Part 2: Application and engineering properties

Alkali activated materials – a new generation of cementless binders for concrete

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A clear demand exists for a new, sustainable generation of building materials, as concrete based on Ordinary Portland Cement (OPC) cannot meet all the challenges of modern society in terms of durability and sustainability. The DuRSAAM action addresses this by establishing a training and research network that contributes to a sustainable built environment and uses alkali-activatable materials as a new generation of cement-free binders for concrete.

The first part of this paper, published in CPI 2/2021, introduced the background to AAM technology and presented a brief industry review. In part 2, mix composition, fresh and hardened properties, and aspects related to life cycle analysis are discussed.

Composition and rheology

The formulations represent one of the biggest issues of the standardization process of AAMs. The reason for this is the fact that under the name AAM there are numerous possible combinations and compositions, which consequently perform differently. There are many factors influencing the systems and choice of right composition often come from empirical studies. The chemical and physical variabilities of precursor materials inhibit to realize a general formulation. Li et al. [1] collected many examples of procedure to get the composition based on specific parameter, performance or statistical model. Duxon and Provis [2] proposed an ideal composition range for glassy aluminosilicate precursor based on network-modifying cations (particularly calcium, magnesium, sodium and potassium) in order to give sufficiently high solubility to supply the necessary aluminium into the growing geopolymer gel.

Within DuRSAAM project, state-of-the-art mix designs of AAM concretes are taken as a starting point to develop and optimise new mixes and to study rheological properties in a more detailed way. DuRSAAM reference mixes were adopted from the RILEM TC 247-DTA 'Durability Testing of Alkali-Activated Materials' [3]. Within this TC different alkali-activated concrete mixes were designed with the aim of providing concretes with different intended performance levels. Based on these reference mixes, DuRSAAM mixes will be optimised using locally available raw materials for specific structural and non-structural purposes.

Fig. 1: Reference mixes based on: OPC, alkali activated fly ash, alkali activated slag and alkali activated slag/iron silica fines [4]

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Durability

AAMs have different physical (pore structure, tortuosity of pores) and chemical (pH and chemical composition of pore solution, composition of hydration products) characteristics compared to OPC. Nowadays, durability represents one of the big issues to the application of AAMs, because degradation mechanisms well known for OPC, still need to be understood for AAMs. Furthermore, testing methods for most of the durability properties are not standardized or validated for AAMs and some of the requirements prescribed for concrete in current standards are not in accordance with the fundamental knowledge of degradation mechanisms. For the demonstration of AAMs as sustainable structural building materials, their durability properties and degradation mechanisms must be understood, as will be tackled in the DuRSAAM project.

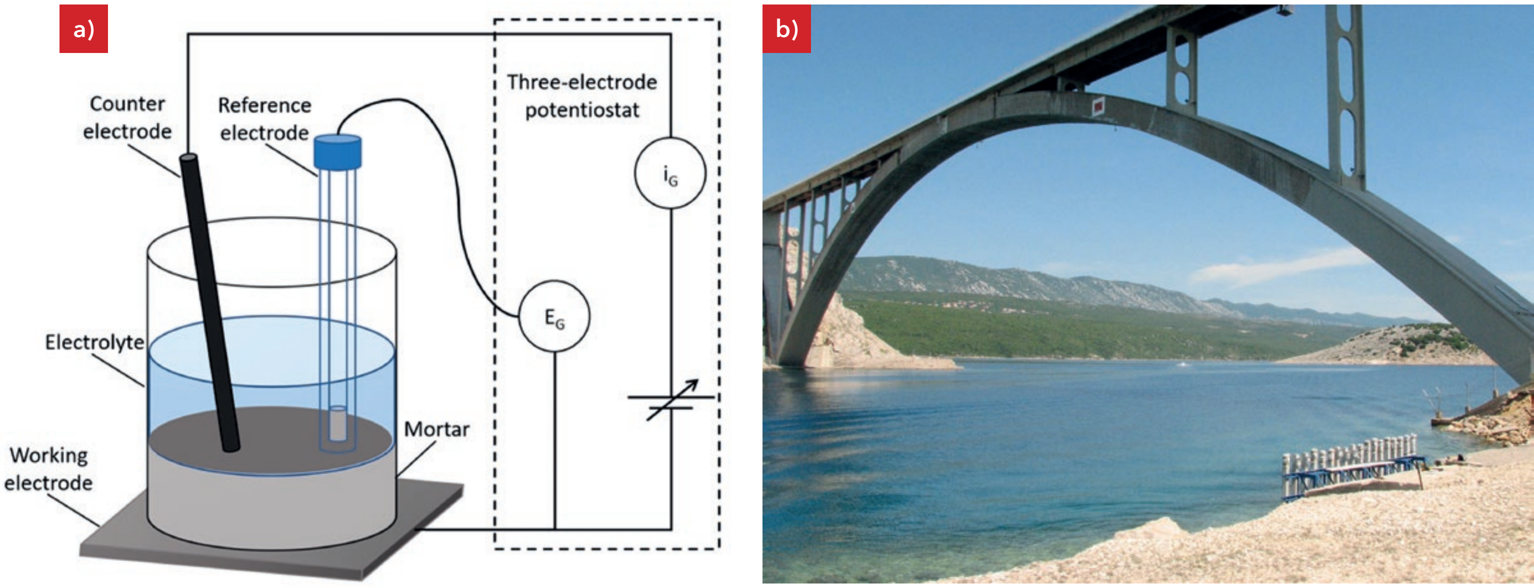

Fig. 2: a) Suggested setup for evaluation of corrosion behaviour of reinforcing steel in AAM concrete [5], b) Exposure site under Krk Bridge in Croatia on which real size AAM-based elements will be exposed to marine environment [6]

Specifically, DuRSAAM projects aims at advancing both analytical (experimental) and conceptual (modelling) approaches to AAM durability beyond the current state of the art, generating new knowledge and tools in an integrated and theoretically sound way. Following aspects of AAM durability will be tackled in DuRSAAM project in detail:

- carbonation - carbonation of the pore solution, decalcification of the Ca-rich phases and carbonation of secondary reaction products,
- corrosion of steel - the ability of optimised AAMs to provide stable chemical environment for the formation of the passive film on the surface of steel, and the physical ability of AAMs to form a barrier that counteracts the ingress of chlorides, water and oxygen towards the surface of the steel,
- freezing and thawing resistance - freeze-thaw damage, with and without de-icing salts, combined with mechanical loading,
- volume stability – early age shrinkage, drying and carbonation shrinkage and creep.

Prediction of long-term behaviour

Complementary an extensive experimental investigation of AAMs, evaluation of long-term behaviour of AAMs and AAMS-based structures can be confirmed using numerical simulations and modelling. However, this is not an easy task, reliable durability predictions require knowledge of the microstructural changes of concrete, an area which has recently received attention and innovation even for OPC-based concrete [7]. For the multi-scale modelling of AAMs, the main challenge is to build up a realistic AAM structure in different scales and upscale the properties from lower scale to engineering scale.

Within DuRSAAM project, focus will be on producing a framework for modelling the geopolymerization reaction process and microstructural formation of alkali activated paste. The output of the framework would be pore solution chemistry, the volume fraction of reaction products and the capillary pore structure of alkali activated paste. This framework, together with the information on degradation mechanisms during single and combined environmental and mechanical loading, will provide the basis for service life prediction of AAM-based concrete, and in return, provide guidance for material design to meet desired service life of concrete structures at prescribed service conditions.

Structural application

Beside lower CO_2 emissions, alkali-activated materials represent a possible alternative binder to ordinary Portland cement due to their high performance or performance which can be tailored for specific applications. The earliest known applications of alkali-activated concretes date back to the 1950s and these structures confirm the high performance of AAMs, durability and chemical resistance [7]. A recent relevant application of alkali-activated slag concrete was made in China. In November 2013 started the construction of the CRICS (Chongqing Research Institute of Construction Science) office building, in the Yuzhong District, Chongqing, the first structural application of site-cast alkali activated slag concrete in China [8]. 550 m^3 of alkali-activated slag concrete (AASC) were used to build the main structural frame of the three floors building.

Within DuRSAAM project focus will be on developing several specific products for structural application of AAM. AAM ready-mix concrete, precast AAM concrete products, AAM-based TRM structural repair kits and AAM-based FRHPC

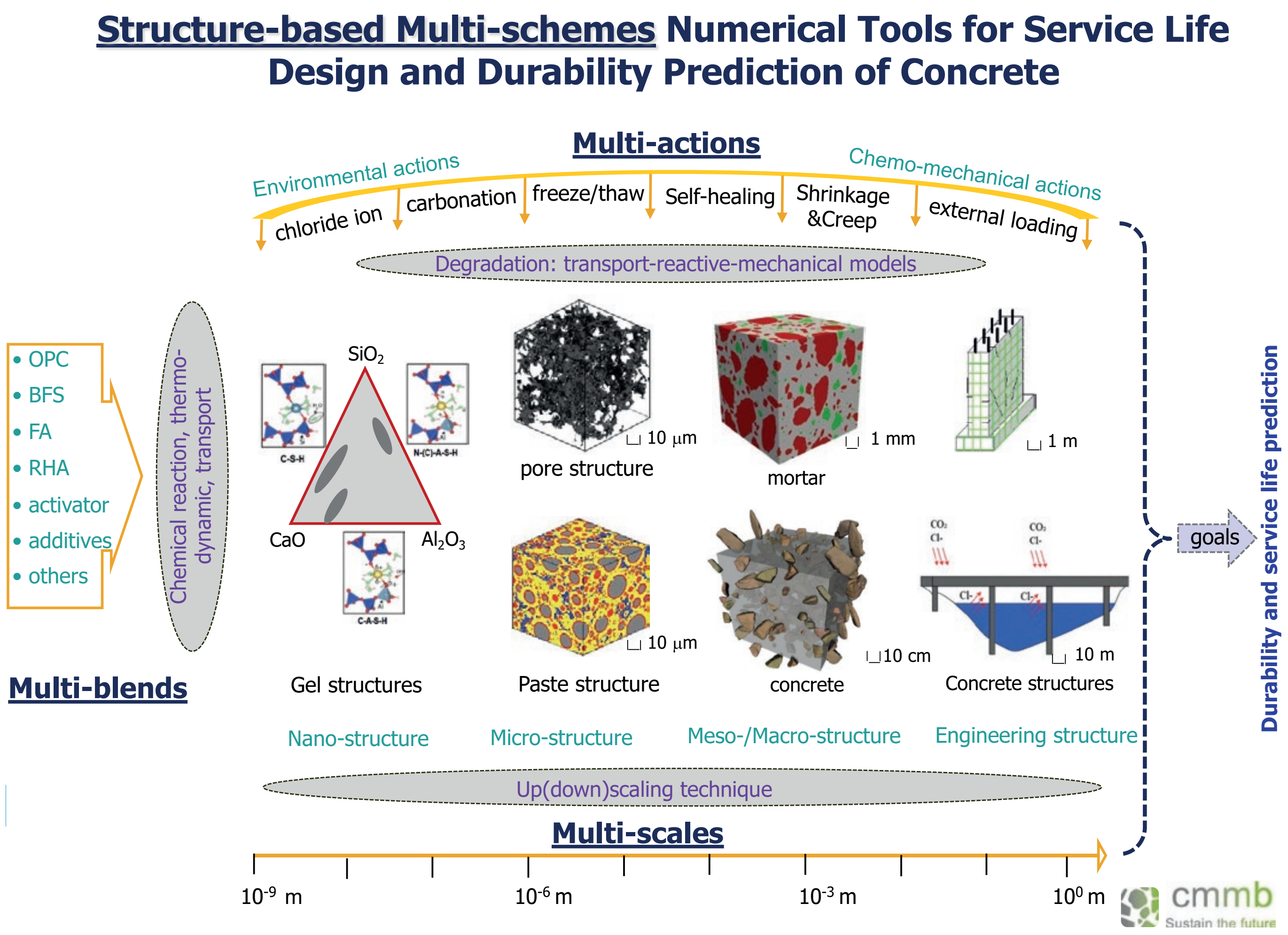

Fig. 3: Framework of multi-scale, multi-ionic reactive-transport-mechanical model (OPC = ordinary Portland cement, BFS = blast furnace slag, FA = fly ash, RHA = rice husk ash)

Fig. 4: Development of AAM-based textile reinforced material for structural repair (courtesy of A. Arce) [9]

premix. Focus of the project is on development and optimisation of these construction products that can then be adopted and applied by industry.

Life cycle analysis

The green profile of AAM structures is one of the main key-selling-points of the new material, hence, a thorough assessment of the environmental performance of AAM structures compared to traditional OPC-based concrete in comparable structures is of paramount importance. The environmental advantages coming from the AAMs application are derived from the reduction (60-80% [10]) of CO_2 emissions connected to clinker production, the lower use of non-renewable resources, and application of by-products or waste materials destined to landfill. The environmental impact from precursors in AAMs is mainly connected to the storage and transportation of precursors material, and eventually to the pre-treatment processes. The activators are considered as the main contributors of the total environmental impacts of AAM concrete. In the case of activators, inventory data variability has a major impact on the final LCA results.

DuRSAAM project is focused on developing a life-cycle analysis (LCA) framework for AAM based structures, approaches and related LCA models, including inventory data for AAM-based structures. The aim of LCA analysis is to prepare sustainability design guidelines, which would facilitate AAM concrete market uptake. Using LCA and analysing material flow (MFA), cost-benefit analysis will be performed, which will be used to identify the most promising circular economy models.

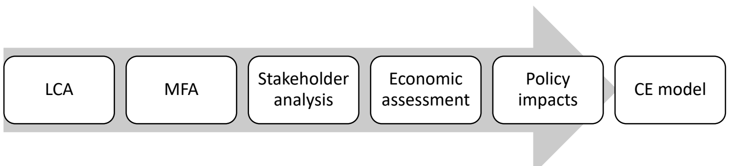

Fig. 5: Framework for identifying the most promising circular economy model for AAM-based structures (courtesy of A. Komkova) [11]

Conclusions and outlook

The DuRSAAM project addresses challenges associated with the successful development and implementation of alkali-activated concrete by forming a group of 13 early-stage researchers, each focusing in detail on a specific challenge of the AAMs, but working together to ensure that the knowledge is comprehensive rather than fragmented. The main strength of the project lies in its strong foundation, based on the fundamental knowledge of academic mentors, the experience of industrial mentors and the motivation of early stage researchers.

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References

[1] Li, N.; Shi, C.; Zhang, Z.; Wang, H.; Liu, Y, "A review on mixture design methods for geopolymer concrete," Construction and Building Materials, vol. 84, no. September 2015, pp. 387–398.
[2] Duxson, P.; Provis, J.; Lukey, G.; Mallicoat, S.; Kriven, W.; van Deventer, J., "Understanding the relationship between geopolymer composition, microstructure and mechanical properties," Colloids and Surfaces A: Physicochemical and Engineering Aspects, vol. 269, 2005, no. 1–3, pp. 47–58.
[3] Provis, J.; Arbi, K.; Bernal, S.A.; Bondar, D.; Buchwald, A.; Castel, A.; Chithiraputhiran, S.; Cyr, M.; Dehghan, A.; Dombrowski-Daube, K.; Dubey, A.; Ducman, V.; Gluth, G.; Nanukuttan, S.; Peterson, K.; Puertas, F. van Riessen, A., Torres-Carrasco, M.; Ye, G.; Zuo, Y. „RILEM TC 247-DTA round robin test: mix design and reproducibility of compressive strength of alkali-activated concretes", Materials and Structures (2019) 52:99
[4] Runci, A., Chloride ingress and corrosion of steel, DuRSAAM project, Karlsruhe meeting, Germany, 2020.
[5] Runci, A.; Provis, J.; Serdar, M. Comparison of chloride-induce corrosion of steel in cement mortar and mortar based on alkali-activated fly ash, 3rd RILEM Spring Convention 2020 Ambitioning a sustainable future for built environment: Comprehensive strategies for unprecedented challenges, Guimarães, Portugal, 2020.
[6] Serdar, M.; Bjegović, D. „Performance of concrete reinforced with corrosion resistant steels exposed to real marine environment", Proceeding MTECH 2017, Zagreb, 2017.
[7] Palomo, A., Krivenko, P., Garcia-Lodeiro, I., Kavalerov, A., Maltseva, O., Fernández-Jiméneza, A., A review on alkaline activation: new analytical perspectives, Materiales de Construcción, Vol 64, No 315 (2014)
[8] Yang, K.; Yang, C.; Zhang, J.; Pan, Q.; Yu, L.; Bai, Y. (2018): First structural use of site-cast, alkali-activated slag concrete in China. In: Proceedings of the Institution of Civil Engineers - Structures and Buildings 171 (10), S. 800–809. DOI: 10.1680/jstbu.16.00193.
[9] Arce, A. Fire behaviour of AAMs, DuRSAAM project, Karlsruhe meeting, Germany, 2020.
[10] Mclellan, B., Williams, R., Lay, J.,Riessen, A., Corder, G. Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement, Journal of Cleaner Production, 2011, 19, 1080-1090.
[11] Komkova, A. Sustainability Assessment of AAM Structures in the Context of a Circular Economy, DuRSAAM project, Karlsruhe meeting, Germany, 2020.