks and screeds). Also in terms of Embodied Energy (EE, in MJ/m^3) the developed solutions performed better than traditional ones (van Gijlswijk et al. 2015). Moreover, a cost reduction up to 15% can be achieved for SUS-CON blocks, panels and screed, depending on the type on SRM used. According to the policies aimed at HSE protection at EU and National level, risk analysis of the SUS-CON products, taking into account the health and safety aspects of workers and end-users, was performed. As an outcome, SUS-CON concretes and products resulted not to be dangerous and the use of traditional PPEs (Personal Protective Equipment) was suggested, as in the case of OPC based concrete products. Finally, the availability of harmonized standards for the final products (EN 13813 for floor screed underlay, EN 14992 for panels for facades and EN 771-3 for concrete blocks) can allow the CE marking of SUS-CON products according to Regulation EU 305/2011 (CPR).

4 Conclusion

In this paper the main research activities and outcomes of SUS-CON project have been presented. The 4-years Project, successfully completed in 2015, developed sustainable and cost-effective concretes using aggregates and binders from SRM. The resulting concretes, suitable for ready-mixed and precast applications, were LW and thermal insulating, with reduced embodied energy and CO_2 footprint.

The Project was structured in three major phases including *material research*, *industrial implementation* and *industrial uptake*. In the first phase concretes based on recycled aggregates (waste PU foams, mixed plastic scraps, end-of-life tyres) and low carbon alkali activated binders (PFA and GGBS) were developed at lab scale. In the second phase the concrete formulations were validated at industrial scale with the production of both precast components (i.e. panels, building blocks) and ready-mixed solutions; these were also installed on real scale buildings. The third phase dealt with LCA, LCC, HSE evaluations and certification issues to create the bases for an effective transferring of results and methodologies developed. SUS-CON final achievements can be summarized as follows: the potential to integrate SRM (as both binders and aggregates) into the production cycle of concrete was fully demonstrated; the technology transfer of concrete solutions, fully based on SRM, was effectively validated at the EU scale, with the industrial production of blocks and panels and their relevant installation on real scale demo buildings; the target of 15% reduction in terms of costs and 50% in embodied energy and CO_2 emissions was achieved; the replication potential of the developed solutions and their compatibility with traditional concrete plants was verified; products and production processes resulted to be non-hazardous.

Ackowledgements. This research was carried out in the framework of the SUS-CON "Sustainable, Innovative and Energy-Efficient Concrete, based on the Integration of All-Waste Materials" project, which has received funding from the EC under FP7 (call EeB-NMP.2011-1/3, grant agreement no. 285463).

References

Attanasio, A., Largo, A., Larraza, I.A., Sonzogni, F., Balaceanu, L.: Sustainable aggregates from secondary materials for innovative lightweight concrete products. Heron J. **60**(1/2), 5–25 (2015)

Baikerikar, A.: A review on green concrete. JETIR **1**(6), 472–474 (2014)

Dave, S.V., Bhogayata, A.C., Arora, N.K.: Utilization of plastic waste in Geopolymer concrete: state of the art re-view. IJAERD **2**(12), 6–10 (2015)

Gayathri, G., Ramya, V.S., Yasotha, T., Dheenedhayalan, M.: Experimental investigation on geopolymer concrete with e-waste. IJRRASE **8**(2), 280–291 (2016)

Petrillo, A., Cioffi, R., Ferone, C., Colangelo, F., Borrelli, C.: Eco-sustainable Geopolymer concrete blocks production process. Agric. Agric. Sci. Procedia **8**, 408–418 (2016)

Suhendro, B.: Toward green concrete for better sustainable environment. Procedia Eng. **95**, 305–320 (2014)

van Gijlswijk, R.N., Pascale, S., Urbano, G.: Carbon footprint of concrete based on secondary materials. Heron J. **60**(1/2), 113–139 (2015)

Vinai, R., Panagiotopoulou, C., Soutsos, M., Taxiarchou, M., Zervaki, M., Valcke, S., Chozas Ligero, V., Couto, S., Gupta, A., Pipilikaki, P., Larraza Alvarez, I.: Sustainable binders for concrete: A structured approach from waste screening to binder composition development. Heron J. **60**(1/2), 27–57 (2015)

Visser, J., Couto, S., Gupta, A., Alvarez, I.L., Ligero, V.C., Mayo, T.S., Vinai, R., Pipilikaki, P., Largo, A., Attanasio, A., Huang, C.H., Soutsos, M.: Sustainable concrete: design and testing. Heron J. **60**(1/2), 59–92 (2015)