Sustainable Construction as a Research Area

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Sustainable development is one of the leading civilization ideas. This term means such a development that satisfies the present needs without a limitation of the possibility of satisfying the needs in the future. Sustainable development in construction is particularly important, as this branch of the industry is consuming enormous amounts of mass and energy. A new research area has been created by this idea. The new fields of investigation are involved with material, energetic, and environmental conditions, but also with such topics as protection against noise and the methods of the evaluation of the efficiency of waste materials storage. Implementation of the idea of sustainable development in the construction industry will be a source of scientific and engineering inspiration for many years to come.

Key Words: sustainable development, sustainable construction, sustainable material, performance concept, sustainable requirements

1 Sustainable development—a challenge for civilisation

The leitmotiv of the renoma ICMR Akita International Conference since 1991 is the beneficial integration of separate idea into new concept, which could provide for sustainable development of human being. Authors try to reply to this Conference main idea on the arena of sustainable construction discussed as the research area.

The notion of sustainable development aspires to the role of a leading civilisational idea. Sustainable development "implies meeting the needs of the present without compromising the ability of future generations to meet their own needs" (UN, 1987) [1]. The term is the most frequently found expression in forecasts and similar studies. It follows from philosophical premises and—in Poland—it is a constitutional prerequisite: "The Republic of Poland shall safeguard the independence and integrity of its territory and ensure the freedoms and rights of persons and citizens, security of citizens, safeguarding of Poland's national heritage, and ensure the protection of the natural environment pursuant to the principles of sustainable development." Therefore, sustainable development constitutes a principle that is to be followed by the Republic of Poland, in turn safeguarding fundamental values. In the Environmental Protection Laws, the definition of sustainable development is expanded further: such socio-economic development, in which—in order to equalise the opportunities to access the environment by individual communities or their members—both of contemporary generations and those still to come—a process of the integration of political, economic, and social actions takes place, maintaining the natural balance and continuity of vital natural processes [2].

Brundtland's definition of sustainable development [1] points out some ethical and ecological aspects. Cywiński, in his philosophy of sustainability [3], underlines the need to generalise the definition of sustainable development and to also consider human spiritual needs. According to Cywiński, sustainable development fulfils the comprehensive, spiritual, and material needs of today's people, without limiting the ability of future generations to satisfy their own respective needs. As a consequence, engineers must be prepared to respond not only to the 'material' question of 'how' but also be able to successfully cope with the 'spiritual' challenges of 'why'. [4].

The principle of sustainable development can also be approached from the point of view of the caution that is included in the second law of thermodynamics. In Clausius' version, the law implies that in isolated systems, processes can only occur if entropy is increased at the same time.

There have always been civilisations that have declined and fallen. In our times, the imperative of the constant growth of scale and sophistication might also bring about a disaster. Daly [5] formulated the following general principles of sustainability (Table 1):

- renewable resources (e.g. water), including food (e.g. fish), must not be used faster than the rate at which they can be regenerated,
- non-renewable resources must not be used faster than they are replaced with renewable substitutes,
- pollution and waste must not be produced faster than they can be absorbed by nature, recycled, or rendered harmless.

Sustainable development is a life necessity. The above summary reflects a general research inspiration, comprising such areas in construction as the rationalisation of energy management (energy + mass), structural durability, maintenance, renovation, repairs, modernisation (including revitalisation), working life,
reclaim and reuse, recycling and the influence on health and the environment. There is also an essential need to determine the "sustainability measures", measurement or calculation methods, and the forecasting tools for the simulation and prediction of the "development of sustainability".

2. Key terms and definitions

In the Polish equivalent of sustainable development, "zrównoważony rozwój", there is no lexical reference to sustainability. "To sustain" means "to keep in existence" and thus – a more literal translation of the term into Polish would incorporate an adjective with the meaning of "constant" or "permanent". That was the case in the first Polish publications addressing the issue, which were published a dozen or so years ago. It is noteworthy that –at that time—a representative of the Building Research Institute brought that matter up [7]. Translating the Polish term "zrównoważony rozwój" literally, we could end up with "balanced development". As can be seen, the Polish version focuses on the determinant of the development (equable), whereas the English term –on the expected results (sustainable). In other languages développement durable (French), Nachhaltige Entwicklung (German), sviluppo sostenibile (Italian), duurzame ontwikkeling (Netherlands), Desenvolvimento Sustentável (Portuguese), устойчивое развитие (Russian), desarrollo sostenible (Spanish) also rather the aspect of long-term durable development is stressed.

The term "sustainable development" in the construction-related literature is usually used to refer to the "construction that meets the requirements of sustainable development". The approach reflects the conceptual scope of sustainable development, which includes the construction industry as one of its many elements. The drawback is the complexity of the term. A shorter version is used as: Sustainable Development in Construction. In English literature, much simpler terms are often used, both for structures (sustainable house, sustainable city, and sustainable structure) and actions (sustainable transport, sustainable design, and sustainable living). It seems that the sequence of "construction that meets the requirements of sustainable development → sustainable development in construction → sustainable development of construction" may also find its final form in "sustainable construction". In anticipation of this notional evolution, the authors dared to use the term in the title of this study.

3. Construction that meets the requirements of sustainable development

The construction industry uses 42% generated power and emits 35% greenhouse gases. The branch of the concrete industry alone uses 20 billion tonnes of aggregates, 1.5 billion tonnes of cement and 800 million tonnes of water per year. That is a lot of matter. Implementing the principles of sustainable development in construction is a necessity, which has found its official acknowledgment in an initiative of the European Commission [9, 10], which announced a draft Regulation to replace the

<table>
<thead>
<tr>
<th>Use of resources/Production of pollution and waste</th>
<th>Environmental impact</th>
<th>Sustainability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faster than natural regeneration</td>
<td>Degradation</td>
<td>None</td>
</tr>
<tr>
<td>Equal to regenerative potential</td>
<td>Balance</td>
<td>Steady state</td>
</tr>
<tr>
<td>Slower than regenerative potential</td>
<td>Regeneration</td>
<td>Development</td>
</tr>
</tbody>
</table>

Figure 1 Activities of CEN/TC 350 as a basis for the harmonisation of requirements
Directive 89/106/EEC. The regulation will introduce sustainable development for the construction industry as a seventh principal requirement: a civil structure should be designed, erected (and also used), and demolished in line with the requirements of sustainable development. As a matter of fact, it will be a superior requirement to all others. Although stipulating the development of construction to be sustainable is defined in an ecological aspect, it is also determined by economic and social views. Sustainable construction has been classified as the second of the six development priorities. It is assumed that by the year 2020 the construction market will have increased 3.5-fold with employment boosted by 70% [10].

The growing awareness of the importance of the influence of construction on environmental protection issues and energy saving makes the need to satisfy the comprehensive criteria of sustainable development particularly vital for buildings and civil structures. The basis for the harmonisation of the respective European requirements should be provided by the standards that were developed by the European Committee for Standardisation CEN, Technical Committee TC 350 "Sustainability of Construction Works", in the following scope (shown in Figure 1):
- evaluation of the effect of buildings on the natural environment,
- preparation of environmental declarations for construction materials/products,
- evaluation of the total life cycle of buildings and civil structures.

4. Sustainable construction — premises and research needs

In order to implement the concept of "construction that meets the requirements of sustainable development", first of all, the requirements must be formulated specifically for the construction industry. In the year 2000, in Great Britain, a government policy for the sustainable development of construction was announced. Since that time, annual reviews have been performed to verify the policy. Nevertheless, it appears that there are still more questions than answers. In 2003, all of the sections of the report ended with a question mark [12]. In 2004, we could read the question again: what is sustainable construction?

The answer to the question was provided in a number of key points [13]:
- cost-efficient design,
- using minimum energy in construction and use,
- producing no pollution,
- preserving the nature around and in turn enhancing biodiversity,
- preserving water resources,
- providing people with comfort and respecting the local "microclimate". The authors admit that most of these guidelines are no less than a simple business principle: minimise loss, maximise efficiency. A lack of new knowledge is distinctly felt [47]. As a result, in all of the European programmes, sustainability is one of the leitmotifs. COST – European Co-operation in the Field of Scientific and Technical Research, which determines research directions by definition, is engaged in the following two actions:
- Action C8: Best Practice in Sustainable Urban Infrastructure [14],

In 2004, RILEM – The International Union of Laboratories and Experts in Construction Materials, Systems, and Structures, Technical Committee TC-92 ECM organised an international symposium "Materials and Systems for Sustainable Development" [16] under the direction of Kashino and Ohama. The symposium summed up the state of knowledge rather than attempting to solve any problems. Earlier, RILEM Technical Committee TC-165 worked on the definition of sustainable construction materials. However, their final report focused on the present situation and the technology regarding dismantling structures and the recycling of demolition waste [17]. Other attempts by RILEM in this area have been very specifically orientated, e.g. Towards Sustainable Roofing, RILEM TC-166 RMS [18]. Sustainable management of resources is an essential part of the latest theme (Theme 6: Environment) within the 7th Framework Programme [19]. In this context, it is surprising that in the policy of European Science Foundation (2007) – Looking Beyond the Endless Frontier – the concept of sustainability was not addressed [20].

5. Sustainable construction — research area

Sustainable construction is a rather rare example of a research theme in engineering. The inspiration for it did not follow from any direct practical needs, but rather from the central idea itself. Interpreting the idea, carrying out research and studies is for streamlining engineering activities. The versatility of the idea enveloped in sustainable development gave rise to a number of fundamental research directions, namely:
- material factors in the sustainable development of construction,
- energy factors in the sustainable development of construction,
- influence of a civil structure on the natural environment (ecology),
- influence of a civil structure on the internal environment (microclimate).

The first two research areas are the most extensive. An example of a direct interpretation of the research challenge contained in the concept of sustainable development is a study by K.Gertis (Director of the Fraunhofer Institute for Building Physics in Stuttgart) [21] that was presented at the conference "Low-energy or low-entropy buildings?" in 2002. The author states that two principal attitudes seem to have recently influenced the lines of thought of architects/building constructors:
- absolutisation of the importance of the low-energy building,
- the primitiveness of an ecological and natural environmentally-friendly building.

However, both terms are either undefined or vague. As a result, Gertis states the following:

"natural environmentally-friendly" means a building with minimum flows of mass and energy (i.e. minimum increase of entropy),
- the most "ecological” action occurs when the flows of mass and energy are minimised (ideally: zero entropy increase),
- a low-energy building will be essential in the future, but it will not suffice,
- anyone familiar with thermodynamics will deduce that the notion of entropy is a key one.

It is typical that Gertis did not introduce the notion of exergy in his study [45, 46, 47].

Accepting sustainable development as the main guideline for progress (Table 2) results in the creation of a new research area, concerning the material factors in the development (Figure 2). The area comprises the following existing fields:
performance criteria of construction materials,
- methods of suitability assessment,
- modification of materials and new material solutions,
- material performance in service conditions,
as well as certain aspects of ecology, waste management, and
the recycling of used construction materials for the construction
industry, and reuse of building materials.

The mere comparison of the amount of waste and the amount
of produced building materials is enough to show that—in the
decades to come,—waste management in the construction industry
will become a civilisational challenge, just like the repairs and
modernisation of the existing assets and ensuing material needs.

<table>
<thead>
<tr>
<th>Development factors (International Concrete, 1998)</th>
<th>Principal requirements (ER 89/106/EEC)</th>
<th>Sustainable Building, factors according to:</th>
<th>Research areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>sustainable development</td>
<td>structural safety: loadbearing capacity and stability</td>
<td>demand for energy and emission of $\text{CO}_2$</td>
<td>performance criteria of construction materials</td>
</tr>
<tr>
<td>environmental impact</td>
<td>fire safety</td>
<td>water use (dm$^3$/person/day)</td>
<td>methods of suitability assessment</td>
</tr>
<tr>
<td>energy saving</td>
<td>hygiene, health, and environment</td>
<td>effect of used materials and products on the environment</td>
<td>modification of materials and new material solutions</td>
</tr>
<tr>
<td>reduced costs of erection, maintenance, dismantling, and recycling</td>
<td>safety of use</td>
<td>evacuation of surface runoff</td>
<td>material performance in service conditions—matching materials with structures</td>
</tr>
<tr>
<td>use of highly-suitable materials; optimisation of structural solutions</td>
<td>protection against noise and vibration</td>
<td>waste management</td>
<td>recycling of construction materials; use of waste material</td>
</tr>
<tr>
<td>big and growing share of repairs and modernisation in construction works</td>
<td>energy-saving properties and thermal insulation</td>
<td>minimised pollution</td>
<td></td>
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<tr>
<td>design focused on the utility of the building/civil structure</td>
<td></td>
<td>health and comfort</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>construction process and building management</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ecology</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Developments in the research areas concerning construction material

- performance criteria of construction materials,
- methods of suitability assessment,
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Figure 2 The research area of the "material factors in sustainable development"
The notion of sustainable development is a premise that spreads over the research and economic areas and—quite possibly—it will become a megatrend in the 21st century. At the same time, the implementation of this idea is linked with finding a solution for one of the most fundamental civilisational problems—waste management, including the concept of DFR—“design for recycling”. It seems that the programme not only aims at rectifying the errors of the past and ensuring a better future for the next generations, but it will also become a creative force of progress—“Smart Material Systems” [24].

Sustainable development is a task for creating a number of balances on various levels (Figure 3). The most general perspective refers to the society, environment, and economy. As far as the construction industry is concerned, it refers to the comprehensive concept of an environmental impact over the whole life cycle of a civil structure or building (Life Cycle Assessment, LCA). Considering the nature of the construction industry, the material factors of structural durability and reliability are particularly important.

It is a vast, and multidisciplinary, task. It may be assumed that the message of sustainable development will be one of the main keynotes of the subsequent European Programmes. Sustainable development in construction in general—and factors determining the choice of materials in sustainable constructions in particular—are naturally becoming a paradigm of the research activity in the field of construction. It is an evolved consequence of the former paradigm—the principal requirements as set forth in Directive 89/106/EEC (1988). At the same time, it is a new approach, charting a new direction in the development of construction materials, which is referred to in Canada as "ISIS—Intelligent Sensing for Innovative Structures". Some elements of the new approach include the "Structural Health Monitoring" and "Building Advanced Composite Materials".

The specific nature of the construction industry makes durability and the reliability of material solutions understood as the material determinants of durability and the reliability of the construction, simply as a prerequisite. As far as the choice of materials is concerned, the central idea is their compatibility, which is understood as a choice of materials with regard to their physical and chemical properties so that the choice would ensure the load-bearing capacity and usability limits of each component of a given system within the designed time and conditions of use.

The policy of sustainable development sets new tasks for construction materials engineers. A sustainable building or civil structure is to meet nine requirements as regards the time of the construction and period of use [10, 22, 23]:
- minimum quantity of materials used (resource conservation), including water,
- maximum reuse of components,
- possibility to renovate or recycle,
- environment protection,
- waste management,
- minimum emission of pollutants,
- construction process management and building management,
- health aspects,
- comfort of use (quality).

Recently, the survivability requirement is being increasingly brought up, especially when referring to a terrorist attack.

The task of waste management and its reuse for construction purposes became a part of the sustainable development idea. The amount of disposed and produced waste clearly shows that their reuse in the construction industry is becoming a necessity.

The research tasks, following from the concept of sustainable development, may be divided into two types:
- intensive—incorporating the demand for sustainable development into existing research themes,
- extensive—creating new fields of research.

The division is vague. However, one can argue that material factors belong to the first type, while energy factors to the second. The intensive tasks face a serious problem of how to define the types and levels of criteria; the notion of usefulness must be redefined to ensure sustainable development.

6. Sustainable development vs. performance concept; product performance criteria

The idea of usefulness in the construction industry has a long tradition. Some aspects of the approach may be found in the Code of Hammurabi (1750 BC), and the books of Vitruvius (dated 20-10 BC). However, only recently has there been the performance concept, i.e., evaluation and selection of materials according to their usefulness, becoming increasingly appreciated throughout the construction industry. In the European standard for concrete, which
is accepted as a Polish standard (PN-EN 206-1), and in many other standards the notion was used in the title. The idea of performance was well grasped in the US building regulations of 1925 [25]:

“Whenever possible, requirements should be stated in terms of performance, based upon test results for service conditions, rather than in dimensions, detailed methods, or specific materials. Otherwise new materials, or new assemblies of common materials, which would meet construction demands satisfactorily and economically, might be restricted from use, thus obstructing progress in the industry.”

The above statements have not lost their validity, and—in light of the sustainable development requirements—they have even become a particularly current necessity. It is especially significant with regard to substitute material solutions (alternative raw

<table>
<thead>
<tr>
<th>Ecology</th>
<th>Economy</th>
<th>Social aspects</th>
<th>Assurance of sustainable material performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission?</td>
<td>Cost/ performance</td>
<td>Joint decision making</td>
<td></td>
</tr>
<tr>
<td>Use of natural resources?</td>
<td>Tendency to incur costs</td>
<td>Transparency Responsibility</td>
<td></td>
</tr>
<tr>
<td>Bio-diversification?</td>
<td>Organisational efficiency</td>
<td>Safety, health, and good mental state</td>
<td></td>
</tr>
<tr>
<td>Balanced system – ecology</td>
<td>Balanced system – economy</td>
<td>Balanced system–social aspects</td>
<td></td>
</tr>
</tbody>
</table>

Table 3  Formulation matrix for the additional requirements to ensure sustainable material performance (based on [14])

![Diagram](image-url)

Figure 4  Defining the performance of a construction product as a derivative of basic principles of sustainable development (based on [14])

![Diagram](image-url)

Figure 5  A diagram representation of the term "integrated building performance" according to CEN TC-350 [29]
materials), and to those construction materials and products that are based on recycled ingredients or components. Moreover, sustainable development imposes the need to consider additional requirements and/or restrictions (Figure 4 and Table 3). A restriction is also a situation when certain technical properties are not used in a given application or when they are redundant, and thereby generate irrational costs (energy input). This implies that there is a need [26], or even an obligation to develop a new research area (and knowledge/skills) to define the performance in terms of the properly selected (type and level) technical properties. The final decision on the choice of a material solution, as a rule, will require an analysis or optimisation involving a number of criteria. There are examples of this approach in the literature, e.g. the polyoptimal method of designing environmentally-friendly buildings [27] considers the values of the total accumulated energy and CO₂ emission of construction materials and main technologies. It should become one of the fundamental activities of the leading research institutes in the field of the construction industry.

The examples of the pursuit of a definition of sustainable performance are usually methods of assessing the environmental impact of buildings [28], which are used as a manual for auditors. As part of the activities of the CEN Technical Committee TC-350 [29], an extended term for "integrated building performance" was introduced (Figure 5).

7. Sustainable construction industry—new fields of research

Energy factors in sustainable development have led to the creation of a few new fields of research, including a method for simulating the energy performance of buildings [30, 31] and a method for determining the energy profile of buildings (implementation of Directive 2002/91/EC) [32]. New terms have been coined, e.g. a "passive building" (Adamson, Feist), i.e. a building in which a comfortable interior climate can be maintained without an active heating and cooling system. Pilot projects have been realised to respond to the new notions [33] along with a whole new library of software to simulate and evaluate energy and environmental effects. The number of specialised programmes is so large that a validation method had to be developed [34].

New themes within the idea of sustainability include the recycling of construction materials, such as concrete [35], and the assessment of the durability of concrete [36] mixed with recycled concrete aggregate. Sustainable concrete has proven to be a satisfying field of research [37, 38]. Studies of concrete recycling show that the process of grinding causes such an expansion of the surface of concrete aggregate that it results in an irregular increase of carbonation intensity [39]; therefore, up to 90% of the carbon dioxide emitted while producing cement is assumed to be absorbed in this way (Figure 6).

Sustainable development in construction opened a new research area, which is connected not only with material performance, energy factors [40], and environmental effects [41], but also protection against noise pollution [42] and the evaluation of the storage efficiency of waste material [43]. The introduction of the principle of sustainable development into the construction industry will provide a source of illuminating and important research inspiration for engineers for many years to come. A successful implementation of sustainable development in construction depends on the results, but it also—and to a large degree—depends on the availability of properly educated specialists. It has been found that—until now—only the British University of Strathclyde launched a Masters' by Research in Sustainable Construction & Infrastructure [44]. This should spur other universities to prepare similar relevant specialisation courses. In order to implement the concept of "construction that meets the requirements of sustainable development", first of all, the requirements must be formulated specifically for the construction industry.

References


Figure 6 Simulated carbonation of concrete, including its recycling. Grinding of concrete during its recycling causes expansion of the surface of concrete aggregate leading to an irregular increase of carbonation intensity (on the figure—after about 70 years)
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