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M&S Highlight—Hansen (1986), Physical structure of hardened cement paste. A classical approach

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T.C. Hansen's 1986 paper "Physical structure of hardened cement paste. A classical approach" [1] is, in essence, an instructional paper elucidating on T.C. Powers' classical model of hardened cement paste [2, 3]. It is intended specifically for use by civil engineers to provide clear description of and *"understanding of some fundamental ideas*" with a distinct focus on pore network, fluids, hydrate phases and how these impact structural characteristics of cement paste. However, it would be unwise to undervalue the worth of this paper to other researchers investigating cement. Given the paper has amassed 221 citations (as of December 2021) since publication according to the Scopus database, the sentiment that "*Knowledge to the structure of cement paste is essential to the understanding of almost all concrete properties of technical importance*" expressed by Hansen over 30 years ago would still appear to hold true. The paper outlines the processes of derivation and application of Powers' work in a clear and concise way, outlining how the application of Powers' model as well as highlighting its limitations.

Powers' work investigated water vapour adsorption isotherms, using them to create a model outlining the formation of hardened cement paste (HCP) structure and physical properties. In the highlighted paper, Hansen [1] provided a broad background to this work by discussing the fundamental concepts involved in the development of a model for HCP; surface and surface forces, state of water differentiation, and impacts of vapour pressure on these. Using these concepts, a clear description of cement gel is provided, and the conclusion that the physical properties of cement is determined by the w/c ratio and degree of hydration in room temperature cured samples is reached. This is followed by a short section how the fractional volumes of the major constituents of hydrated cement can be estimated given this relationship, and the implications this has for analysing physical properties (strength, elasticity, creep, shrinkage, permeability and thermal properties). Given that the focus of the paper is to outline to engineers the importance of these concepts, the link back through to practicalities is essential.

The volumetric composition of hardened cement paste is similarly discussed in terms of its fundamental principals and shown to be valid as long as there is

This commentary is part of our celebration of 75 years of RILEM, highlighting Materials and Structures most highly influential and cited publications.

Highlighted paper: Hansen, T.C. Physical structure of hardened cement paste. A classical approach. 1986, Materials and Structures. 19(6), pp. 423–436

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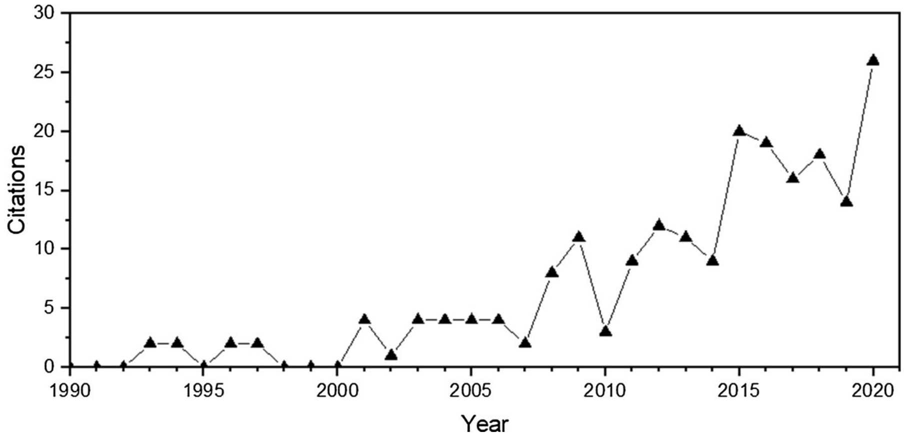

Fig. 1 Number of citations per year for T. C. Hansen "Physical structure of hardened cement paste. A classical approach" 1986 (data taken from Scopus database, December 2021)

sufficient space or all hydration products and sufficient water to allow the hydration process. The resulting Powers' model remains capable of explaining the physical properties of HCP – and more importantly, despite debate about the model validity; a reminder that models are only theoretical descriptions aiming to explain observed experimental data and provide additional insight into the behaviour of a material. "**A model cannot, and should not, be considered to be a correct description in any absolute sense**" [1]; this is why more than one model can be valid for the same scenario.

Although the highlighted paper does not actually present any original research, the key contribution of the paper is that it does package up complex theories into manageable applied bundles and demonstrates them with worked examples. It does not shy away from the limitations of the Powers' model – the fact that the model fundamentals are robustly debated is no secret. However, as Hansen states, the use of the model in an applied scenario **works** – this is no small thing. So engineers who are to use it need to understand *why* it works, and *where* are the limitations in its use. This paper demonstrates this.

As outlined above, the contributions of the paper to the wider research community are perhaps less easy to define than for other articles. However, the broader influence in the wider literature and RILEM work groups can be seen through the multidisciplinary approach and varied technical backgrounds of TC members. Having said this, the Hansen paper is cited in RILEM publications on varied topics, including super absorbent polymers mitigating autogenous shrinkage [4] and ultrasonic monitoring of capillary porosity evolution [5]. The relevance of the paper contents is further illustrated by the steady increase in citations accrued in the past 15 years (Fig. 1).

As observed by Brouwers [6], the work of Powers and Brownyard, which Hansen outlines, is also widely cited although perhaps not as widely read. This further highlights the important niche that Hansen's paper fills by demonstrating the application of the initial model. Given that Scopus records the total number of accesses overall as 1595 whilst citations are 221 (as of December 2021), it seems like Hansen's work is informing much more than it is actually cited.

Recent citing articles for this paper have been on both experimental and modelling based investigations, on subjects including chloride permeability, shrinkage, multiscale modelling, electric polarisation of water, gas migration mechanisms, and steel corrosion. The sub-fields this paper influences are wide ranging due to the fundamental nature of the work visited in it, and the applicability of these concepts to such a wide range of research niches.

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