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Van Breugel, Klaas

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Sustainable Civil Engineering Structures and Construction Materials, SCESCM 2016

Societal burden and engineering challenges of ageing infrastructure

Klaas van Breugel^{a,*}

^a*Technical University Delft, Faculty of Civil Engineering & Geosciences, Stevinweg 1, 2628 CN Delft, The Netherlands*

Abstract

Ageing is an inherent feature of nature and, hence, of materials, structures and systems. Yet, it seems a rather new topic in both science and engineering. The main reason for increasing attention for ageing as a topic is the growing awareness that, particularly in industrialized countries, ageing of our assets is a financial burden for the society. It touches our environment and a country's economy. It affects the overall sustainability of our planet and deserves, therefore, our utmost attention. In this contribution the urgency and challenges of ageing of concrete structures are addressed. Recent estimates of the extent of the issue and how ageing problems are dealt with in different disciplines, reactive or pro-active, are mentioned. The complexity of ageing problems will be evaluated by looking in more detail to the evolution in concrete mix design and the consequences thereof for the long-term performance of concrete structures. In this evaluation different kinds of driving forces contributing to ageing will be identified. Emphasis will be on ageing of concrete infrastructure and the need of research on ageing phenomena will be addressed.

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Keywords: ageing; infrastructure; risks; societal impact; concrete; research investment.

1. Infrastructure – Backbone of a country's prosperity

Architecture has been defined as the *art and science of designing and constructing* buildings and other physical structures for human shelter or use. In this definition the word shelter is meant in the broadest sense of the term. Going back to ancient times people needed shelter for protection against storms, rain and snow, direct sun shine and cold weather. For protection against hostile tribes cities were built surrounded by massive city walls. Dykes were built to protect against floods. Besides the need for shelter an increasing need for mobility emerged. For mobility of people roads and waterways were built. Aqueducts were built to transport water over long distances. With the

* Corresponding author. Tel.: +31 (0)15 27 84954;

E-mail address: k.vanbreugel@tudelft.nl

industrial revolution there was also an increasing need of energy and energy transport, requiring the design and construction of energy supply systems. To save densely populated cities from catastrophic water pollution, sewage systems were designed and installed. Large railway systems were built to enable long-distance transport of people and goods by train. Via bridges, viaducts and tunnels otherwise isolated transport networks became connected. All this illustrates that a modern society is inconceivable without a well-developed physical infrastructure. An infrastructure which, according to Long [1], accounts for about 50% of the country's national wealth.

When putting this in a global perspective, the infrastructure's value has been rated at € 37 trillion [2,12]. This is the value of the *existing* infrastructure, which is considered crucial for the prosperity and well-being of our society. In this respect Gann [3] argues that "The construction's significance to wealth creation and quality of life extends *beyond* its direct economic contribution. The products create an infrastructure that supports existing and newly emerging social and economic activities". And he continues saying; "If inadequate or inappropriate buildings and structures are produced, or they are poorly maintained and adapted, then social and economic life is compromised".

In a recent study of the McKinsey Global Institute [2] estimates were published of future investments in infrastructure worldwide needed to ensure economic stability and growth. In order to catch up with the prognosticated economic growth an investment of more than € 41 trillion was considered necessary in the period 2013-2030. This figure included the infrastructure for transport (roads, ports, rail, airports), water, telecommunications and power plants. This amount was based on an evaluation of money spent on infrastructure in 84 countries, accounting for more than 90% of the global gross domestic product (GDP). Table 1 gives the breakdown of investments over different categories.

Table 1. Estimated needs for global infrastructure in different categories in the period 2013-2030 [2].

Category	Reference	Required investment ⁴ × € 1,000,000,000,000
Roads	OECD ¹	12.2
Rail	OECD	3.3
Ports	OECD	0.5
Airports	OECD	1.4
Power	IEA ²	8.8
Water	GW ³	8.4
Telecommunication	OECD	6.8
Total		41.4

1) Organization for Economic Co-operation and Development

2) International Energy Agency

3) Global Water Intelligence

4) Conversion rate 2013: 1 US\$ = € 0.73

There is no doubt: economic stability and growth are unconceivable without an appropriate infrastructure. Without this infrastructure the economy would come to a complete stop. The infrastructure, however, is subject to *ageing*. Our assets – roads, railways, energy infrastructure, etc. - are still in use, but many of them beyond their initially presumed lifetime. The ageing process to which our assets are subjected is not a matter of bad luck or poor workmanship. In essence it is a natural law. If ageing and its potential impact on the quality of a country's infrastructure is not well diagnosed, this may lead to a situation of uncertainty or even societal instability. It is for this reason that stakeholders want to increase their knowledge and perception of ageing phenomena. Owners want to know how long it will take before on-going ageing processes require intervention or result in damage or even fatal failure. For this purpose reliable predictive tools are needed to forecast the rate and impact of ageing processes.

2. Ageing as a general phenomenon

2.1. The omnipresence of ageing

Ageing is everywhere around us [4]. Huge mountains seem to keep their shape, but from a closer look at the surface of rocks we learn that this surface gradually changes. Snow, rain, frost, light, wear, wind and sunshine are powerful enough to crumble the strongest rock. Mountains age! Like mountains, also man-made infrastructure works are exposed to climate conditions and change their performance,beit in a very slow process of ageing. As indicated in the foregoing, the infrastructure and industrial facilities can be considered as the ‘physical hardware’ of a modern society. All this hardware is ageing. Sometimes for better, but generally for worse. Ageing is everywhere! The ubiquitousness of ageing is an inherent feature of materials, structures and systems, either natural or man-made.

2.2. Driving forces

In general terms ageing is defined as a change of performance with elapse of time. It is not immediately clear, however, how time *per se* can result in a change of performance. How can a material ‘at rest’ change its performance? For an answer to this question it is important to realize that time is not a ‘loading’ to which a material is exposed, but the *domain* in which we describe changes in performance. Time *as such* is not the *cause* of these changes. But if time *as such* is not the cause of changes, what is, then, the cause of changes of a material, structure or system that is, at the macro scale, in a status of ‘rest’?

A closer look at any piece of matter tells us that the status of rest only applies to a certain level of observation. Going down to the atomic scale there is motion all the time. Any change of position of atoms, or *basic building blocks*, takes place in the time domain and is considered the origin of ageing of materials. Hence, ageing is an *inherent feature* of materials.

On top of this inherent feature of matter we see, at a little larger scale, a variety of *gradients*, which promote basic building blocks of matter to start moving. These gradients concern, for example, temperature, humidity and radiation, and they may cause changes at the surface of the material. In heterogeneous materials – and below a certain scale all materials are heterogeneous! – numerous interfaces exist. All these interfaces are preferred locations for the occurrence of a variety of gradients. Interfaces also offer sites for chemical and electrochemical activity, resulting in changes of the microstructure with elapse of time.

Porous materials continuously communicate with their environment and never reach a moment of ‘rest’. This ongoing communication of these materials, or better, systems, induces alternating stress and strain fields in the system, gradually affecting the micro- and nanostructure of a material and hence its performance.

The foregoing survey illustrates that a status of ‘rest’ is hardly conceivable. At smaller scale there is motion all the time. Gradients in temperature and stress promote basic building blocks to change their position, resulting in infinitesimally small changes, i.e. ageing. In fact basic entropy laws ‘explain’ why the basic building blocks of materials want the change position and hence cause ageing. This perception of ageing may enable us to understand ageing phenomena and to develop strategies for mitigating the impact of ageing.

3. Ageing assets

3.1. Ageing infrastructure

In the Introduction it has been mentioned that the value of the worlds infrastructure has been estimated at € 37 trillion. When with elapse of time ageing causes a loss of performance of infrastructure buildings, enormous amount of money are involved! Reports from the United States indicate that the effect of ageing on the infrastructure performance has been dramatically underestimated. Hoff [5] refers to a 1990 report of the National Research Council of the USA in which it was indicated that \$2 to \$3 trillion are needed over the next 20 years to repair all the concrete structures in the USA that were suffering from corrosion or poorly built and maintained. For repair and upgrading of bridges in the USA a budget has been estimated of US\$ 140,000,000,000 [6]. In his thorough survey of the state of

US infrastructure Lange [7] quoted the ASCE Infrastructure Report Card [8], which estimates a required investment by 2020 of \$ 3.6 trillion for repair and maintenance of infrastructure. This investment was considered a must for ensuring the vitality of the infrastructure as basis for the US economy, but also for accomplishing new sustainability goals. Ageing was mentioned as a prominent issue this respect. Lange [7]: “Ageing is relevant to sustainability because long service life is the best way to make concrete construction more sustainable. Ageing has many attributes, but materials durability is among the most threatening”.

A substantial part of the infrastructure stock has been built between the fifties and eighties of the past century. The presumed average service life of infrastructure buildings is 50 to 80 years. This means that in the coming decades these structures reach the end of their lifetime and a period of renewal is eminent. Schematically this is shown in Fig. 1. Note that in this figure only the prognosticated cost for replacement of obsolete infrastructure is considered. Costs for maintenance and repair of the structures is not involved, but are huge. According to the Office for National Statistics of the UK 55% of all the money spent in the building industry is spent on new-built and 45% is spent on repair and maintenance [10].

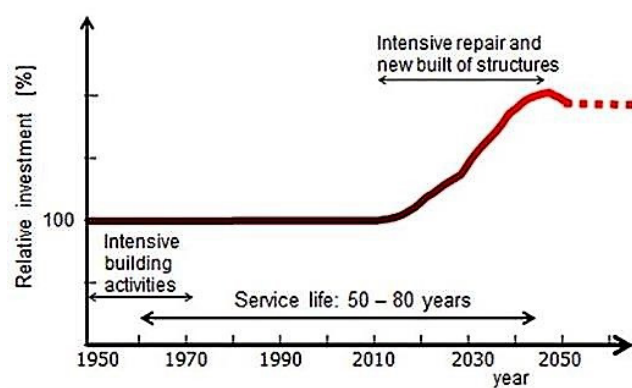


Figure 1 Stages in the lifetime of buildings: End of the lifetime of many structures is eminent [9].

It has to be mentioned that an assumed service life of 50 to 80 years applies to structures built according to, at that time, modern standards and presupposes good workmanship and, hence, good quality structures. In upcoming economies the quality of the infrastructure and the estimated service life of structures can substantially differ from the above mentioned figures. The average service life of civil buildings in China has been reported to be 20-30 years and of marine ports 10-20 years [11]. This is much shorter than the above mentioned 50 to 80 year service life required for many large infrastructure projects in Europe and further emphasizes the need of serious consideration of ageing phenomena.

3.2. Ageing plants

Another category of infrastructure where ageing is a major issue is that of large (petro)chemical and power plants. A brief summary of data, facts and concepts is given below.

3.2.1. Chemical plants

Chemical plants and refineries are vital for production of a variety of products. The size and complexity of chemical plants make them vulnerable for accidents. Chemical plants have got their present size through a process of gradual expansion. Subsequent extensions of plants were designed according to different codes and built with different materials while using different building technologies. Whereas the typical life cycle of a plant has been estimated at 25 years, the ‘effective’ age of large plants is highly heterogeneous with respect to both its real age and its functional age. Because of this heterogeneity it is not easy to judge the actual state of ageing of these plants.

Research Report RR 8238 “Plant ageing study” of the Health and Safety Executive [13] gives an overview of ageing issues in chemical plants. The report gives definitions of ageing and discusses the impact of ageing on plant safety. Based on three principal databases of three incidents reports, i.e. RIDDOR [14], MARS [15] and MHIDAS [16], the relevance of ageing was illustrated. The MARS study showed that approximately 60% of incidents could be related to technical integrity and, of those, 50% have ageing as a contributory factor. Hence, ageing is a contributory factor in 30% of the incidents. The percentage of incidents with ageing as a contributory factor is considered likely to increase with time as assets age. Ageing may affect the installations, piping and containments as well as the Electrical, Control and Instrumentation (EC&I) equipment. Figure 2 shows the results of the MARS incidents with ageing as the cause of failure.

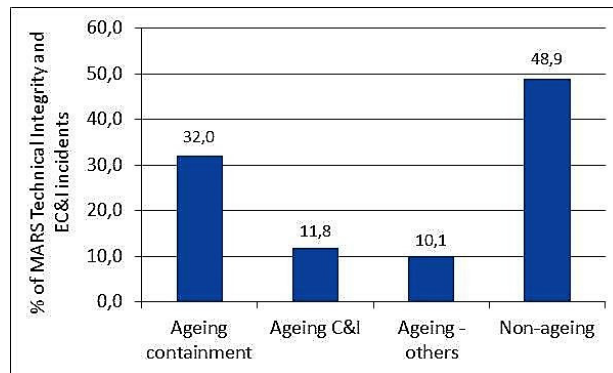


Figure 2 Proportion of incidents on chemical plants with ageing as the cause (After [15]; MARS study).
(EC&I: Electrical, Control & Instrumentation equipment)

3.2.2. Nuclear Power Plants

Maybe more than in any other industrial sector ageing is a key-issue in the nuclear industry. In the 1990s the International Atomic Energy Agency (IAEA) [17] started publishing a comprehensive set of reports on ageing management. The urgency for doing this was the fact that the majority of existing nuclear power plants had reached an age of 20-30 years. These plants were then old enough to discover new ageing phenomena that had slowly developed over the preceding decades. Moreover, new ageing phenomena were emerging as a result of more severe service conditions associated with increased plant performance, e.g. through implementation of the long-term operating experience obtained and/or the application of new technologies.

Even though predictions of the consequences of failure of components of a nuclear power plants vary and can be contradictory, there is no doubt that major accidents should be prevented at ‘all’ costs. For that reason emphasis in this sector is on *proactive* management of ageing. This in contrast with a ‘run to failure’ strategy, whereby components are replaced once they fail. The primary aim of proactive ageing management programs is to ensure the availability of safety functions throughout the service life of the plant. Moreover, effective management of ageing is also essential for achieving the desired plant performance and profitability of the plant, which is, in the end, of importance for the society as a whole.

The aim of materials ageing management of structures, systems and components is to maintain the design safety margins above the specified requirements. Based on experience it is known that many failures are the result of ageing mechanisms, such as general and local corrosion, erosion-corrosion phenomena, radiation, thermal embrittlement, fatigue, creep, vibration and wear [17]. To ensure a high level of plant safety it is recommended to manage ageing effectively and proactively. Effective proactive ageing management presupposes that we know how far we actually stay away from the moment a material, structural component or system will fail. This, on its turn, presupposes that we have predictive models for the relevant ageing mechanisms and that we are able to monitor the progress of degradation with time accurately and reliably [12]. In this respect the effect of radiation on the long-term properties of materials is a serious point of concern. Gamma radiation does affect the microstructure of cement

paste. In the late fifties it has been reported already that the compressive strength of the primary reactor shield in the Oak Ridge National Laboratory-Graphite Reactor was decreased within the first layers, i.e. within one foot of ordinary concrete, due to radiation [18]. Since then a negative effect of radiation on the compressive strength of concrete has been confirmed several times (see for example Basyigit et al [19]).

Not only the cement paste, but also the aggregate may suffer from radiation. According to William et al. [20] the reactivity of silica-rich quartz to alkali can increase significantly by exposure to nuclear radiation, thus increasing the risk of alkali-silica reaction in concrete containing aggregates that are otherwise known as typically nonreactive.

According to the IAEA report Nr. 62 [17], radiation embrittlement that leads to changes in bulk material properties has been successfully modelled already. The predictability, however, of corrosion, wear and high cycle fatigue, however, which produce changes at material surfaces and interfaces, was considered relatively low. The resulting uncertainty about the performance of vital plant components has caused significant nuclear power plant unavailability and increased costs for operation and maintenance.

Important to mention is that operating experience in the nuclear industry has revealed degradation and failures caused by previously unrecognized ageing mechanisms. Hence, the IAEA stated that, in addition to improving the understanding and predictability of known ageing mechanisms, there is a need to develop technology and techniques for early detection of new ageing mechanisms. Sensitive and reliable monitoring and control devices are needed and thorough understanding of running processes in a plant. Particularly performance of materials under coupled loads requires more research [20]. In-depth mono-scale and multiscale models are among the promising strategies to address these complex problems [21].

4. Strategies to mitigate the impact of ageing

If ageing is an all-present and practically unavoidable phenomenon from which materials, structures and systems always suffer, the question rises how the rate of ageing can be controlled and reduced. For an answer to that question we have to go back to the driving forces of ageing again. Internal interfaces, stress concentrations and different types of gradients were mentioned in this respect. Having this in mind a few basic approaches can be distinguished for decreasing the proneness to ageing, viz: 1) Materials design; 2) Adaptive approach and 3) Symbiosis [12].

4.1. Materials design

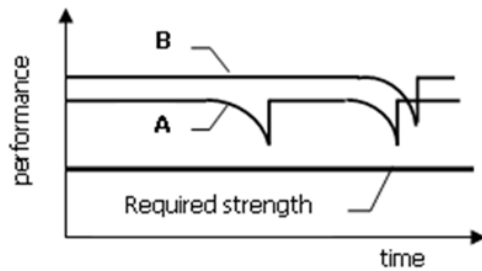
Since ageing is an inherent feature of materials, solutions for ageing require interventions at fundamental materials level. Knowing this, solutions for ageing problems can be sought in different directions. At the materials level basically two approaches are conceivable, i.e. the preventive approach and the reactive approach.

a. Materials design - preventive approach

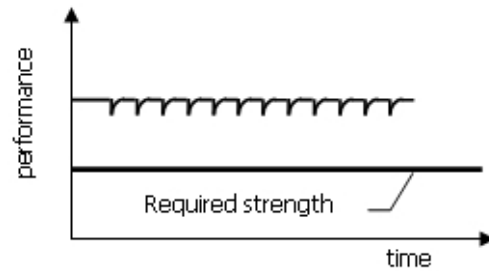
Heterogeneous materials, characterized by many internal interfaces and stress and strain concentrations, are prone to minor damage, i.e. microcracking. Knowing this, designing materials with less internal heterogeneity and hence less internal interfaces and less concentrations of stress and strain, will yield materials that are less prone to ageing. A more homogenous material, however, may also exhibit a higher brittleness. How a material performs in a structure, therefore, depends on the type of loading and load combinations to which the structure is exposed. The price of advanced materials with a reduced proneness to ageing will generally exceed that of traditional materials. Maintenance and repair costs, however, will be lower. Schematically this is shown in Fig. 3a, where the performance with elapse of time of two systems is presented [23,24]. System A is made of a traditional material and system B of a low-ageing material. Fig. 3c shows the evolution of the costs of those systems with time. Taking both the initial costs and the costs for repair and maintenance of the two systems into account, the total life cycle costs of system B will be lower than of the initially chapter system A. In other words: Spending more money initially to ensure a higher quality pays off [25].

b. Materials design - reactive approach

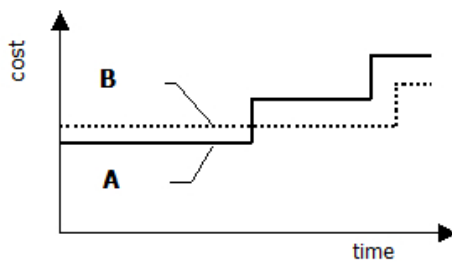
Since materials always exhibit some sort of heterogeneity, and hence of internal concentrations of stress and strains, the occurrence of internal damage can be considered as an unavoidable fact. In that case designing for *self-healing* might be a solutions for ageing problems. Damage is then seen as the *trigger* for starting a self-healing process that heals the damaged zone. In this way the lifetime of the material can be extended. Figure 3b schematically shows the performance of a structure made with self-repairing material [23,24]. On the occurrence of a small crack or the start of any physical or chemical degradation process, the material gradually starts to repair itself and the structure will regain its original level of performance or a level close to that. The initial costs might be substantially higher (Fig. 3d). The absence of maintenance and repair costs, however, can finally result in a financially positive situation for the owner. It has to be born in mind that also a healed material is still a material that ages!



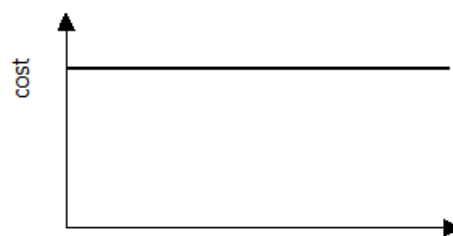
3a Traditional system A and low-ageing system B



3b System made with self-healing material



3c Evolution of costs of traditional and low-ageing systems



3d Evolution of costs of a self-healing system

Figure 3 Performance of a traditional (A) and low-ageing (B) system. b: Performance of a self-healing system. c: Costs of traditional and low-ageing systems A and B. d: Costs of self-healing system. Note: Interest and inflation not considered [23,24]

4.2. Adaptive approach

Often the materials used for designing and realizing structures are ‘just there’, not leaving room for any modification of the material in order to reduce their proneness to ageing. In those cases it is crucial to know the dominant ageing mechanisms of these materials and the dominant influencing factors. Aware of the relevant ageing mechanisms and influencing factors, structures can be designed in such a way that ageing phenomena will proceed in a controlled way. May be also the exposure conditions can be controlled in order to control or slow down ageing processes, thus extending the lifetime of the structure or system.

4.3. Symbiosis

Particularly in architecture situations are conceivable where ageing can be considered an acceptable, or even wanted phenomenon. Facades which deteriorate in a controlled manner, mirroring the ‘seasons’ of a particular building, may add something to the architectural design. Also structures for which only a short lifetime is required may benefit from inherent ageing phenomena. In this symbiosis approach ageing is not an enemy that has to be

beaten, but a collaborator to reach an ageing-stamped goal. It should be emphasized that the symbiosis approach is not a matter of 'let it happen'. It still requires in-depth understanding of the prevailing ageing process in order not to be surprised by any unexpected discrepancy between desired and actual performance of the structure.

5. Ageing of concrete structures - example

5.1. Observations regarding the performance of concrete bridge deck

If we want to learn about ageing studies of the performance of old structures may be helpful. Such a study has been undertaken by Mehta in 2001 [26]. A brief discussion of this study was published recently [27] and will be presented below.

Mehta analyzed the performance of concrete bridge decks of bridges built in four subsequent periods in the twentieth century. The first period was the period before 1930, the second between 1930 and 1950, the third from 1950 to 1980 and the fourth from 1980 to present. The concrete mixtures used for the bridge decks were characterized by the chemical composition and the fineness of the cement. The cements used in the first period, before 1930, had a C_3S content less than 30% and a Blaine surface of 180 m^2/kg . Consequently the rate of hydration was low. The performance of many bridge decks made with these cements was quite good.

The cements used in the second period were ground finer, to a Blaine fineness between 180 and 300 m^2/kg . The construction and building technology used for the bridge decks were similar to those used in the first period. The authors reported that the bridge decks built in the second period were less durable than those built before 1930.

The structures that were built between 1950 and 1980 appeared to have more durability problems than those built before 1950. The cements used in this period had a fineness up to 400 m^2/kg and a C_3S content beyond 60%. With the aim to get a denser and more durable concrete the w/c ratio was lower than in the first two periods. The higher C_3S content and the higher fineness of the cement had increased the early strength of these mixtures. This made it possible to build faster. This, however, had resulted in a higher probability of early-age thermal cracking and, on top of that, higher autogenous shrinkage of the low water-cement ratio mixtures. The higher proneness to early-age (micro)cracking was the most plausible reason for durability problems at later ages.

In the fourth period the tendency to go for higher strengths continued. Generally this was realized by using mixtures with a low water-binder ratio. The use of low water-binder mixtures further increased the risk of cracking. For bridge decks moderate strengths between 30 and 45 MPa were found. Among 29 bridge decks the cracking in 44 MPa bridge decks was twice that in 31 MPa bridge decks.

5.2. Ageing of more advanced concrete mixtures – possible causes

Mehta's inventory of the performance of bridge decks illustrates how the pressure from the market to build faster has created a demand for mixtures with a high early strength. This was made possible by using finer cements with a higher C_3S content. The price of this, however, was a higher probability of early-age cracking of the bridge decks.

Generally speaking it holds that for realizing thinner and more slender structures concretes with a higher final strength are required. A high final strength is attainable by reducing the water-binder ratio. The use of (super)plasticizers has made it possible to reduce the water-binder ratio of concrete mixtures to values even below 0.2. With these low water-binder ratio mixtures dense concretes are obtained with a very low permeability. This is good for the concrete's resistance against ingress of aggressive substances. At the same time, however, the concrete's proneness to (micro)cracking increases, mainly because of increased autogenous shrinkage.

Another reason for a higher cracking risk of high strength and ultra-high strength concretes are the high temperatures that occur as a result of high cement contents. By optimizing the particle packing of the aggregate fractions the amount of cement, and hence the peak temperatures, can be reduced. A low cement content is also considered positive from the sustainability point of view (lower carbon footprint). A low cement content, however, also has a drawback: it reduces the inherent self-healing capacity of the concrete. From the self-healing point of view a not too low cement content and the use of 'old', coarsely ground cement is favorable. This partly explains the outcome of Mehta's inventory that old bridge decks performed better than newer ones. In the terminology of this paper we would say that the old concrete mixtures with coarse cement and with a low C_3S content were less prone to

ageing than modern mixtures with finely ground cements with a high C_3S content. Moreover, it lends support to the plea of Aitcin et al [28] for using 'good old' Type I/II clinker if good performance of concrete structures is our goal.

6. Investments for the research agenda in view of mitigating the impact of ageing

In the forgoing sections it has been explained that ageing of infrastructure buildings is a huge financial burden for the society. A possible way to reduce this burden is by reducing the maintenance costs and extending the lifetime of infrastructure. The possibilities for realizing savings on the long-term were briefly addressed in section 4 (see also Fig. 3). In that section it was indicated, however, that for generating saving higher initial costs have to be faced. A related question is how much money we have to spend in research that might lead to those savings. A few thoughts on this will follow below (see also [12]).

In the Introduction the global value of the infrastructure stock has been estimated at € 37 trillion. Let us assume an average lifetime of these infrastructure assets of 50 years. Each year € 740 billion has then to be spent on replacement of obsolete assets. Let us further assume that through dedicated research the average lifetime can be increased by 10%, i.e. from 50 to 55 years. The yearly replacement costs would then decrease to from € 740 to € 670 billion. This is a reduction of replacement costs of € 70 billion per year. Let us assume that for saving these € 70 billion we have to invest 20% of this amount in research, i.e. € 14 billion per year. Let us further assume that 50% of the required research money, i.e. € 7 billion, has to be spent on management-oriented research and the other 50% on science-oriented research on materials and structures. A part of this science-oriented research has to be spent on ageing research. A reasonable, though conservative assumption is that 10% of science-oriented research, i.e. € 0.7 billion per year, should be spent on fundamental ageing research. This € 0.7 billion is 5% of the required research budget for realizing the savings of yearly replacement costs and only 1% of the targeted savings. Schematically this is shown in figure 4. By varying the assumptions in this exercise other values for required investments are obtained, but do not change the order of magnitude of these figures. If we judge the required research budget on ageing against the savings that can be realized the conclusion is justified that research pays off!

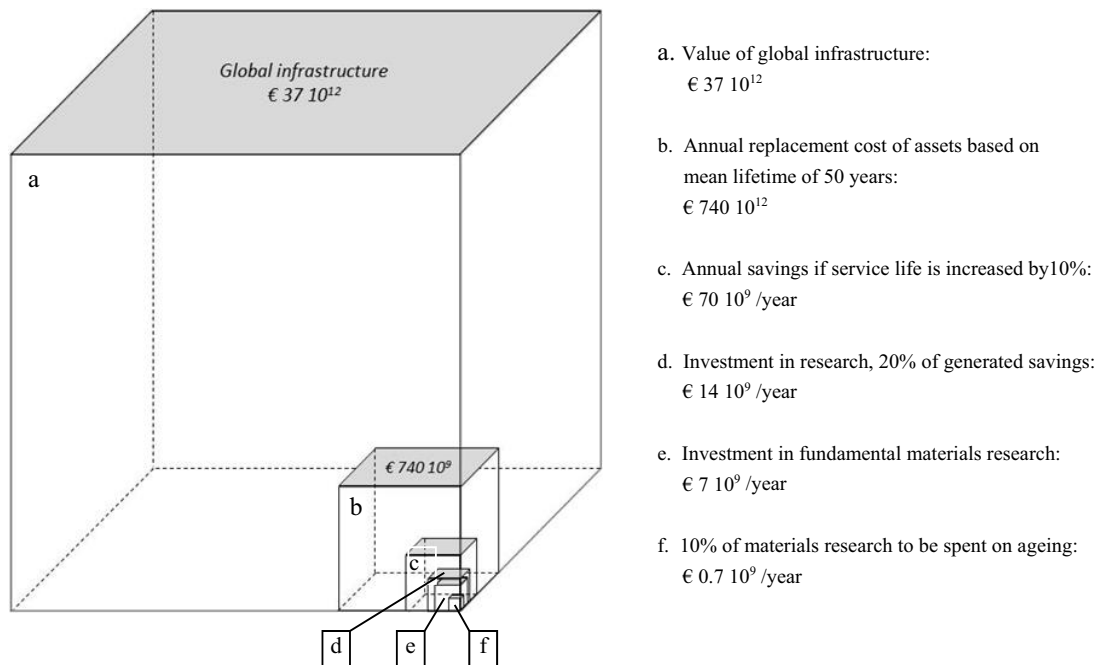


Figure 4 Schematic presentation of required investment in ageing research for realizing an extension of the mean service life of infrastructure of 10%. (interest / inflation not considered). Estimated average lifetime 50 years (after Van Breugel et al [12], modified).

7. Discussion and conclusions

The world's infrastructure increases rapidly in volume and complexity. At the same time the well-functioning of a society heavily depends on proper functioning of this infrastructure. To guarantee reliable functioning of the infrastructure an integral, or holistic approach is becoming a prerequisite [29]. In such an integral approach materials aspects are inherently coupled with a variety of aspects like logistics, availability, changes in environmental awareness, aesthetics and land-use planning, to mention only a few of them. The growing complexity of the issue implies that service life design is no longer a matter of only predicting the decay rate, or ageing, of a building material. Today service life design also requires a strategy for ensuring undisturbed operation of transport systems for a predefined period of time under a set of yet unknown changes of the boundary conditions.

The total value of the world's infrastructure is estimated at € 37 trillion. This infrastructure is ageing! With the existence, growth, maintenance and replacement of ageing infrastructure a huge responsibility comes to all actors involved in planning, designing, building and operating our assets. It is a matter of *responsible stewardship* to mitigate the environmental impact that comes along with realizing and operating our infrastructure.

Increasing size and complexity of structures, systems and plants make reliable judgment of the actual state of ageing of our assets extremely difficult. The development of new building materials, today often introduced with the claim of being environmental friendly but for which long-term experience is still lacking, further complicates the whole issue. The consequences of failure of infrastructure buildings, however, can be enormous. Catastrophic accidents on large chemical plants, for example, can result in huge direct losses of life and property. Not to mention the indirect losses, which may easily reach ten times the direct losses. The indirect losses include, for example, the risk of process interruption, interruption of supply of electricity and, as a consequence of this, failing safety systems and loss of confidence in the robustness of our society. Mitigating the probability of ageing-induced failures should have, therefore, a high priority.

Ageing is an *inherent* feature of materials. Hence ageing is an inherent feature of any device, structure, system or plant, simply because they are all made of materials that age. Loss of performance due to ageing is, therefore, different from damage or failures caused by design errors, poor workmanship, production failures or inadequate maintenance. Ageing is a typical materials related issue. This means that dealing with ageing and solving ageing problems require a fundamental materials science oriented approach.

Fundamental research on ageing is recommended in order to improve the tools for accurate and reliable predictions of the long-term performance of ageing infrastructure. Monitoring the performance of old and new structures, made with traditional and new concrete mixtures and different types of cement, may explain why old structures seem to be less prone to ageing than modern structures. From these observations lessons can be learned in view of designing structures with a low susceptibility to ageing.

Like many other industries, also the building industry is under pressure. Structures have to be realised faster, but with lower environmental impact. Any product, however, realised 'under pressure', irrespective of what kind of pressure, has an inherent tendency to age (entropy principle). To cope with the risk of increasing ageing rates, in-depth knowledge of the performance of materials and structures with elapse of time is needed.

The costs associated with ageing infrastructures is a heavy financial burden for the society and a burden for the environment as well. Controlling ageing-induced degradation processes, and hence reducing costs of new-built and of maintenance of existing infrastructure, contribute to reduce this burden. For developing low-ageing concepts and models we have to invest in research. An example has been presented, illustrating how investments in research can result in savings for the society that far exceed the investments needed to generate these savings. An increase of the average service life of our infrastructure by 10% would save tens of billions of euros each year. The investment to realise these savings was estimated at 20% of these savings. Half of this amount was assumed to be needed for research on materials and structures, of which amount 10% was assumed to be needed for fundamental research on

ageing phenomena at the materials level. Setting such targets for savings is not only challenging and a stimulus for research and innovation. The figures also illustrate that caring for our infrastructure finally pays off!

Since ageing is an inherent feature of all materials we know, a better understanding of ageing will potentially improve the way we use materials and how we design and produce structures and systems. In the end a more appropriate use of materials is a matter of responsible stewardship!

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