Sustainability of Constructions. Special aspects of concrete structures

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Preface

The elaboration of the current thesis started in 2009, when the author has been accepted for a doctoral scholarship at the Politehnica University of Timisoara, Department of Civil Engineering, under the supervision of Prof. Corneliu Bob. The author has been asked to shed some light regarding sustainability in the field of construction, a relatively new and unknown topic in Romania, but with high preoccupations on international level.

Special considerations are reserved to my supervisor Prof. Corneliu Bob, who saw the great oppertunities related to this topic and who continuously offered moral and material support during the doctoral stage. I would also like to thank other colleagues from the Department, who helped with usefull advices.

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Sustainability of Constructions. Special aspects of concrete structures

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Keyword: constructions, sustainability, assessment tools, concrete, carbonation, CO_2 uptake

Abstract:
The topic approached in the frame of the doctoral program refers generally to the matter of sustainability in construction. In particular, the research focused on the sustainability performance evaluation of different types of construction works, using specialized assessment tools. As a contribution to the environmental dimension of sustainability, the CO_2 absorption capacity of concrete structures through carbonation has been experimentally investigated.
Two evaluation models have been developed, both of which permit the quantification, aggregation and communication of a large number of parameters, which, combined in a rational way, can offer an overall perspective of the construction work's sustainability performance level.

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SYMBOLS AND ABBREVIATIONS

Symbols

Latin lower case letters

a	Degree of carbonation
c	Correction factor for binder type
d	Discount rate
d	Correction factor for CO_2 concentration
e	Escalation rate
f	Frequency
f_c	Concrete compressive strength
h_d	Daily number of working hours
h_i	Number of hours in use of equipment i
k	Constant that equals 0.161
k	Safety factor
k	Correction factor for RH
m	Mass per unit of the partition
n	Number of surface parts
r_1	Reference distance from sound level
r_2	Distance to target
t	Number of time periods (years) between the present time and the time the cost is incurred
t_{ch}	Charring time
w/c	Water to cement ratio
$\overline{x}$	Carbonation depth

Lattin upper case letters

A	Annually recurring cost
A_0	Annually recurring cost at base-date prices
A_0	Reference Area
A_i	Aria of the roof
A_w	Total glazed area of windows
B	Width
C	Cement content
C	Final CO_2 content
C_0	Initial CO_2 content
C_a	Applatization factor
C_{max}	Theoretical maximum CO_2 content
C_t	Future cost occurring in year t
CLO	Clothing
D	Total duration of the construction work
D_c	Degree of carbonation
D_n	Normalized airborne sound insulation
H	Height
K	Correction factor for the lateral transmission of noise
K	Stiffness
L_0	Initial sound level
$L_{n,w}$	Level of sound pressure measured on finished floor slab
L_{nweq}	Level of sound pressure measured naked floor slab
L_s	Sound level at specific distance

L_{savg}	Average sound level
L_{si}	Sound level at specific distance for equipment i
M	Correction factor for dirt
M	Molar weight
MET	Metabolic Rate
N	Number of time periods (years) over which A_0 recurs
P_i	Calculated value of parameter i
P_i^R	Reference value of parameter i
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PS_d	Partial Score of dimension
PS_i	Partial Score of criteria i
R_{max}	Maximum number of workers on site, at the same time
R	Sound Reduction Index
R	Area-weighted average reflectance of the room surfaces
RT60	Reverberation time
S	Sum of all room surfaces
Sa	Total surface absorption of the room in Sabin's
T	Sound transmission coefficient
T	Glass transmission factor
TA	Air Temperature
TR	Mean Radiant Temperature
U	Uptake
V	Volume of the room
W	Worload
W_d	Weighting of the dimension
W_i	Weighting of criteria i

Greek letters

α_i	Weighting factor of parameter i for environmental dimension
β	Charring rate
β_i	Weighting factor of parameter i for economic dimension
γ_i	Weighting factor of parameter i for social dimension
ΔB	Increase of bending moment
ΔL_w	Reduction in noise
$\rho_0 \times c$	Acoustic impedance
θ	Angle of visible sky

Abbreviations

ADF	Average Daylight Factor
AFm	Tetracalcium aluminate ferrite monosulfate hydrate
AFt	Ettringite
BEE	Built Environment Efficiency
BMVBS	Bundesministerium für Verkehr, Bau und Stadtentwicklung Federal Ministry of Transport, Building and Urban Affairs
BREEAM	Building Research Establishment Environmental Assessment Method
BSI	Building Sustainability Index
C	Cost
C_2S	Dicalcium silicate (Belit)
C_3A	Tricalcium aluminate (Celit II)

C_4AF	Tetracalcium aluminoferrite (Celit I)
C_3S	Tricalcium silicate (Alit)
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
CC	Calcium Carbonate
CEN	European Committee for Standardization
Cf	Comfort
CFRP	Carbon Fibre Reinforced Polymer
CH	Calcium Hydroxide (Portlandite)
CO_2	Carbon Dioxide
CP	Construction process
CS	Construction Site
CSH	Calcium Silicate Hydrate
DGNB	Deutsche Gütesiegel für Nachhaltiges Bauen German Sustainable Building Certificate
DTA	Differential Thermal Analysis
DTG	Derived Thermogravimetric curve
EDAX	Energy-dispersive X-ray spectroscopy
Ef	Efficiency
EN	European Norm
En	Energy
EPD	Environmental Product Declaration
G	GHG Emissions
GBCA	Green Building Council of Australia
GBFS	Granulated Blast Furnace Slag
GBTool	Green Building Tool
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GI	Global Impact
GOP	Ground occupancy percentage
HK-BEAM	Hong Kong Building Environmental Assessment Method
HVAC	Heating, Ventilation, and Air Conditioning
ID	Impact Duration
IDP	Integrated Design Process
IEQ	Indoor Environmental Quality
iiSBE	International Initiative for a Sustainable Built Environment
ISO	International Organization for Standardization
JaGBC	Japan Green Building Council
JSBC	Japan Sustainability Building Consortium
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LEED	Leadership in Energy and Environmental Design
LI	Local Impact
LR	Load Reduction
LW	Land Use and Water Consumption
MR	Materials and Resources
N	Noise
NC	New Construction
NIST	National Institute of Standard and Technology
OPC	Ordinary Portland Cement
PCA	Portland Cement Association
PCR	Product Category Rules

PM	Project Management
PM10	Particle Matter <10µm
Q	Enviornmantal Quality
RCA	Recycled Concrete Aggregate
RH	Relative Humidity
RP	Regional Priorities
SBC	Sustainable Building Conference
SBTool	Sustainable Building Tool
SC	Subcommittee
SEM	Scanning Electron Microscopy
SI	Sustainability Index
SRI	Solar Reflective Index
TC	Technical Committee
TG	Thermogravimetric curve
TGA	Thermogravimetric analysis
TR	Technical Report
TVOC	Total Volatil Organic Compounds
USGBC	U.S. Green Building Council
WG	Working Group
WGBC	World Green Building Council
WI	Work Item
XRD	X-Ray Diffraction

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REZUMAT

Cuvinte cheie: construcţii, sustenabilitate, modele de evaluare, beton, carbonatare, absorpţie de CO_2

Teza de doctorat analizează atât probleme legate de sustenabilitatea construcţiilor, cât şi studiul capacităţii betonului de a lega CO_2 din atmosferă prin carbonatare, evidenţiind astfel o proprietate ecologică a acestui material. Tema abordată este de mare actualitate, atât pentru domeniul de construcţii cât şi pentru toate domeniile activităţilor umane, deoarece urmăreşte atât preocupările pentru cerinţele generaţiilor actuale cât şi satisfacerea nevoilor generaţiilor care vor veni.

Domeniul de construcţii joacă un rol foarte important în dezvoltarea socio-economică, având însă şi un impact foarte mare asupra mediului înconjurător. Este principalul consumator de resurse naturale, apă şi teren şi produce cantităţi mari de deşeuri. Conform unor statistici, industria de construcţii consumă aproximativ 40% din totalul materialelor care întră în economia mondială. În statele membre ale Uniunii Europene clădirile consumă 50% din necesarul de energie şi contribuie cu aproape 50% la emisiile de CO_2 în atmosferă. Din aceste motive elaborarea unor metode inovatoare cu impact cât mai mic asupra mediul înconjurător a devenit principala preocupare a întregii industrii de construcţii. O construcţie sustenabilă se manifestă prin durabilitate, costuri reduse de exploatarea şi întreţinere, eficienţă energetică, adaptabilitate, confort şi posibilitatea de reciclare reutilizare.

Betonul sub forma betonului simplu, armat sau precomprimat constituie principalul material de construcţie. Practic nu există structură importantă, oriunde în lume, la care să nu se folosească ciment sau beton sub diferite forme. În acelaşi timp betonul este considerat un material de construcţie neecologic, deoarece prin arderea materialelor prime pentru obţinerea clinkerului de ciment se degajează o cantitate mare de CO_2, un gaz responsabil pentru încălzirea globală. În ziua de azi producerea unor betoane cu impact minim asupra mediului este obligatorie. Aceste deziderate se pot realiza prin utilizarea unor tipuri de ciment cu adaosuri, prin optimizarea compoziţiilor de betoane, dar cel mai important, prin exploatarea proprietăţilor benefice ale structurilor de alungul vieţii acestora. Aceste proprietăţi sunt: durabilitate, rezistenţă la foc, izolare la zgomot, dar şi legarea de CO_2 din atmosferă prin fenomenul de carbonatare, o proprietate neglijată mult timp a acestui material. Astfel, impactul structurilor din beton asupra mediului este mai redus, având o contribuţie pozitivă la dimensiunea ecologică a dezvoltării durabile.

În urma unei analize a domeniului au fost definite următoarele obiective:

- definirea corectă a conceptului de sustenabilitate, cu aplicabilitate în domeniul construcţiilor, considerând toate cele trei dimensiuni: ecologic, economic şi social;
- transformarea aspectelor de sustenabilitate în parametri cuantificabili, pentru a putea fi utilizaţi ca o bază de decizie şi selecţie;
- elaborarea unor procedee şi modele de calcul, care permit aprecierea sustenabilităţii diferitelor tipuri de lucrări de construcţii;
- determinarea capacităţii betonului de a absorbi şi a lega dioxid de carbon prin carbonatare;
- elaborarea unei formule practice care permite calcularea cantităţii de CO_2 absorbit şi includerea acestui fenomen în evaluarea ciclului de viaţă a structurilor din beton.

Teza de doctorat este structurată pe opt capitole, după cum urmează:

Cap. 1 „Introducere” prezintă o succintă introducere în problematica temei de cercetare, stabilind motivaţiile, obiectivele precum rezumatul tezei de doctorat.

În **Cap. 2.** „Sustenabilitatea lucrărilor de construcţii” sunt trecute în revistă preocupările pe plan internaţional în domeniu. Sustenabilitatea/dezvoltarea durabilă ”este dezvoltarea care urmăreşte satisfacerea nevoilor prezentului, fără a compromite posibilitatea generaţiilor viitoare de a-şi satisface propriile nevoi" (raportul Brundtland 1987). În multe ţări europene şi mondiale există deja coduri şi directive de evaluare a performanţelor clădirilor. O serie de normative internaţionale au fost sau sunt încă în curs de elaborare de către ISO/TC59/SC17 şi CEN/TC350, cum are fi: ISO 15392:2008; 21929-1:2011; 21930:2007; 21931-1:2010; 13315-1:2012; EN 15643-1:2010; 15643-2:2011; 15643-3:2012; 15643-4:2012; 15978:2011; 15804:2012; TR 15941: 2010, *etc.*

S-a realizat o evaluare critică asupra unor modele de certificare existente pe plan mondial cum ar fi BREEAM, LEED, DGNB, CASBEE, HK-BEAM, Green Star, SBTool şi OPEN HOUSE, identificând următoarele aspecte:

- certificatele existente sunt aplicate predominant pe clădiri întregi, de diferite tipologii, fără a avea specificaţii pentru alte tipuri de lucrări;
- majoritatea certificatelor nu respectă definiţia de sustenabilitate, punând accent doar pe partea ecologică, aspectele economice şi sociale fiind neglijate;
- certificatele conţin un număr foarte mare de parametri, însă multe dintre ele sunt doar calitative, iar astfel se induce un grad mare de subiectivism;
- sistemele de punctare şi ponderare nu sunt unitare, iar acordarea de credite/puncte este în multe cazuri foarte dificilă, deoarece necesită multe valori de referinţe;

Evaluare critică a certificatelor existente a stat la baza dezvoltarii a doua modele proprii.

Cap. 3. „Modele originale pentru aprecierea sustenabilităţii lucrărilor de construcţii” prezintă detaliile legate de cele două modele propuse şi dezvoltate de doctorand. Prima parte din capitol este dedicată modelului global şi sunt prezentate condiţiile de margine, principiile de selectare şi cuantificare a parametrilor, acordarea punctajelor, distribuţia ponderilor, prezentarea rezultatelor si schemele logice pentru modul de funcţionare a programului de calcul elaborat pentru cele trei dimensiuni: ecologic, economic şi social.

Modelul global este un program cuprinzător, dezvoltat în Microsof Excel, care are ca scop evaluarea performanţelor de sustenabilitate ale unor cladiri de locuit, tip familial. Modelul respectă definiţia dezvoltării durabile, cuprinzând în mod aproape egal parametrii celor trei domenii: ecologic, economic si social (40%-30%-30%). Sunt cuprinse în total 13 categorii de sustenabilitate şi peste 50 de parametri de performanţă, încluzând întregul ciclu de viaţă a construcţiei. Selectarea parametrilor s-a făcut pe următoarele considerente: recomandările făcute în normativele internaţionale de specialitate; pe baza unui studiu bibliografic cuprinzător asupra modelelor existente; iniţiativă proprie.

Modelul foloseşte un sistem unitar de punctare între 0 şi 5. Punctele se acordă proporţional în funcţie de valorile de referinţă definite pentru practici insuficiente şi pentru practici foarte bune. Aceste punctaje urmează a fi ponderate, în funcţie de durata lor de impact, nivelul lor de importanţă şi categorie de impact. Rezultatele sunt reprezentate pe baza unui index de sustenabilitate, cu o valoare între 0 si 5. Pentru un index mai mare de 4, se acordă calificativul de „Best practice”, pe când la un index sub 2.5 se acordă „Insuficient practice”.

Modelul specific este un model mai simplificat, însa cu o aplicabilitate mai mare. Scopul acestui model este de a oferi o metodă de comparare a diferitelor soluţii în termeni de sustenabilitate. Acest model poate fi utilizat pentru lucrări parţiale de construcţii, soluţii de reabilitare, mijloace de transport, *etc.*

Evaluarea soluţiilor se face în urma aplicării unor formule matematice simple. Termenii relaţiilor sunt valorile cuantificate ale diferiţilor parametri ai celor trei dimensiuni, raportate la o valoare de referinţă, stabilită ca o valoare optimă. Astfel, rezultatul final este un indice de sustenabilitate, cuprins între 0 şi 1. Ponderea celor trei dimensiuni rămâne neschimbată, însă definirea şi selectarea parametrilor diferă faţă de modelul global. Fiecare situaţie este analizată separat, iar parametri aleşi caracterizează lucrarea din mai multe puncte de vederi.

În **Cap. 4.** „Studii de caz" sunt prezentate lucrările de construcţii analizate cu cele două modele elaborate de doctorand. Astfel modelul global a fost aplicat pe o casă familială recent construită, iar modelul specific s-a utilizat pentru evaluarea unor soluţii pentru transportul de elemente prefabricate pe ruta Timşoara – Galaţi şi pentru lucrări de reabilitare la un tronson al Universităţii de Vest din Timişoara şi fabrica de bere „Timişoreana". Se remarcă analiza detaliată a cazurilor, acestea reprezentând un ghid excelent şi pentru alte aplicaţii.

Cap. 5 „Aspecte speciale privind structurile din beton. Absorbţia de CO_2 de către beton prin carbonatare" este împărţit pe trei subcapitole. Primul prezintă teoria legată de compoziţia şi chimia betonului, mecanismul şi rata de carbonatare. În această parte sunt prezentaţi principalii compuşi a betonului care participă la procesul de carbonatare şi recarbonatare, fiind redate reacţiile chimice asociate acestui fenomen. Se prezintă studii legate de macanismul şi factorii care influenţează şi formule pentru calculul adâncimii de carbonatare.

Al doilea subcapitol prezintă ciclul parcurs de CO_2 în structurile din beton. Sunt evidenţiate sursele de emisii generate la diferite etape din viaţa construcţiei (producerea materialelor componente, transportul, etc.) şi posibilele absorbţii/ reduceri de alungul duratei de exploatare (utilizare de adaosuri în locul cimentului, absorbţia de CO_2 prin carbonatare). Ultima parte prezintă cercetările existente pe plan mondial în acest domeniu. Acestea cuprind atât studii existente privind bilanţul de emisie şi absorbţie a structurilor din beton în diferite ţări, cât şi metode de calcul pentru determinarea cantitativă a dioxidului de carbon absorbit.

Cap. 6. „Programul experimental" reprezintă o importantă contribuţie la stabilirea capacităţii betonului de a absorbi CO_2. În acest capitol sunt redate proprietăţile fizice, chimice şi mecanice ale materialelor folosite, compoziţia celor şapte serii de beton, condiţiile de păstrare, standul pentru carbonatare accelerată, procesul experimental de uscare şi cântărire, determinări experimentale prin SEM/ EDAX (Microscopie electronică de baleiaj), XRD (difracţie cu raze X) şi TGA (analize termo gravimetrice).

S-au realizat şapte reţete de betoane, parametri variabili fiind: raportul apă/ciment, dozajul şi tipul de ciment şi rezistenţa la compresiune. S-au utilizat cimenturi de tip CEM I 42.5R şi CEM II/A-LL 42.5R. Prepararea epruvetelor s-a realizat în condiţii de laborator, fiind turnate 126 cuburi de 150x150x150mm şi 21 prisme de 100x100x300mm. Determinările iniţiale efectuate pe tipurile de ciment, betonul proaspăt şi betonul întărit (la 28 de zile) au fost:

- rezistenţa la compresiune şi compoziţia chimică a tipurilor de ciment;
- tasare;
- rezistenţele la compresiune şi întindere a celor şapte serii de betoane;
- uscarea şi cântărirea probelor până la masă constantă, difracţii cu raze X (XRD) şi analize termogravimetrice (TGA) pe probe pulverizante.

Epruvetele au fost introduse în incinte cu condiţii de carbonatare accelerată (CO_2≈40%, T≈18°C, RH≈50-70%), pe perioade de 30, 60 şi 120 de zile. Pentru determinarea capacităţii betonului de a lega CO_2 s-a utilizat o metodă originală. Conform mecanismului de carbonatare, pentru fiecare mol de CO_2 absorbit se deliberează un mol de apă. Deoarece masa molară a apei (18g/mol) este mai mică decât cea a CO_2 (44g/mol) masa probei va creşte prin carbonatare. Astfel s-a considerat că diferenţa între masele constante înainte şi după carbonatare reprezintă exact absorpţia. Această valoare este combinată cu volumul betonului carbonatat, obţinut prin despicarea probelor pe cele două direcţii şi pulverizat cu o soluţie de fenolftaleină. Pentru o precizie mai ridicată, area carbonatată s-a obţinut prin procesarea imaginii suprafeţelor colorate, iar volumele au rezultat prin înmulţirea acestora cu adâncimea medie de carbonatare pe direcţia perpendiculară. Acest procedeu a fost aplicat după fiecare interval stabilit pe câte trei epruvete.

În paralel au mai fost efectuate următoarele analize, având ca scop:

- SEM/EDAX – determinarea cantitativă a compoziţie betoanelor înainte şi după carbonatare;
- XRD – detectarea calitativă a diferitelor structuri cristaline formate în urma carbonatării;
- TGA – determinări cantitative privind gradul de carbonatare şi CO_2 absorbit.

Cap. 7. „Rezultate experimentale” este dedicat analizei şi interpretării rezultatelor obţinute privind: variaţia masei epruvetelor, rezistenţa la compresiune, profilul şi adâncimea de carbonatare, aborbţia de CO_2 de către betonul celor şapte serii, gradul de carbonatare în funcţie de rezistenţa la compresiune. Deasemenea sunt prezentate rezultatele obţinute prin procedeele SEM/EDAX, XRD şi TGA.

În urma proceselor de uscare şi cântărire a epruvetelor se pot sublinia câteva aspecte importante: scădera relativă a masei înainte de carbonatare a fost visibil mai mare decât după carbonatare, datorită eliberării de apă prin carbonatare; valorile medii pentru creşterea masei absolute (absorpţia) au variat între 49g după 30 zile până la 130g după 120 zile de carbonatare; după carbonatare, porii din betonul carbonatat s-au închis parţial, structura devenind foarte densă şi aproape impermeabilă. Acest fenomen a mărit timpul de uscare, dar a condus şi la creşterea rezistenţei la compresiune cu 7% - 15% faţă de epruvetele păstrate în condiţii de laborator. Timpul necesear de uscare a crescut semnificativ de la 80 ore (beton necarbonatat) până la 180 ore (120 zile de carbonatare) la o temperatură de 140-150°C.

Rezultatele adâncimii de carbonatare funcţie de perioada de expunere pentru cele şapte serii de epruvete din beton sunt într-o concordanţă mulţumitoare cu datele teoretice. Influenţa cea mai importantă a avut rezistenţa la compresiune, tipul de ciment având un efect nesemnificativ.

Prin corelarea absorbţiei cu volumul de beton carbonatat a rezultat capacitatea de absorbţie a celor şapte serii de betoane. Combinând valorile experimentale cu consideraţii teoretice a rezultat gradul de carbonatare. S-a constatat că aceast parametru nu are o valoare constantă. Astfel, pe baza rezultatelor experimentale s-a propus o formulă de calcul pentru absorbţia de CO_2.
În urma determinărilor prin metodele SEM/EDAX, XRD şi TGA s-a constatat o bună corelare cu rezultatele obţinute prin procedeul original propus.

Cap. 8. „Concluzii şi contribuţii personale” prezintă ideile principale desprinse din lucrare şi subliniază contribuţiile personale aduse prin elaborarea tezei de doctorat.

Concluzii:

- Sustenabilitatea este un termen complex, iar pentru a fi interpretat corect, trebuie definit clar şi concis;
- Domeniul de construcţii are un rol foarte important în dezvoltarea socio-economică, cu impact mare asupra mediului;
- O evaluare corectă a performanţelor de sustenabilitate în domeniul construcţiilor necesită un echilibru între impactul asupra mediului, laturii economice şi aspectele sociale;
- Evaluarea, quantificarea şi combinarea unui număr mare de parametri se poate realiza prin utilizarea unor modele/programe speciale;
- Betonul este cel mai utilizat material de construcţii. Deşi este considerat neecologic datorită cantităţilor mari de CO_2 emis prin producerea cimentului, betonul are proprietatea de a reabsorbi o parte din CO_2 emis;
- Pentru calculul absorpţiei sunt necesari doi parametri importanţi:
  - Adâncimea de carbonatare;
  - Capacitatea betonului de a absorbi CO_2 (gradul de carbonatare).

Contribuţii personale:

Contribuţii privind analiza şi prezentarea diverselor aspecte ale domeniului:

- Prezentarea generală şi pe domeniul construcţiilor a conceptului de „sustenabilitate/dezvoltare durabilă";
- Prezentarea, evaluarea şi compararea critică a diferitelor standarde şi certificate existente pentru aprecierea sustenabilităţii construcţiilor;
- Prezentarea unui studiu documentar legat de capacitatea betonului de a absorbi CO_2 prin carbonatare;

Contribuţii teoretice:

- Prezentarea unui model global/general de apreciere a sustenabilităţii unor construcţii de tip clădiri/case familiale, pentru care s-a dezvoltat şi un program de calcul in Microsoft Excel;
- Propunerea unui model specific pentru calculul indicelui de sustenabilitate al diferitelor tipuri de lucrări de construcţii, model caracterizat prin supleţe, rapiditate de aplicare, obiectivitate şi flexibilitate;
- Propunerea unei formule proprii pentru calculul absorbţiei de CO_2 de către elementele din beton;

Contribuţii experimentale:

- Propunerea şi realizarea unui program extins de carbonatare accelerată a şapte serii de betoane, utilizând două tipuri de ciment, oferite de Holcim România, determinările fiind făcute în două etape, fiecare fiind extinsă pe 120 de zile;
- Folosirea unei metodologii proprii de determinare a absorbţiei de CO_2 prin uscarea şi cântărirea până la masă constantă, înainte şi după carbonatare;
- Realizarea unor determinări moderne/clasice prin SEM/EDAX, XRD şi TGA, pentru validarea/confirmarea rezultatelor obţinute prin procedeul propus. Determinările au fost efectuate în colaborare cu instituţii specializate: Institutul National de Cercetare-Dezvoltare pentru Electrochimie şi Materie Condensată şi Institutul de Chimie Timişoara al Academiei Române.

Diseminarea rezultatelor

- 1 monografie la o editură internaţională;
- 1 lucrare la o revistă română (ISI);
- 10 lucrări la congrese şi conferinţe internationale (2 ISI)

1. INTRODUCTION

1.1. Generalities

The topic approached in the frame of the doctoral program refers generally to sustainability in construction. In particular, the research focuses on the sustainability performance evaluation of different construction works, using specialized assessment tools. The tools allow the quantification, aggregation and communication of a large number of parameters, which, combined in a rational way, can offer an overall perspective of the construction work's performance level. As a contribution to the environmental dimension of sustainability, the CO_2 absorption capacity of concrete structures through carbonation has been experimentally investigated.

The term "sustainability" is a very complex and ambiguous expression so in order to be approached correctly by an engineer it needs to be clearly defined and measurable. Engineers need rational facts as they are considered individuals who give solutions to real problems. Thus, from a conceptual point of view, sustainability has to be reformulated, from a mythic, qualitative, highly normative construct, in a phrase that is culturally acceptable and useful for quantitative applications in engineering disciplines.

Concrete plays a double role in the development of a sustainable future. First of all, concrete in its plain, reinforced or prestressed form, is the most frequently used man-made construction material. The estimated consumption of concrete was between 21 and 31 billion tons in 2006, according to [1]. It is the second most consumed material on Earth after water [2]. The production of brick structures is only about one-tenth of the amount of concrete by weight, while wooden structures are built less than 5% from the total of the annual concrete production in the world, measured by weight basis [3]. More so, concrete structures have a potential to obtain a very long life span. For this reason, it is important to explore the many beneficial properties of concrete during its service life.

In order to design efficient and advanced technological systems, products and services, good engineers are needed. But, if these products and services are also environmentally friendly, with high social performances in a globalizing economy, we can talk about sustainable engineering. As a system becomes more complex, also the cultural and institutional framework within which engineers and others operate, suffer changes. Thus, the modern engineer faces a world where not only his/her task becomes more complicated, but also the environment in which they must practice.

1.2. Motivation and objectives

Sustainability is one of the most up-to-date topics, which defines a common platform for different domains in order to share results and knowledge so that a common goal can be achieved, a sustainable world. The evidence that sustainability is in continuous increase lies in the researches done by Kajikawa et al. [4]. They stated that over 3000 papers on sustainability issues are currently published annually in different journals specialized on the sub-domains of sustainability. Even if there is a great preoccupation on the subject, sustainability still represents a vast area of study. The concept of sustainability is in many cases misunderstood, not clearly defined or incorrectly interpreted. It is the case of the construction sector, where sustainability is in many times connected only to the environment and the environmental impacts.

The construction industry plays an important role in socio-economic development, but it also has a great impact on the local and global environment. It is a major consumer of land and raw materials and it generates a great amount of waste. Furthermore, constructions through their entire life cycle use significant amounts of nonrenewable energy and contribute to the emission of greenhouse gases and other gaseous wastes. According to some institutes, the building and construction industry uses 40% of the materials entering the global economy, consumes approximately 50% of the total energy supply and contributes with almost 50% to the total CO_2 emissions released into the atmosphere through different stages, including construction, operation and demolition [5], [6].

A sustainable construction develops the idea of low embodied energy, reduced greenhouse gas emissions, low operation and maintenance costs, responsibly sourced materials with recycled content, durability, adaptability, safety and comfort. It has recently been identified as one of the lead markets for the near future of the whole world. It has the potential and the ability to respond to market needs, the strength of the world's industry and the necessity to support it through the implementation of public policy measures.

For a long time, concrete has been considered a non-ecological building material due to its great amount of CO_2 emissions, an important greenhouse gas responsible for climate change. The amounts of CO_2 and other combustion gases embodied in concrete are primarily a function of the cement content, because most of the emissions are released during its manufacturing process (calcination). The CO_2 emissions can range from 112 kg/m^3 for a 20-MPa concrete with 50% slag cement to 313 kg/m^3 for a 35-MPa concrete [7].

Nowadays the production of concrete structures with a minimum of environmental impact is done on a regular basis, but it is also important to explore the many beneficial properties of concrete during its service life. The impact can be limited by optimized concrete mixtures, using cement replacement materials, minimizing transportation, but also taking into consideration the important factors during its service life. The most important parameters cover aspects of durability, thermal mass, fire resistance properties but also carbon dioxide uptake through carbonation, an issue that has been neglected during the performance of life cycle assessment analysis.

The arguments mentioned above represent the main motivational reasoning for performing the theoretical and experimental studies related to sustainability in construction and the CO_2 absorption property of concrete. The results can have significant practical and theoretical contributions to engineers in evaluating the sustainability performances of different construction works, while the CO_2 absorption property of concrete can reduce the environmental impact of such structures.

The main objectives of the thesis are:

- a detailed definition of sustainability, considering all the three dimensions: environmental, economic and social;
- the transformation of sustainability goals into quantifiable issues, in order to be used as a decision making support;

- the development of a calculation tool for engineers, which permit the sustainability performance evaluation of different construction works;
- the determination of the CO_2 uptake capacity of concrete through carbonation;
- the development of a practical calculation procedure, which permit the inclusion of CO_2 uptake in the life cycle analysis of RC structures.

1.3. Overview of the thesis

The thesis is composed of eight chapters and two appendices totalising 169 pages. Essentially, the thesis is focusing on two main aspects: sustainability of construction works and the ability of concrete to absorb CO_2 through carbonation, as a contribution to the environmental dimension of sustainability.

The first chapter outlines the frame the paper is set into, it states the motivations and objectives of the project and it also contains a short overview of the thesis.

Chapter 2 provides a general presentation about sustainability, highlighting its applicability in the field of construction. The international standardazitions of ISO and CEN regarding sustainability in construction are noted, followed by a short overview of existing certification and rating tools of building sustainability performances. Details regarding the sustainability issues, weightings, scoring and ranking are provided for BREEAM, LEED, DGNB, CASBEE, HK-BEAM, Green Star, SBTool and OPEN HOUSE. Advantages and disadvantages of these tools are outlined considering the definition of sustainability.

Chapter 3 presents details of the two evaluation models elaborated in the thesis, mainly the global and specific model. In the first part of the chapter the applicability and system boundaries of the global model are discussed upon, followed by a description of the developed scoring and weighting system. An important part of the chapter is dedicated to the selection and quantification of the sustainability issues, criteria and key performance indicators. Furthermore, the utilization procedure of the „Building Sustainability Index BSI" software tool is described. The last part of the chapter focuses on the specific model, where the formulas for the calculation of the sustainability index are presented.

Chapter 4 is dedicated to case studies using the developed evaluation models. The global model is applied on a typical family house near Timisoara, while the applicability of the specific model is shown in three examples: Rehabilition of the Timisoreana Brewery, rehabilitation of some elements from the Western Timisoara University and the transport of prefabricated elements on the Timisoara – Galati route. The use of the developed models is described, which also represents an excellent guide for other applications as well.

Chapter 5 is centered around a brief literature study regarding the CO_2 absorption capacity of cement-based materials through the process of carbonation. This chapter is divided in three parts. The first part addresses the theoretical background of concrete chemistry, carbonation mechanism and carbonation rate. The second part presents the CO_2 cycle in concrete structure, outlining the sources of emissions and possible reductions/ uptake. The last part is a state of the art in the field, presenting existing reasearches and calculation methods of CO_2 uptake.

Chapter 6 represents an important contribution from the author's part in the determination of the CO_2 absorption capacity of concrete. This chapter shows the experimental program, including material properties, concrete mix designs, description of the experimental procedure, stand for accelerated carbonation test, experimental determinations by direct mass gain, SEM/EDAX (Scan electron microscopy/Energy-dispersive X-ray spectroscopy), XRD (X-Ray diffraction) and TGA (Thermogravimetric analysis).

Chapter 7 is reserved for the analysis and interepretation of the experimental results. Using the original procedure through direct mass gain, the mass variation, increase of concrete compressive strength, carbonation profile, CO_2 uptake and degree of carbonation have been obtained. Alternative results have been obtained by SEM/EDAX, XRD and TGA.

Chapter 8 showcases the main idea from the theoretical and experimental works. Practical tools for engineers have been developed in order to appreciate the sustainability performance of a construction work and to calculate the CO_2 uptake of concrete elements. The chapter also contains an outlook provided for future research directions, concluded by an account of the author's publications and personal contributuions to the work.

Appendix A contains the entire material database regarding embodied energy, CO_2 emissions, and other material properties which have been implemented in the developed assessment tools.

Appendix B displays all experimental measurements during the drying and weighting process.

2. SUSTAINABILITY ASSESSMENT OF CONSTRUCTION WORKS

2.1. Sustainability. General aspects

The word "sustainability" is derived from the Latin word "sustinere" which means the ability to sustain, maintain or support something. The term has been used initially in context with the ability of the ecosystem to maintain a level that is able to ensure the supply of food, forestry, fishery, agriculture and other providential resources to the growing population. In this sense, sustainability is linked to the environment and the ecology that provide us with food, land and other important products and services.

The meaning of sustainability has changed over the centuries growing up to a trend of the modern society. Sustainability or sustainable development becomes a complex idea that can neither be unequivocally described nor simply applied [8].

Many definitions have been proposed for sustainability, but one of the most widely accepted and most frequently quoted one is the definition that came after the Brundtland Report by the World Commission on Environment and Development (WCED) in 1987. It stated: *"sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* [9]. The concept of sustainability/ sustainable development was the first to link the environment to the development. Sustainability linked together the issues of the natural system to the social challenges and the economic growth, in a time frame of present and future. This is the reason why it becomes common to represent sustainable development as a confluence of the three pillars: environment, economy and society (Fig.2.1) [10].

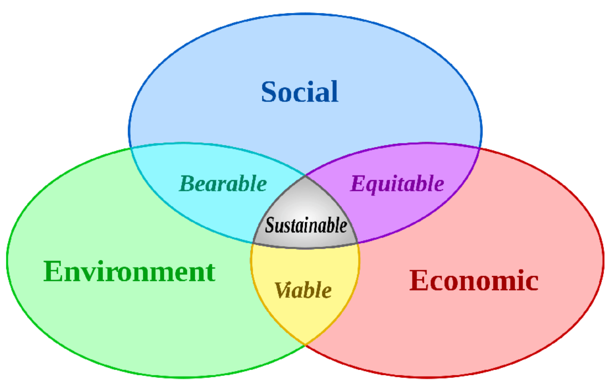


Figure 2.1. Scheme of sustainable development: at the confluence of three dimensions.
Source: http://en.wikipedia.org/wiki/Sustainable_development

Sustainability can be defined in each of these pillars individually, but the significance of the concept is given by the interrelation between them. Each of the domains has its own aims and can contribute either positively or negatively to the sustainable development.

Environmental sustainability focuses on the protection of the ecosystem, trying to maintain a balance between human activities and natural resources, in order to ensure that the natural capital is healthy recoverable, so it can also be used by the future generations. Unsustainable situations appear, if the resources are used carelessly and inefficiently. They contribute to the degradation of the ecosystem and, on a global scale, to the extinction of biodiversity.

The aim of social sustainability is to influence the development of people and societies in such way, that justice, well-being and health play the important role. Through education, the sustainable way of thinking and living should be implemented. Unsustainable behavior can lead to social disruptions such as war, crime and corruption, issues that can damage the capacity of the society to plan for the future.

In economic sustainability the focus is set on the development of the economic infrastructure and the efficient management of natural and human resources. Sustainable business practices can integrate ecological concerns with the social and economic ones. Unsustainable business, also called "uneconomic growth" can lead to a decline in the quality of life [11].

The building and construction industries are key sectors for sustainable development. The construction, operation and demolition of buildings generate substantial social and economic benefits to society, but may also have serious negative impacts, in particular on the environment. Areas of key concern include energy use with associated emission of greenhouse gases (GHG), land and raw material consumption, waste generation, water use and discharge, and integration of buildings with other infrastructures and social systems.

According to some institutes, the building and construction industry uses 40% of the materials entering the global economy, consumes approximately 50% of the total energy supply and contributes with almost 50% to the total CO_2 emissions released to the atmosphere through different stages, including construction, operation and demolition [5], [6]. Furthermore, it provides 5-10% of employment at national level and normally generates 5-15% of the GDP. It literally builds the foundations for sustainable development, including housing, workplace, public buildings and services, communications, energy, water and sanitary infrastructures, and provides the context for social interactions as well as economic development at the micro-level [12].

The concept of sustainable construction aims to integrate the objectives of sustainable development into the construction activities. A sustainable construction develops the idea of low embodied energy, reduced greenhouse gas emissions, low operation and maintenance costs, responsibly sourced materials with recycled contents, durability, adaptability, safety and comfort.

Du Plessis [13] describes sustainable construction as: "A holistic process in which the principles of sustainable development are applied to the comprehensive construction cycle, from the extraction and beneficiation of raw materials, through the planning, design, and construction of buildings and infrastructure, until their possible final deconstruction, and management of the resultant waste".

The concepts involved in sustainability are highly complex and under constant study. There are no definitive methods for measuring sustainability or confirming its accomplishment. A measurement of sustainability must combine the individual and collective actions to sustain the environment as well as to improve the economy and satisfy societal needs [14], [15].

The sustainability of construction works is a very complex issue. It includes a lot of factors with clear defined relations. A structure of building sustainability has been developed, which clearly reflects the concept of sustainable construction and respects the definition of sustainable development (Fig. 2.2) [16].

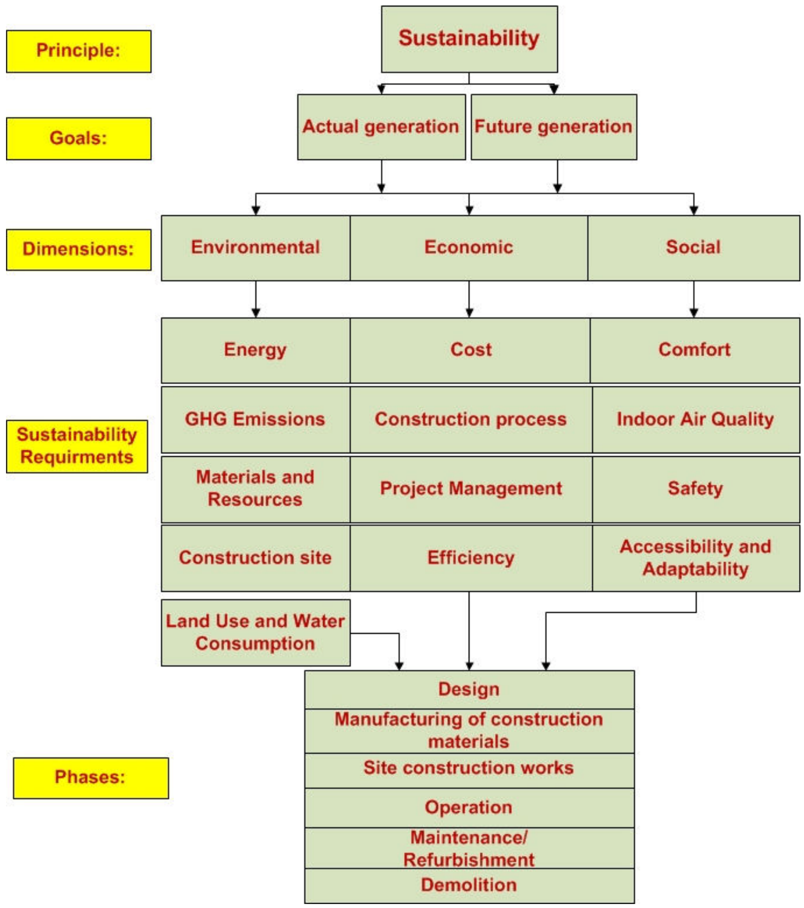


Figure 2.2. Structure of building sustainability

The principles of sustainable development applied to construction industry are not entirely new. In many countries directives, standards and certificates have still been developed and adopted, which evaluate the environmental performances of buildings but also consider other important issues of sustainability. The connection between construction practices and standards and a range of environmental quality issues is increasingly recognized. In the following sections international standards and certification tools related to sustainability in construction are shortly presented.

2.2. International standardizations related to sustainability in construction

Standards play an important role in our every day lives, although their effects are sometimes invisible. The presence of standards is necessary, because they assure the quality, safety, efficiency or reliability of the products we buy and use day by day.

The idea to offer and assure sustainable solutions for construction works led to the fact that international and national organizations for standardization started to develop new standards which apply the principles of sustainable development in the field of construction. The standardization of sustainability in construction works focuses on the idea that during the life cycle of a building, environmental, economic and social aspects have to be taken into consideration, beyond the existing technical and functional ones.

The Technical Committees of the International Organization for Standardization (ISO/TC), but also the European Committee for Standardization (CEN) are preoccupied with the development of new standards related to sustainability issues in the construction sector. They have already published similar works, but they consider only specific aspects of the sustainability concept:

- ISO 15686 – 1 to 11, Buildings and constructed assets – Service life planning;
- ISO 14020/21/24/25, Environmental labels and declarations;
- ISO 14040, Environmental management - Life cycle assessment;
- EN 15603, Energy Performance of Building;
- EN ISO 15927, Hygrothermal performance of buildings; *etc*.

2.2.1. ISO Standards

The first ISO Committee, which treated sustainability in its works and developed series of standards for building construction, is the ISO/TC59/SC17 (Building Construction – Sustainability in Building Construction). The works were carried out by five working groups [17]:

- WG 1: General Principles and Terminology;
- WG 2: Sustainability Indicators;
- WG 3: Environmental Declarations of Building Products;
- WG 4: Framework for Assessment of Environmental Performance of Buildings;
- WG 5: Sustainability Indicators for Civil Engineering Works.

The ISO/TC 59/SC 17 is developing a suite of international standards which are focused on issues related to sustainability in building construction. Figure 2.3 presents a scheme of the standardization work of the TC. The intended users of the suite of International Standards include (in alphabetical order): builders, certification bodies, clients, contractors, designers, facility managers, fund providers, governmental and non-governmental organizations associated with the United Nations (NGOs), insurers, manufacturers, owners, planners, policy makers, promoters, real estate agents, regulators, researchers, standards developers, users (tenants, as well as public), *etc*.

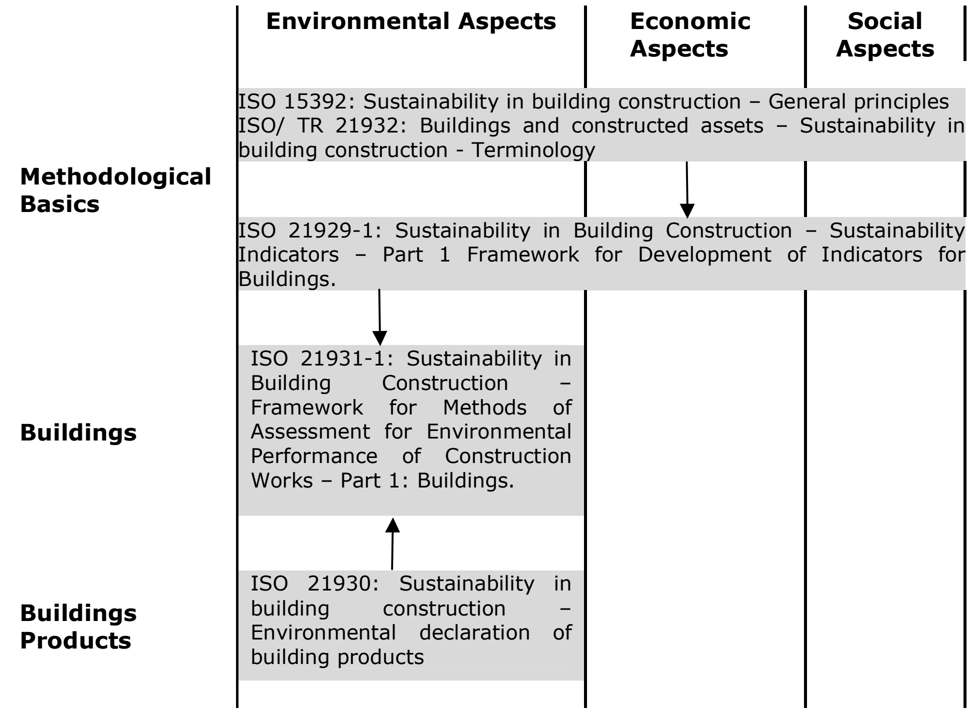


Figure 2.3. Suite of related International Standards for sustainability of buildings and construction works [18]

The suite of international Standards include the followings:

ISO 15392: 2008 – *Sustainability in building construction – General principles*, developed by WG 1, is a standard which identifies and establishes general sustainability principles of the construction works over their entire life cycle, from the inception to the end of life. The standard can be applied to buildings or other construction works, as well as to materials, products or processes, related to any life cycle. As it is visible on Figure 2.3 this International Standard forms the basis for deriving evaluation criteria and indicators for the assessment of the buildings' contribution to sustainable development. It enables users to apply the principles in their decision making but does not provide any benchmarks or ratings that can serve as a basis of assessment for different stakeholders [18].

ISO 21929-1:2011 *Sustainability in Building Construction – Sustainability Indicators – Part 1 Framework for Development of Indicators for Buildings*, developed by WG 2, establishes a core set of indicators which have to be taken into account by the sustainability assessment of new or existing buildings over their life cycle phases: design, construction, operation, maintenance, refurbishment and end of life. These indicators represent aspects of buildings with an impact on areas of protection related to sustainability.

ISO 21929-1:2011:

- adapts general sustainability principles for buildings;

- includes a framework for developing sustainability indicators which are used in the assessment of economic, environmental and social impacts of buildings;
- determines the aspects to take in consideration when defining a core set of sustainability indicators for buildings;
- establishes a core set of indicators;
- describes how to use sustainability indicators;
- gives rules for establishing a system of indicators;
- does not give guidelines for the weighting of indicators or the aggregation of assessment results [19].

According to the standard all aspects of sustainable development are inter-related and attention should be paid to the issues presented in Figure 2.4, when analyzing sustainability relative to a specific building as a whole.

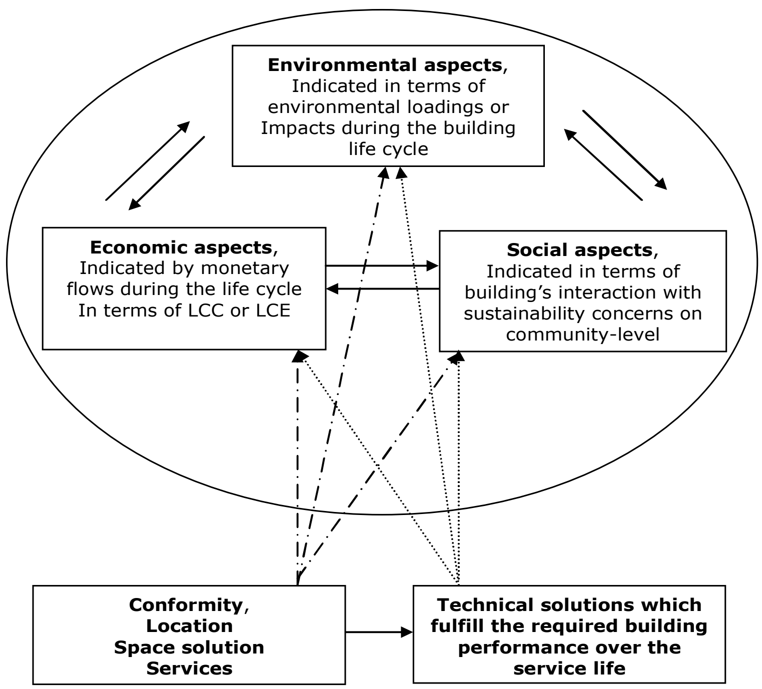


Figure 2.4. Aspects of sustainable buildings [20].

ISO 21930:2007 *Sustainability in Building Construction – Environmental Declaration of Building Products*, developed by WG 3, provides the principles and requirements for Type III Environmental Declarations (EPD's) of building products. It also provides a framework for the basic requirements of product category rules as defined in ISO 14025. Type III EPD's, as described in ISO 21930, are primarily intended for use in business-to-business communication, but their use in business-to-consumer communication under certain conditions is not excluded [21].

ISO 21931 – 1: 2010 *Sustainability in Building Construction – Framework for Methods of Assessment for Environmental Performance of Construction Works – Part 1: Buildings*, developed by WG 4, provides a general framework for improving the quality and comparability of methods for assessing the environmental performance of new or existing buildings through their entire life cycle stages. Each of these stages has an impact on the building's environmental performance throughout its lifetime and assessment methods are integral in determining its overall sustainability. ISO 21931-1:2010 is intended to be used with:

- ISO 14020 Environmental Labeling Standards
- ISO 14040 on life cycle assessment
- ISO 15392 on general principles of sustainability in building construction.

The new standard aims to bridge the gap between regional and national methods by providing a common framework for their expression [22].

ISO 21929-2 *Sustainability in building construction – Sustainability indicators – Part 2: Framework for the development of indicators for civil engineering works* is under the development of WG 5.

ISO 13315-1: 2012 *Environmental management for concrete and concrete structures – Part 1: General Principles*, developed by TC 71, SC8, aims to provide the basic rules on environmental management for concrete and concrete structures. It will help owners, designers, manufacturers, constructors, users, certification bodies, and environmental standard developers.

The standard is intended to contribute to the continuous improvement of the environmental impacts resulting from concrete-related activities. It ensures consistency with the ISO 14000 series on environmental management. ISO 13315-1:2012 covers the secondary effects of the production of concrete and of concrete structures which consume large amounts of resources, such as water, energy, cement and steel and emit large amounts of CO_2 in their production processes [23].

2.2.2. CEN Standards

Another important Committee which addresses sustainability of construction works is the European Committee for Standardization CEN TC350 *"Sustainability of Construction Works".* Contrary to the ISO standards, which refer in their works to other existing standards, the CEN TC350 is based on the development of voluntary horizontal standardized methods and principles. Their standards describe a harmonized methodology for the assessment of environmental, economic and social performances of a whole building over its life cycle. One of the most important element of the TC350 standards is, that they provide the means to quantify the impacts of each criterion in order to better understand the results of its decisions [24].

The general concept of sustainability assessment follows the principles that in carrying out assessments, only at the building level is it possible to provide necessary scenarios and a functional equivalent for the building. Assessment at the building level means that the descriptive model of the building, with the major technical and functional requirements, has been defined and is the same for each part of the assessment - as illustrated in Figure 2.5 [25]. The outer box with the dotted line represents the area to be standardised by CEN/TC350 and the concept of sustainability assessment of buildings.

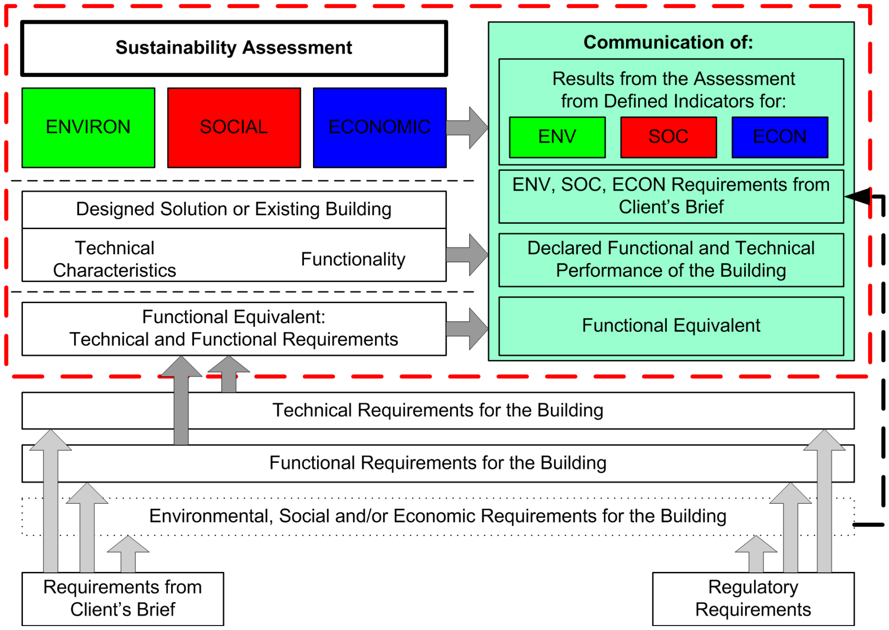


Figure 2.5. The concept of building sustainability assessment by CEN/TC350 [26]

Developing a framework for the sustainability assessment of buildings as a contribution to implementing sustainability in construction works is a multi-step procedure. The first revision of this framework standard will combine all four parts of the framework of this suite of standards into one framework standard (Figure 2.6).

According to the work programme of CEN/TC 350 a suite of standards and documents have been developed and published. But there are still some which are under development or approval and will be finalized in a few years. The development of the standards within the TC has been divided to working groups (WG) as follows:

WG 1 – Environmental performance of buildings;
WG 2 – Building life cycle description;
WG 3 – Product level;
WG 4 – Economic performance assessment of buildings;
WG 5 – Social performance assessment of buildings.

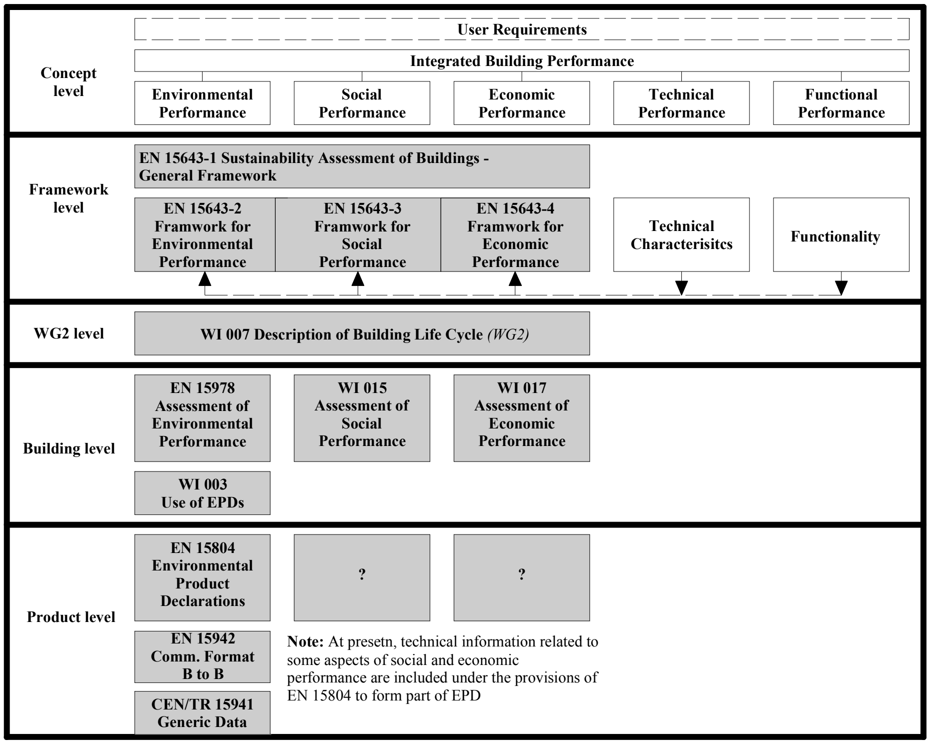


Figure 2.6. The work program of CEN/TC350 [25].

The already developed standards of the WG's are:

EN-15643-1: 2010, *Sustainability of construction works — Sustainability assessment of buildings — Part 1*: *General framework*, provides the general principles and requirements, expressed through a series of standards, for the assessment of buildings in terms of environmental, social and economic performance taking into account the technical characteristics and the functionality of a building. The assessment quantifies the contribution of the construction works to sustainable development. The framework applies to all building types and is relevant for the assessment of the environmental, social and economic performance of new buildings over their entire life cycle, and of existing buildings over their remaining service life and end of life stage. The standards developed under this framework do not set the rules for how the different building assessment schemes may provide evaluation methods. Nor do they prescribe levels, classes or benchmarks for measuring performance [26].

EN-15643-2: 2011, *Sustainability of construction works — Assessment of buildings — Part 2: Framework for the assessment of environmental performance,* is a framework for the assessment of environmental performances. It provides specific principles and requirements, expressed through a suite of standards, for the assessment of environmental performance of buildings in terms of quantitative environmental aspects and impacts, taking into account the technical characteristics and functionality of a building. The framework applies to all types of buildings, both new and existing. Furthermore it presents the requirements for the calculation methods of building's environmental performance, including the LCA approach. This standard takes ISO 219931 – 1 into consideration and intends to replace it [27].

EN-15643-3: 2012, *Sustainability of Construction Works — Assessment of Buildings Part 3: Framework for the assessment of social performance* provides the specific principles and requirements, expressed through a suite of standards, for the assessment of social performance of buildings, taking into account the technical characteristics and functionality of the construction works being assessed. The assessment quantifies the contribution of the construction works to sustainability in social terms. The framework applies to all building types, both new and existing. The social dimension of sustainability concentrates, in this first generation of standards, on the assessment of impacts of a building related to its occupants and other users expressed with quantifiable indicators. The social performance measures are represented through indicators for: health and comfort, accessibility, maintenance, safety and loadings on neighbourhood [28].

EN-15643-4: 2012, *Sustainability of Construction Works — Assessment of Buildings Part 4: Framework for the assessment of economic performance*, provides the general principles and requirements, expressed through a suite of standards, for the assessment of buildings in terms of economic performance taking into account technical characteristics and functionality of a building. The assessment quantifies the contribution in economic terms of the assessed construction works to sustainable construction and sustainable development. The framework applies to all building types, for both new and existing. It includes economic aspects of a building related to the built environment within the area of the building site. EN 15643-4 does not include economic aspects beyond the area of the building site, e.g. such as the economic impacts of construction on local infrastructure, economic impacts resulting from the transportation of the building occupants or the economic impacts of a construction project on local community. The rules for assessment of economic aspects of organizations are not included within this framework. However, the consequences of decisions or actions that influence the economic performance of the object of assessment are taken into account [29].

EN – 15978: 2011 – S*ustainability of construction works – Assessment of environmental performance of buildings - Calculation method* is a standard intended for the evaluation and assessment of design options and specifications for new and existing buildings and refurbishment projects. The standard provides the calculation method, based on Life Cycle Assessment (LCA) to assess the environmental performance of a building and gives the means for the communication of the outcome. It gives:

- the description of the object of assessment;
- the system boundary that applies at the building level;
- the procedure to be used for the inventory analysis;
- the indicators and procedures to be used for the impact assessment
- the requirements for presentation of the results;
- the requirements for the data necessary for the calculation;

The approach of the assessment covers all stages of the building life cycle and it is based on data obtained from the Environmental Product Declarations

(EPD), from their "information modules", (EN 15804) and from appropriate other information related to the environmental performance of the building as a whole. It includes all building-related construction products, processes and services, over the life cycle of the building. The interpretation and valuation of the results of the assessment are not within the scope of this standard [25].

EN – 15804: 2012 – *Sustainability of construction works — Environmental product declarations. Core rules for the product category of construction products,* provides core Product Category Rules (PCR) for all construction products and services. It provides a structure to ensure that all Environmental Product Declarations (EPD's) of construction products, construction services and construction processes are derived, verified and presented in a harmonized way.

An EPD communicates verifiable, accurate, non-misleading environmental information for products and their applications, thereby supporting, scientifically based, fair choices and stimulating the potential for market driven continuous environmental improvement. EPD information is expressed in information modules, which allow easy organization and expression of data packages throughout the life cycle of the product. The approach requires that the underlying data should be consistent, reproducible and comparable. This European Standard provides the means for developing a Type III environmental declaration of construction products and it is part of a suite of standards that are intended to assess the sustainability of construction works. This European standard provides core product category rules (PCR) for Type III environmental declarations for any construction product and construction service:

- defines the parameters to be declared and the way in which they are collated and reported;
- describes which stages of a product's life cycle are considered in the EPD and which processes are to be included in the life cycle stages;
- defines rules for the development of scenarios;
- includes the rules for calculating the Life Cycle Inventory and the Life Cycle Impact Assessment underlying the EPD, including the specification of the data quality to be applied;
- includes the rules for reporting predetermined, environmental and health information, that is not covered by LCA for a product, construction process and construction service where necessary;
- defines the conditions under which construction products can be compared based on the information provided by EPD.

For the EPD of construction services the same rules and requirements apply as for the EPD of construction products [30].

EN 15942: 2012 - *Sustainability of construction works - Environmental product declarations - Communication format business-to-business* is applicable to all construction products and services related to buildings and construction works. It specifies and describes the communication format for the information defined in EN 15804 for business-to-business communication to ensure a common understanding through consistent communication of information. The aim of this European Standard is to harmonize the way in which environmental product declarations (EPD) are communicated in Europe [31].

PD CEN/TR 15941:2010 – *Sustainability of construction works. Environmental product declarations. Methodology for selection and use of generic* *data,* is a supporting document referenced in EN 15804. The Technical Report provides guidance for the selection and use of different types of generic data available for practitioners and verifiers involved in the preparation of EPD in order to improve consistency and comparability. It assists in using generic data according to the core product category rules during the preparation of EPD, of construction products, processes and services in a consistent way, and also in the application of generic data in the environmental performance assessment of buildings according to EN 15978 [32].

WI 00350007 *Sustainability of Construction Works—Description of the Building Life Cycle* is developing a technical report, which is meant to describe the building life cycle within the framework standard. This TR focuses on processes and scenarios related to the building life cycle, in order to complement other work items. This work item has not been started [24].

The standards of ISO and CEN related to sustainability in building construction which have been published or are still under development/ approvel are summarized in Table 2.1.

Table 2.1. International standards published and under development and/or approval by ISO and CEN

Standards related to Sustainability of Building Construction				
ISO		**CEN**		
Published	**Under Development**	**Published EN**	**Published EN**	**Under Development**
15392:2008	21929-2	15643-1:2010	15978:2011	WI 007
21929-1:2011		15643-2:2011	15804:2012	WI 015
21930:2007		15643-3:2012	15942:2012	WI 017
21931-1:2010		15643-4:2012	TR 15941: 2010	
13315-1:2012				

2.3. Certification programs and rating tools for the sustainability evaluation of building construction

Building sustainability assessment involves various relations between built, natural and social environment. Therefore it comprises hundreds of parameters, most of them interrelated and partly contradictory. To deal with this complexity and to support the sustainable building design, it is necessary to implement a real methodological work. The main objective of a systematic approach is to define sustainable building concept through tangible goals in order to be able to achieve the most appropriate balance between the different sustainability dimensions [33].

During the last two decades a significant number of environmental and sustainability assessment tools for buildings have been developed. The rating and certification tools are intended to encourage the implementation of sustainable criteria in the design, construction, operation, maintenance, and deconstruction phase of buildings [34]. The tools can be used as a decision making support, since they transform the sustainability goals into quantifiable issues, which evaluate the overall performances of a building [35].

In the next sections different environmental and sustainability assessment methods, certificates and tools are presented, highlighting their characteristics, assessment procedures and contributions to sustainability of building construction.

To realize this work only readily available, public documents and published reports has been used, which cover the building certification programs and rating tools. Further details can be found by purchasing the program manuals from the presented rating systems.

2.3.1. BREEAM

BREEAM (Building Research Establishment Environmental Assessment Method) is one of the world's leading and most widely used assessment methods for buildings. It was conceived by BRE and was first used in 1990. BREEAM offers a set of standards for sustainable design, construction and operation of buildings. Furthermore BREEAM evaluates and assess the environmental performances of a building. Although this method was initially developed for the United Kingdom's context, nowadays there are some modules that could be applied at the European level or in a different context like the Middle East. Versions are updated regularly according to changing UK Building Regulations. Aim of BREEAM is:

- to reduce the impact of buildings on the environment;
- to enable buildings to be recognized according to their environmental benefits;
- to provide a credible, environmental label for buildings;
- to stimulate the demand for sustainable buildings.

The BREEAM schemes can be used for different types of projects, such as new constructions, major refurbishments of existing buildings, or fit-outs at design or post-construction stages. They cover a variety of developments and functional typologies, such as industrial, residential, multi-residential, courts, office, healthcare, education, retail, *etc*.

The number and type of issues differs from one building type to the other, but all BREEAM rating tools cover nine main categories of sustainability and an additional section for innovation. Each category consists in a number of issues, criteria and credit points, but with different weightings. The module „BREEAM Office 2008" summarizes a total of 59 criteria and 115 credits. The environmental categories and weightings for new buildings, in BREEAM Office 2008, are shown in Figure 2.7.

Management 5 Criteria, 10 credits 12 %	**Health and Wellbeing** 13 Criteria, 13 credits 15 %	**Energy** 7 Criteria, 24 credits 19%
Transport 6 Criteria, 10 credits 8 %	**Water** 4 Criteria, 6 credits 6 %	**Materials** 7 Criteria, 13 credits 12.5 %
Waste 4 Criteria, 7 credits 7.5 %	**Land Use and Ecology** 6 Criteria, 10 credits 10 %	**Pollutuin** 7 Criteria, 12 credits 10 %
Innovation 10 Credits Additional		

Figure 2.7. Environmental categories, credits and weightings of BREEAM Office 2008

The issues tend to reduce the impact on the environment, because they define the overall ecological performances of the building and set target values, which have to be met in order to achieve a final certification. In most cases, to achieve a high rating level, the performance targets goes beyond the minimum standards defined by the Building Regulation or other legislation.

The rating and scoring procedure of BREEAM schemes are based on four important elements:

- BREEAM rating benchmarks;
- minimum BREEAM standards;
- environmental weightings;
- credits for innovation.

The rating benchmarks for BREEAM 2008 are shown in Table 2.2 and are applicable to new buildings, major refurbishments and, where possible, to fit-out projects.

Table 2.2. BREEAM 2008 rating benchmarks

BREEAM Rating	Score
Unclassified	<30%
Pass	≥30%
Good	≥45%
Very Good	≥55%
Excellent	≥70%
Outstanding	≥85%

To achieve a BREEAM rating of any level, mandatory credits have to be met for different criteria, complied with the rating level shown in Table 2.2.

Beside the regular credits, additional innovation credits can be provided for a building. An additional 1% score can be added to the final score for each innovation credit achieved. Maximum innovation credits achievable are 10, so maximum 10% can be awarded to the final BREEAM rating.

The final rating is calculated by a BREEAM assessor using the BREEAM Assessor's Spreadsheet Tool and associated calculators. Five steps need to be done in order to determine the BREEAM rating level:

1. The number of credits for each BREEAM category are determined;
2. The percentage of the achieved credits is calculated for each BREEAM category;
3. The percentage achieved in step two is weighted with the corresponding section weighting, obtaining the category score;
4. The category scores are summarized to give the overall BREEAM score, which is compared to the benchmarks and verified if all minimum standards for the complied level are met;
5. Additional innovation scores can be added to the final score.

To achieve an Outstanding BREEAM rating level, the building must achieve a final score ≥85%, it also has to meet the mandatory standards for this rating level and must provide material for the production and publication of a case study on the "Outstanding" related building. Additionally, the building has to obtain a "BREEAM in Use Certification of Performance" within the first three years of operation and use in order to keep this rating [36].

The system is very powerful and rigorous in energy and environmental related issues, but does not subscribe to the definition of sustainable development, which considers also economic and social concerns in a similar manner. BREEAM is rather an evaluation tool for "green buildings" than for "sustainable buildings".

2.3.2. LEED

Founded in 1993, the aim of the U.S. Green Building Council (USGBC) was to define and measure the performances of "green buildings", in order to offer an instrument to change the concept of design, construction and operation of buildings. In the new concept, a building should be energy and cost efficient, durable, environmental friendly, comfortable and healthy. The WGBC has expanded the global system beyond US, in countries like Germany, UK, and other states which joined several years ago, like Italy, Netherland, Poland, Spain and Romania.

The Leadership in Energy and Environmental Design (LEED) systems are internationally recognized green building certification tools that evaluate the environmental performances of entire buildings over whole life cycles. LEED constitutes a set of performance standards that are based on energy and environmental issues. The LEED systems can be used in the design, operational, maintenance and construction phases of buildings of different functional typologies, sectors and project scopes: core and shell, new constructions, schools, neighborhood developments, retail, healthcare, homes and commercial interiors.

The first LEED Pilot Project Program, LEED Version 1, was launched in 1998, while the newest version is LEED Version 3, released on 27 April, 2009.

Flexible and transparent, the LEED 2009 takes the advantages of the technologies and advancements in building science and is concentrated on energy efficiency and CO_2 reduction.

One of the new rating tools is the LEED 2009 for New Construction and Major Renovations. It was designed mainly for new commercial buildings, but can be applied also for other building types. Beside the certification of new buildings, LEED 2009 certifies design and construction activities for major renovations of existing buildings.

Like every LEED rating system, LEED 2009 covers five environmental and two additional topics, which consider innovative solutions and local conditions. The evaluation system is based on the allocation of credit points based on a set of impact categories with potential environmental effects and human benefits. For the fundamental impact categories 100 base points are available. Additional 10 credit points can be allocated for Innovation in Design and Regional Priority. Every credit point is a whole and positive number and each criterion is minimum one point worth, in order to assure a consistent and useable rating system. Figure 2.8 shows a summary of the topics with their number of criteria, available credit points and weightings.

Sustainable Sites 15 Criteria, 26 credits 26 %	**Water Efficiency** 4 Criteria, 10 credits 10 %	**Energy & Atmosphere** 9 Criteria, 35 credits 35%
Materials & Resources 9 Criteria, 14 credits 14 %	**Indoor Environmental Quality** 17 Criteria, 15 c., 15 %	
Regional Priority 1 Criteria, 6 credits Additional	**Innovation in Design** 2 Criteria, 4 credits Additional	

Figure 2.8. Environmental categories, credits and weightings of LEED 2009 for New Construction and Major Renovations

Like in case of the BREEAM Schemes, to persuade a LEED certification of any level, mandatory performance targets have to be met. The LEED 2009 credit weighting process involves 3 main steps:

1. The environmental impacts of a reference building will be estimated in 13 categories, with a typical building pursuing LEED certification;
2. The relative importance of the building impacts in each category will be compared with the weightings developed by the National Institute of Standard and Technology (NIST);
3. The building impacts are quantified by modeling, life-cycle assessments, transportation analysis and simulations and are used to allocate points to individual criteria.

The weight of each category in the overall performance depends on the building type under assessment. Table 2.3 presents the weight of the main categories of LEED 2009 according to the project type.

Table 2.3. Weight of the main categories of LEED 2009 according to the project type

Main categories	Weightings in function of building type [%]				
	New construction	Commercial	Existing Buildings	Schools	Core & shell
Sustainable sites	26	21	26	24	28
Water efficiency	10	11	14	11	10
Energy and atmosphere	35	37	35	33	37
Materials and resources	14	14	10	14	13
Indoor environ. quality	15	17	15	19	12
Innovation in design	6	6	6	6	6
Regional priority	4	4	4	4	4

The final score is obtained by summarizing the points granted for each criterion. The LEED certifications for New Construction and Major Renovations are awarded according to Table 2.4 [37].

Table 2.4. LEED rating benchmarks

LEED Rating	**Score**
Certified	40-49 points
Silver	50-59 points
Gold	60-79 points
Platinum	≥80 points

The main advantage of LEED is the ease of use and the interface, which can be understood in terms of overall results, but it can be used only for the evaluation of “green buildings”. The economic and social dimensions of sustainability are not covered.

2.3.3. DGNB Certification Programme

Founded in 2007, the German Sustainable Building Council together with the Federal Ministry of Transport, Building and Urban Affairs (BMVBS) developed a voluntary certification system for sustainable buildings, the “German Sustainable Building Certificate”. The objectives of the DGNB are the development and promotion of sustainability in the planning, construction and operation process of a building. The DGNB certificate is based on the concept of integral planning that sets, at an early stage, the aims of sustainable construction. In this way, sustainable buildings can be designed based on the current state of technology and they can communicate their quality with this new certificate.

The first developed system has been available for the building type „New Construction of Office and Administration Buildings" since 2009. On the basis of this system further types of buildings have been covered by DGNB, such as retail, industrial, educational, hotels and housing. In this section, the "New Construction Office and Administration" module, in the version 2008, is presented [38].

As a second-generation certification system, DGNB presents some advantages: active contribution to sustainability; cost and planning certainty; minimized risk; praxis-oriented; focused on life cycle; comprehensive quality of property; more than „Green Building"; flexibility.

The DGNB is a transparent and comprehensible rating system that was developed based on real-world circumstances. It defines the quality of buildings in a comprehensive way and enables auditors to conduct an evaluation systematically and independently. A user-friendly software supports the auditor with the documentation and evaluation process. The software visualizes the capabilities of a building in a way that is concise and easy to understand. Already during the planning process, it marks the influencing parameters where the building can be optimized with regard to sustainability.

The DGNB covers the relevant areas of sustainable construction. Although it is the newest, DGNB is the most complete tool in terms of sustainable development. The certificate is defined by six topics, with a total of 49 individual criteria. The quality of location, which has six criteria, is treated separately, to have a rating system independent from the location.

The topics are weighted differently in the overall assessment of the building, depending on their relevance. The economical, ecological, socio-cultural and functional quality has the same weighting (22.5% each). Process quality is weighted with 10% and the quality of the location is not included in the final grade but it is presented separately. Figure 2.9 shows the topics of the DGNB and other characteristic information.

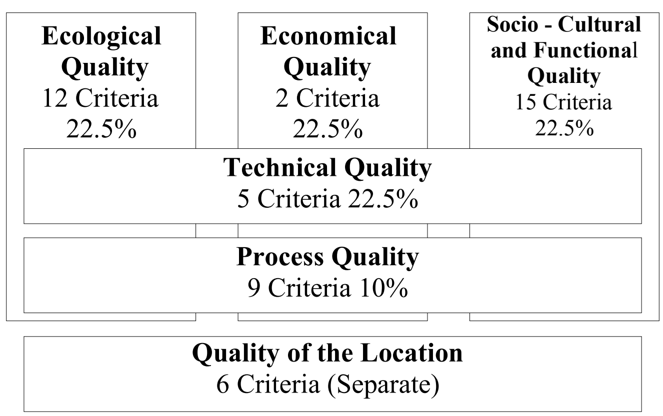


Figure 2.9. Characteristic parameters of the DGNB certification tool

The rating of the building is based on an evaluation matrix with a scoring system for each topic and criterion. Each qualitative or quantitative criterion can be scored with up to 10 points. Depending on their importance and relevance, they are weighted with a factor from 0 to 3. After each criterion is scored and weighted a score is obtained, that represents the fulfillment of the respective topic.

Summarizing the partial fulfillments, the total fulfillment is achieved, called "Degree of Compliance". The bronze, silver or golden building certificate is awarded in function of the total degree of compliance according to Table 2.5.

Table 2.5. DGNB rating benchmarks

DGNB Rating	Score
Bronze	> 50%
Silver	> 65%
Gold	> 80%

Alternatively, the total degree of compliance is indicated by a grade, as presented in Table 2.6.

Table 2.6. DGNB alternative rating benchmarks

Degree of Compliance	Grade	Degree of Compliance	Grade
95%	1.0	50%	3.0
80%	1.5	35%	4.0
65%	2.0	20%	5.0

The output of the assessment is displayed in a clear and transparent way, by a software generated matrix, as shown in Figure 2.10. The diagram summarizes the results of the topics and individual criterion, offering a differentiated image of the building performances.

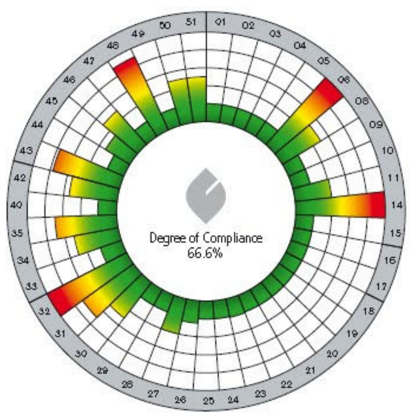


Figure 2.10. A software-generated evaluation diagram of the DGNB [38]

2.3.4. CASBEE

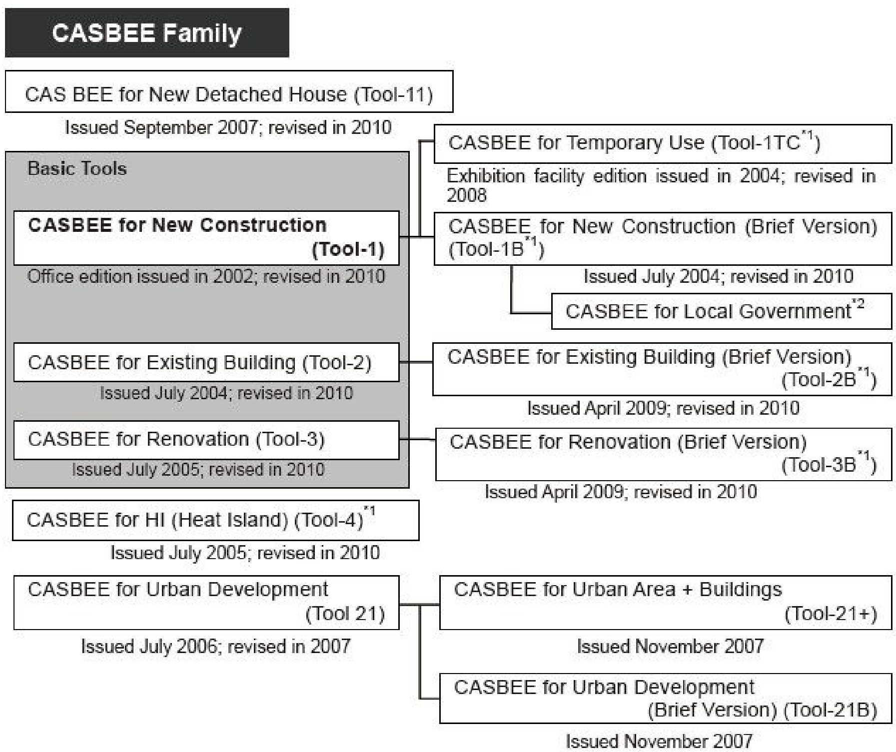
Comprehensive Assessment System for Built Environment Efficiency (CASBEE) is an assessment tool which is based on the environmental performance of buildings. CASBEE has been developed by a research committee – The Japan Green Building Council (JaGBC)/ Japan Sustainability Building Consortium (JSBC), established in 2001 as part of a joint industrial/ governmental/ academic project with the support of the Ministry of Land, Infrastructure, Transport and Tourism.

The CASBEE system is under continuous development and updating, which comprises different assessment tools, known as the „CASBEE Family", as shown in Figure 2.11. The assessment tools were developed on three basic principles [39]:

- comprehensive assessment throughout the life cycle of the building;

- assessment of the „Building Environmental Quality (Q)" and Building Environmental Load (L);
- assessment based on the newly-developed Building Environmental Efficiency (BEE) indicator.

CASBEE is developed in a suitable position according to architectural design process, which starts from the pre-design stage and continues through design and post design stages. This method is composed of four assessment tools, served at each stage of the design process and taking care of the building's life cycle. These tools are [40]: CASBEE for pre-design (CASBEE-PD); CASBEE for new construction (CASBEE-NC); CASBEE for existing building (CASBEE-EB); CASBEE for renovation (CASBEE-RN).



*1 HI: Heat Island, TC: Temporary Construction, B: Brief version
*2 CASBEE tools are adapted in municipalities nationwide, including CASBEE-Nagoya (April 2004), CASBEE-Osaka (October 2004) and CASBEE-Yokohama (July 2005).

Figure 2.11. Structure of the CASBEE Family [39]

In this section, the structure and assessment method of the CASBEE - NC (new constructions) tool will be presented. It evaluates environmental Quality (Q) and environmental Load Reduction (LR) based on design specifications of new buildings. The main assessment categories, sections and other characteristics are shown in Figure 2.12.

Q-Building Environment Quality & Performance		
Q1. Indoor Environment 13 Criteria 40 %	**Q2. Quality of Service** 9 Criteria 30 %	**Q3. Outdoor Environment on Site** 2 Criteria 30%
LR-Reduction of Building Envrionmental Loadings		
LR1. Energy 2 Criteria 40 %	**LR2. Resources & Materials** 10 Criteria 30 %	**LR3. Off-site Environment** 6 Criteria 30%

Figure 2.12. Main characteristics of the assessment categories

The scoring system is based on a 1 to 5 scoring scale, one for minimum conditions, based on regulations and three for ordinary practices. There is a separate score for built environmental quality Q and reduction of building environmental loadings LR and ultimately assessed built environmental efficiency BEE, based on LR and Q. Separate scoring criteria are available for each building type, based on benchmarks values. The scores are multiplied by a weighting coefficient and result in SQ, which is the total score for Q, or SLR, which is the total score for LR.

In CASBEE, assessment values for Q and LR differs from 1 to 5, while the BEE is calculated using Equation 2.1.

$$BEE = Q/L = 25 \times (SQ - 1)/25 \times (5 - SLR) \tag{2.1}$$

Where: BEE is the Building Environmental Efficiency, SQ is the score for the Building Environment Quality & Performance (Q), and SLR is the score for the Reduction of Building Environmental Loadings (LR).

In the performance assessment classification, the higher the Q value and the lower the L value is, the better is the solution. There are five levels of performance: C (Poor), B⁻ (Fairy Poor), B+ (Good), A (Very Good) and S (Excellent), each corresponding to the areas in the diagram presented in Figure 2.13.

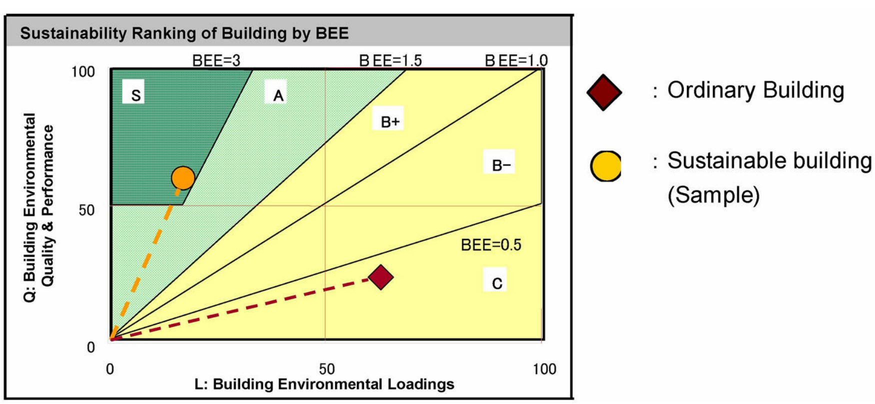


Figure 2.13. Sustainability ranking of building by BEE [40]

The BEE rating which is determined by finding the intersection of Q (Building Environmental Quality and Performance) and L (Building Environmental Loadings), is a number, which is generally in the range of 0.5 to 3, that corresponds to a building class, from class S (highest for BEE ≥ 3.0) to classes A (BEE=1.5-3.0), B+ (BEE=1.0-1.5), B- (BEE=0.5-1.0) and C (BEE≤0.5).

2.3.5. HK-BEAM

The Hong Kong Building Environmental Assessment Method (HK-BEAM) scheme was established in 1996 by the HK-BEAM Society, largely based on BREEAM. The HK-BEAM covers all types of new and existing buildings: residential, commercial, institutional and industrial. It embraces exemplary practices in the planning, design, construction, commissioning, management and operation of buildings in the context of Hong Kong's densely populated development.

HK-BEAM Version 4/04 covers the new buildings, while Version 5/04 is used for existing buildings. In this section the structure and assessment method of Version 4/04 „New Buildings" is presented [41].

HK-BEAM 4/04 aims to reduce the environmental impacts of new buildings whilst improving quality and user satisfaction, by adoption of the best techniques available within reasonable cost. A notable attribute of HK-BEAM 4/04, as compared to most schemes in use is that an assessment for new building is not finalized until the building is completed, ensuring that „green" and „sustainable" design features are actually implemented and the construction practice meats the required performance standards. The assessment seeks to reduce negative impacts on neighbors and rewards efforts that are aimed to improve the quality of the immediate surroundings. The assessment categories covered by HK-BEAM 4/04, but also other characteristics are presented in Figure 2.14.

Site Aspects 18 Criteria 17 %	**Materials Aspects** 12 Criteria 18 %	**Energy Aspects** 22 Criteria 25%
Water Aspects 7 Criteria 10 %	**Indoor Environmental Quality** 28 Criteria 30 %	**Innovations & Enhancements** 2 Criteria 15% bonus

Figure 2.14. Main categories and weightings of the HK-BEAM 4/04

Regarding the scoring system, most of the criteria are awarded with one credit, if the requirement is fulfilled. For energy issues up to 10 credits can be obtained based on energy reduction percentages. Some criteria are excluded from scoring. The overall assessment grade is based on the percentage of applicable credits gained. Given the importance of IEQ a minimum percentage of credits for IEQ must be obtained in order to qualify for the overall grade. The award classifications are according to Table 2.7:

Table 2.7. HK-BEAM 4/04 rating benchmarks

	Overall	IEQ	
Platinum	75%	65%	Excellent
Gold	65%	55%	Very Good
Silver	55%	50%	Good
Bronze	40%	45%	Above average

HK-BEAM has well covered environmental issues but it is not so flexible, it does not cover economic issues and the social issues present major gaps. The scoring of the criteria is not comprehensive and there is no aggregation of the score.

2.3.6. Green Star

Green Star, developed in 2003 by the Green Building Council of Australia (GBCA), is a voluntary building rating system that evaluates the environmental design and construction of Australian buildings. Green Star is based, in part, on existing rating and certification systems, such as BREEAM and LEED, but contains individual environmental measurement criteria relevant to the Australian marketplace. It was developed for the property industry in order to:

- establish a common language;
- set a standard of measurement for „green buildings”;
- promote integrated, whole-building design;
- recognize environmental leadership;
- identify building life-cycle impacts;
- raise awareness of green building benefits.

Green Star covers most of the building types by its various rating tools, which include [42]:

Green Star Education, v1
Green Star Healthcare, v1
Green Star Multi Unit Residential, v1
Green Star Retail Centre, v1
Green Star Office Interior, v1.1
Green Star Office Design, v2, v3
Green Star Office as Built, v2, v3
Green Star Industrial, v1
Green Star Public Building-Pilot
Green Star Convention Centre-Pilot

All Green Star rating tools cover nine environmental impact categories with direct consequences of the projects site selection, design, construction and maintenance. These categories are divided into credits, which address an initiative that improves or has the potential to improve environmental performance. Points are awarded in each credit for actions that demonstrate that the project has met the overall objectives of Green Star. The categories and available points for „Green Star Multi Unit Residential” rating tool are presented in Figure 2.15. Point distribution may vary by building type.

Management 8 Criteria 18p	**Indoor Environmental Quality** 10 Criteria 20p	**Energy** 4 Criteria 26p
Transport 5 Criteria 14p	**Water** 6 Criteria 12p	**Materials** 16 Criteria 25p
Land Use & Ecology 5 Criteria 11p	**Emissions** 9 Criteria 18p	**Innovation** 3 Criteria 5p

Figure 2.15. Characteristics of the "Green Star Multi Unit Residential" rating tool

The scoring system is based on credit points. Each category has a specific number of credit points available, while the category score is obtained in percentage as the ratio between achieved and available points. The Assessment Panel may award a rating of one to six stars. Projects that are awarded with one to three stars may not be certified, but those awarded with four or more stars may be certified and are recognized, based on the achieved score as follows [43]:

4 Stars 45-59% - „Best Practice”
5 Stars 60-74% - „Australian Excellence”
6 Stars ≥ 75% - „World Leadership”

Green Star is rather a „Green Building” than a „Sustainable Building” rating tool.

2.3.7. SBTool (GBTool)

The formerly known GBTool (Green Building Tool), now called SBTool (Sustainable Building Tool) has been developed since 1996 by the International Initiative for a Sustainable Built Environment (iiSBE). It has been discussed in annual Sustainable Building Conferences (SBC) and applied worldwide to assess the built environment [44]. The SBTool rating system is a Microsoft Excel based software, which can be developed by international third parties to suit their own regions and building types. It is based on the SB Method, which is a generic framework for rating the sustainable performance of buildings and projects. The main upgrade to GBTool is that it covers a wide range of sustainability issues, not just green building concerns.

The newest version of SBTool has been released in 2012 and consists of two distinct assessment modules that are linked to phases of the life-cycle: one for Site Assessment, carried out in the Pre-Design phase and another for Building Assessment, carried out in the Design, Construction or Operations phases. Each of these assessment modules is further divided into two files, File A related to settings relevant to the generic project type in a specific region, and one or several File Bs which take their values from the single File A. Thus, one File A can be established that will set weights and benchmarks for many projects, with each one described in a separate File B.

All criteria used in SBTool are structured under Issue and Category headings that are related to impact categories. The main issues are shown in Figure 2.16.

A Site Regeneration & Development 13.8%	**B Energy and Resource Consumption** 19.6%	**C Environmental Loadings** 49.7%
D Indoor Environmental Quality 6.3 %	**E Service Quality** 5.9%	**F Social, Cultural and Perceptual Aspects** 3.4%
G Cost and Economic Aspects 1.2 %	**Site location, available services and site characteristics** Additional	

Figure 2.16. Issues and weightings of SBTool 2012

The evaluation level of the system can be modified, incorporating a number of criteria which can range from over 100 to half a dozen [45].

The weighting system for SBTool 2012 can be described as quasi-objective and is designed to strike a balance between scientific correctness and usability. SBTool follows the general principles of separating loadings and impacts; loadings being inputs or outputs related to the project and impacts being the effects on natural or human systems. The main factors used in the SBTool weighting system include the following, which are given point scores and then multiplied together [46]:

a. Extent of potential effect
b. Duration of potential effect
c. Intensity of Potential Effect
d. Importance of primary system directly affected
e. Regional adjustment, which gives authorized third parties the ability to adjust the score factors derived from a*b*c*d up or down a maximum of 10%.

The scoring process in SBTool relies on a series of comparisons between the characteristics of object building and the national or regional references for minimally acceptable practice, "good" practice and "best" practice, as shown in Figure 2.17.

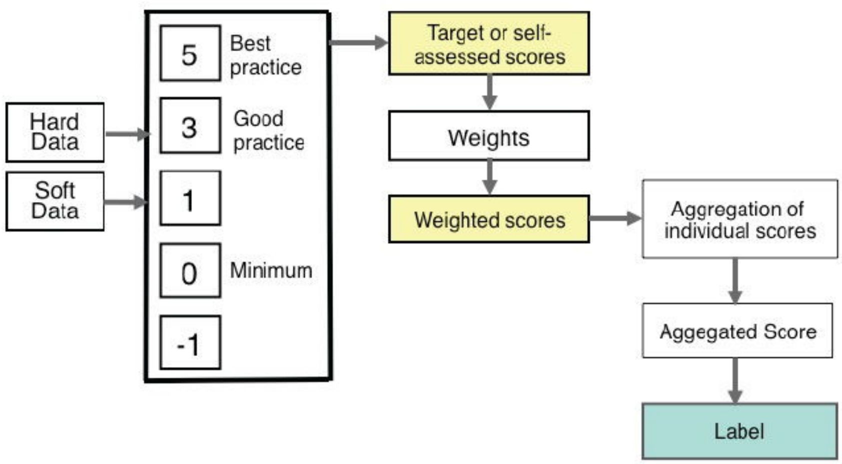


Figure 2.17. Schematic of SBTool scoring and weighting [46]

The SBTool is one of the most comprehensive and practical evaluation tools on the market. It combines issues of all three dimensions, is very flexible, it implements the integrated design process, it uses a semi-objective weighting system, it permits the modifications of benchmarks to local conditions and it offers clear results. As a remark on the tool, the three dimensions of sustainability are not equally represented. The environmental aspect has a much higher influence in comparison to the economic and social ones.

2.3.8. OPEN HOUSE

"OPEN HOUSE – Benchmarking and mainstreaming building sustainability in the EU, based on transparency and openness (open source and availability) from model to implementation" is an Integrated Project launched and funded by the European FP7. It consists of 19 European partners located in 11 countries. The overall objective of OPEN HOUSE is to develop and to implement a common

European transparent building assessment methodology, complementing the existing ones, following the baseline of both CEN/TC 350 and ISO TC59/ SC 17 standards, for planning and constructing sustainable buildings by means of an open approach and technical platform [47]. An OPEN HOUSE Platform will be built up (around the end of 2012) facilitating a pan EU effort towards a common view on building sustainability. OPEN HOUSE baseline concept will be widely disseminated among stakeholders through its Platform.

The assessment tool consists of six main categories, connected to all life-cycle stages of a building (product stage, construction process, use stage and end-of-life stage), while each category is composed of several indicators assessing different key issues of sustainability, as indicated in Figure 2.18. Each indicator is further divided into one or more sub-indicators that evaluate a precise issue covered by the indicator topic.

Environmental Quality 14 Indicator 33.33%	**Social/ Functional Quality** 18 Indicator 33.33%	**Economic Quality** 2 Indicator 33.33%

Technical Characteristics
7 Indicator (Extra)

Process Quality
9 Indicator (Extra)

The Location
6 Indicator (Extra)

Figure 2.18 Main categories of the OPEN HOUSE

The assessment of the building is assisted by a web-based tool, which leads the assessment and automatically produces a high quality standardized and well-structured report of building performance, as shown in Figure 2.19. The OPEN HOUSE methodology is available in two steps: as a "basic and quick sustainability assessment" and as a "complete assessment". The "basic and quick sustainability assessment" gives a first idea of the sustainability level of the building and proposes actions to improve the level. This assessment is applied best in earlier planning phases and it is based mainly on estimations as well as design targets. It is based on the OPEN HOUSE full system with its 56 indicators. The "complete assessment" can be done when the building is finished. It is based on calculations and precise documentation. After the evaluation of all indicators, a label can be awarded. The first version of OPEN HOUSE assessment tool can be applied on office buildings, but due to its flexible framework it will be easily implemented for other building types in further progress of the project. [48].

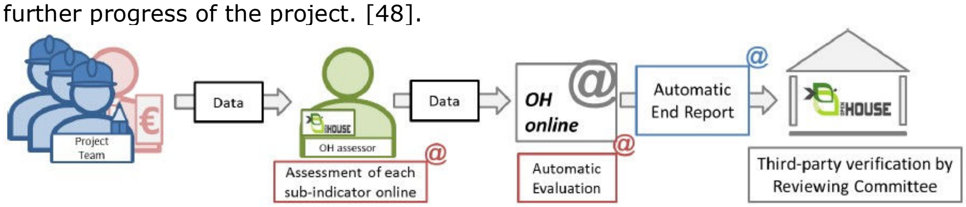


Figure .2.19. OPEN HOUSE Assessment process [48]

The scoring process consists of different steps, from the evaluation of each sub-indicator to the global performance of the building. Depending on the fulfillment of the preset requirements, each sub-indicator is awarded with points from 0 to 100. Each sub-indicator is weighted from 0 to 4, (0 irrelevant, 4 high importance). The score of each indicator is the weighted average of the points awarded for the sub-indicator. The indicators are then also weighted from 0 to 4, and the score achieved for each category is the weighted average of the points awarded for the indicators. The final score is obtained by calculating the average of the environmental, social and economic scores, which are equally weighted (33.33%). The categories Technical Characteristics, Process Quality and The Location will be displayed as an extra note and are not part of the main assessment [49]. Finally, the results are compared with buildings, in terms of the degree of performance in relation to the building standards of the specific EU country. A direct comparison of results would lead to confusion, as location specific standards, requirements for construction and guidelines are used for the assessment.

This tool fulfills best the definition of sustainability, as it takes into consideration all three dimensions in equal way. It is transparent, flexible and offers a common, standardized platform for European countries to evaluate the sustainable performances of a building. In opinion of the author, the main disadvantage of the OPEN HOUSE method represents the high number of sub-indicators which has to be assessed (175). Although calculation tools, that fasten the assessment, are incorporated, many sub-indicators could be neglected, as they are not so relevant for a building.

Analyzing the most important sustainability certification tools, some important ideas can be underlined:

- the target of the certificates is predominantly composed of entire buildings, of different typologies, without detailed specifications for other type of construction works;
- most of the certificates do not respect the definition of sustainability, focusing mainly on environmental issues; functional, technical and economic issues are mainly neglected;
- cover a great number of criteria, but many of them are qualitative, which introduce a high degree of subjectivity in the certification;
- the scoring systems are not unitary and the according of points/ credits are mainly difficult and needs many benchmark values for comparison;
- with few exceptions, the weighting systems are based on subjective criteria, without a real justification, which can lead to the over or underestimation of some criteria;

3. ORIGINAL MODELS FOR THE SUSTAINABILITY ASSESSMENT OF CONSTRUCTION WORKS

In Romania the residential sector is the most significant among the construction market, so it is a priority to develop assessment models which can be used to evaluate and rate the sustainability performances of such building types, in both the design and the operational phase.

The execution of a construction project implies in general series of phases, which define the life cycle of the construction work. There are different approaches on this topic in the specialized literature, but the life cycle phases of a traditional construction project in Romania are generally as presented in Figure 3.1. The phases in this figure include important activities, which may have major effects on the final result.

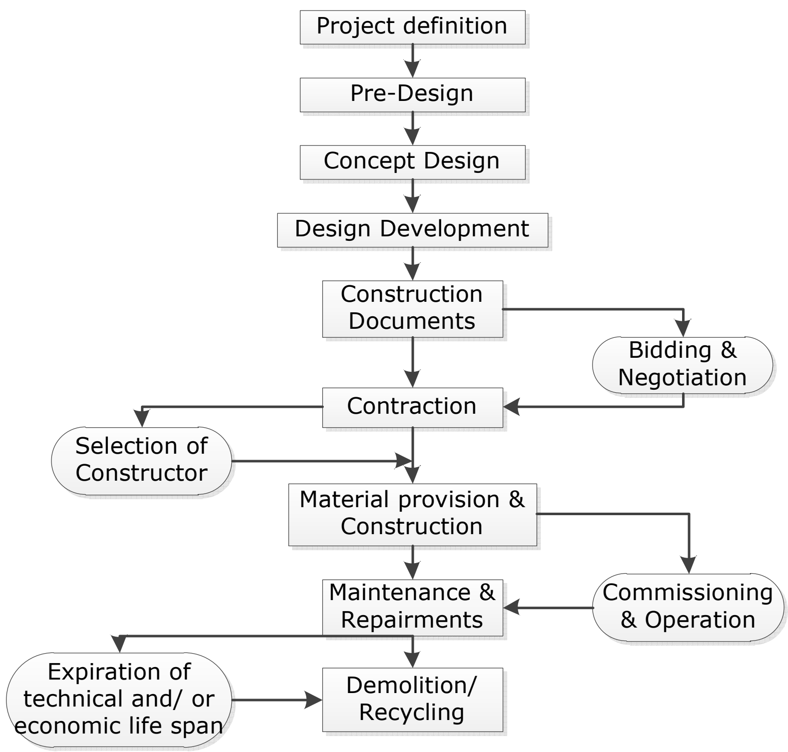


Figure 3.1 Schematic representation of a traditional construction project's life cycle

It is obvious that the traditional life cycle of a construction project, especially the design process, is mainly linear, due to the successive contributions of the members involved in the project. This can often lead to a limited possibility of optimizations during design phase and to an almost impossible one during operation.

The aim of the proposed assessment models is to introduce the idea of integrated design, considering, in the same time, the principles of sustainability. The Integrated Design Process IDP is defined as a collaborative method for designing buildings which emphasizes the development of a holistic design [50].

On the other hand a correct assessment of building sustainability performances involves the parallel and integrated consideration of the primary aspects of sustainability – economic, environmental and social – in relation to the construction works.

3.1. Global model

The global model is a comprehensive assessment tool, which has been developed for the sustainability evaluation of entire buildings, mainly residential dwellings and family houses. Incorporating the idea of integrated design and respecting the principles of sustainability, the model is intended to become an important tool for civil engineers and architects in the rating of residential houses. The main advantages of the global model are:

- covers the environmental, economic and social dimensions of sustainability in almost equal way;
- uses an interactive and semi-objective weighting systems, which allows the assessor to adjust the weightings of each parameter in function of their importance and impact but always keeping the initial proportions (40% - 30% - 30%);
- can be applied in the design phase and also on existing buildings;
- most of the parameters are quantitative and not qualitative, which reduces the subjectivism of the assessment;
- contains pre-set benchmark values for a typical family house, which can be modified and adapted;
- offers simplified calculation tools for almost every parameter, which permits a fast assessment;
- the results are presented in a clear and suggestive way, which allows an easy identification of the building's strengths and weaknesses;

The developed model also presents some disadvantages:

- covers only one type of building;
- requires a significant amount of data and knowledge from different domains of construction;
- the pre-set benchmark values need further calibration on other buildings;
- the incorporated data sets cover only the major construction materials and processes;

3.1.1. System boundaries

The evaluation model is developed for the assessment of residential buildings, which include mainly traditional family dwellings.

The objectives of assessment within the tool include the building itself, with its entire components (foundation, resistance structure, envelope, finishes, and technical equipment), the construction site, but also some habits of the building occupants. The assessed components, quantified through different issues and parameters, may have an impact on the local environment. This includes the quality of the building itself, the health and comfort of the occupants and the surrounding neighbourhood. On the global level, the environmental impacts refers to climate change, pollution, resource depletion, *etc*. The schematic representation of the system boundaries is shown in Figure 3.2. Some issues affect only the local environment, others have an impact both on local and global environment, while the rest only affects the global one.

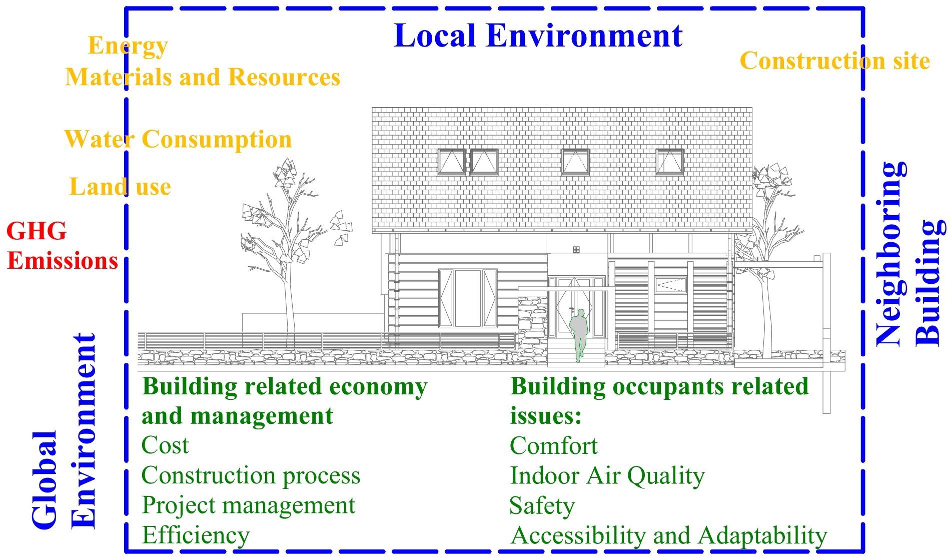


Figure 3.2. Boundary conditions of the global model

The time boundary of the assessment model is defined by a life cycle approach. The building is evaluated considering all its life cycle stages divided into three main phases:

- initial phase, which includes operations related to manufacturing and transport of building materials and on-site construction;
- operational phase, which is the most time consisting and includes the utilization of the building itself, maintenance and refurbishments;
- after end of life, which includes the activities related to the demolition, disposal, re-use or recycling of materials or structural elements.

Key performance indicators are associated to the different life cycle stages, offering together an overall image of the building's performance regarding the respective issue.

The use and application of the model are possible on a building which is still in the design phase or on already built ones. Using the model early in the design phase can lead to major benefits in the final result:

- benchmarks for a conventional design can be established, by setting values for best and unacceptable practices, but also performance targets for the building;
- conceptual design can be developed proposing different solutions for building structure and envelope, HVAC system, sanitary fixtures, *etc.*;

- simulations and comparisons can be performed in order to see which of the proposed solutions is the most suitable and most sustainable;
- detailed strategy for design, construction and operation can be developed.

Applying the assessment model on already constructed buildings offers the possibility to evaluate the real level of sustainability. On the other hand modifications and improvements are difficult or almost impossible to perform. Strengths and weaknesses can be identified and some solutions for improvements can be proposed. The benchmark values for very good and unacceptable practices remain unchanged, but the values of the parameters are based on real data and measurements and not on the design values.

3.1.2. Scoring and weighting system

The proposed evaluation model uses a scoring system, which permits a unitary scoring of the parameters, without taking into consideration the importance of each one at this point. The principle is simple: each parameter is scored between 0 and 5 points, where 5 points are accorded for very good practices while 0 point is accorded for insufficient practice. The points are given using different techniques and methods [51]:

- scaled scoring – is applied on parameters where an upper and lower limit is defined. The limits are either benchmark values established on a reference building for very good and insufficient practices or are regulated by standards or other statutory documents. In this case the scores are assigned proportionally;
- comparison with benchmarks or other available options – is applied on parameters, which are not regulated by statutory documents, but the scores are assigned proportionally by comparing two or more options and calculating the relative performance among those solutions;
- subjective marking – this method is often based on the assessor's judgement and experience. This kind of evaluation method is applied mostly on indicators, which cannot be quantified.

In order to differentiate the importance of each criterion, weighting is needed. Because there are no commonly agreed methods for weighting, the model uses a semi-objective weighting system, similar to the model presented in [45]. This method takes into consideration different factors, each with a specific impact coefficient. It considers if the impact of the parameter is based on a local or global level, it has potential short - or long - term effects or if it is of regional importance. Table 3.1 presents all factors with their corresponding impact coefficients.

Table 3.1 Impact factors and coefficients of the semi-objective weighting system

Impact categories	Impact factors	Impact coefficient
Regional priorities RP	Very Low Priority	1
	Low Priority	2
	Normal	3
	High Priority	4
	Very High Priority	5
Impact duration ID	0 to 5 years	2
	5 to 25 years	4
	Building life	8
Local impact LI	Efficiency	2
	Occupants financial investments	2

	Building quality and durability	4
	Occupants well-being	6
	Occupants health	8
	Occupants and building safety	10
Global impact GI	Financial risk or benefit for investor	3
	Disturbance of neighbour/ neighbourhood	3
	Depletion of non-renewable resources other than primary fuels.	9
	Depletion of land resources with ecological or agricultural value.	6
	Contamination of land and water resources	9
	Depletion of non-renewable primary fuels	12
	Depletion of non-renewable freshwater resources.	12
	Climate change impacts	15

The system has the advantage of being very flexible. If some parameters are modified or dis-activated, the system readjusts itself and the weightings are recalculated. But in order to respect the definition of sustainability, the three dimensions have almost an equal importance: environmental 40%, economic 30% and social 30% [52].

The final weighting of the criteria is obtained through a partial score, according to equation 3.1. The partial score is the product of the coefficients of the impact categories. If the criterion has multiple effects within the local and/or global impact categories, the impact coefficients are summed and then multiplied with the coefficients of the other impact categories, as it can be seen on the example in Figure 3.3.

$$W_i = \frac{PS_i}{\sum PS_d} \times w_d = \frac{RP \times ID \times (Li + Gi)}{\sum PS_d} \times w_d \qquad (3.1)$$

Where:

- W_i - weighting of the criterion;
- PS_i - partial score of the criterion;
- $\sum PS_d$ - sum of the partial scores of the current dimension;
- w_d - weighting of the dimension (40% for environmental and 30% for economic and social)

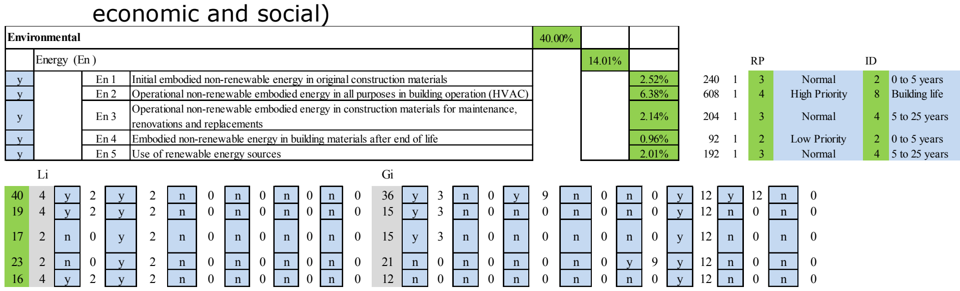


Figure 3.3. Example of weighting calculation for energy issues

In situations where one or more criteria are considered unnecessary or they cannot be applied within the project, they can be dis-activated. The weightings will be then readjusted and recalculated, with the initial conditions being kept. In this way the system offers high flexibility for the assessor to adjust the weightings project oriented. The default weightings for a traditional house are presented in Figure 3.4.

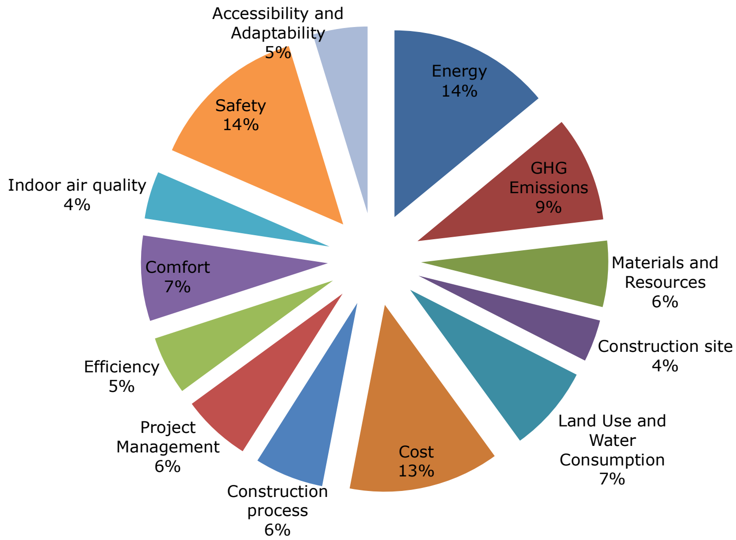


Figure 3.4. Weightings of a traditional family house

3.1.3. Selection and quantification of the sustainability issues, criteria and key performance indicators

The principles of sustainable construction are derived from those of sustainable development with more focus on the specific impacts of the construction industry on the elements of the triple bottom line. For this reason the global model defines 13 major sustainability issues (Table 3.2), with 46 criteria and over 50 qualitative or quantitative key performance indicators covering the environmental, economic and social aspects of sustainable construction.

When developing and selecting indicators, the starting point is the identification of the main users and user needs. Sustainability indicators for construction works are needed by a number of interested parties in the building and construction sector. For this reason indicators must fulfill three main functions: quantification, simplification and communication. Indicators must describe complex phenomena in a clear and simple form, in order to be easily used and understood. Indicators should be objective and the results should be repeatable [19].

At the selection of the parameters the following aspects have been taken in consideration:

- principles and parameters proposed in the frameworks of international standards related to sustainability in construction;
- brief literature study, critical review and interpretation of existing assessment tools and methods;
- personal initiative, based on practical observations and discussions with experts and potential clients;

The issues are intended to raise the comfort, safety and quality of the building occupant's life, to assure long term affordability, quality and efficiency and to reduce negative environmental impacts by the use of recycled materials, renewable energy sources and by minimizing raw material, energy and water consumption, GHG emissions and land use.

Table 3.2. Sustainability issues of the global model

Environmental 21 Criteria 40%	**Economic 12 Criteria 30%**	**Social 13 Criteria 30%**
Energy	Cost	Comfort
GHG Emissions	Construction Process	Indoor Air Quality
Materials and Resources	Project Management	Safety
Construction Site	Efficiency	Accessibility and Adaptability
Land Use and Water Consumption		

Detailed explanations of each issue and parameter are presented in the next sections.

Environmental

Energy (En)

En 1. Initial embodied non-renewable energy in original construction materials

Scope: Efficient construction process through advanced technical equipment and selection of materials with low embodied energy, in order to reduce the consumption of fossil fuels.

Indicator: Annualized embodied primary energy used for structure, envelope and major interior components, normalized on the gross floor area, E_i [$MJ/m^2/y$].

Assessment method: This criterion can be calculated by using specialized LCA software, or manually, having proper datasets. Within the developed model the initial embodied energy is calculated using the free datasets from [53], [54]. The datasets include average European values for embodied energy and CO_2 emissions for the manufacturing and disposal of common construction materials but also for the different means of transport. The datasets are compiled in a simplified material database, which can be easily accessed and used for the purpose of the model. The material database can be completed with new materials but the existing values can also be modified for specific local conditions. Some material densities may differ, so they should be verified during assessment.

The embodied energy results from three different sources: manufacturing of the materials, transportation of the materials to site and the use of construction machines and equipment during construction. The input parameters are: the list of materials, their quantities with the proper units and the transportation distance. If the introduced unit does not match with the unit from the database, it will be transformed, based on the material density (e.g. if $1m^3$ of concrete is introduced, but the embodied energy is given in MJ/ kg, the quantity will be transformed in kg, depending on its density). In the case of construction machines and equipment, the required input parameters are: effective time in use, energy source (mainly diesel and/or electricity), power and/ or fuel consumption. The output parameters are obtained by the adaptation of the energy sources to the desired unit.

The final value of the criterion is the sum of the three energy sources, normalized to the gross floor area of the building and annualized over the designed life span. In case of existing buildings, without available input data, the criterion should be dis-activated.

Benchmarks: E_i = 180MJ/m^2/y – **0p**;
E_i = 60MJ/m^2/y – **5p**.

The final score is obtained by linear interpolation.

En 2. Non-renewable embodied energy in all facilities of building operation (HVAC)

Scope: To improve energy efficiency by minimizing the operational non-renewable embodied energy used for heating, cooling, hot water, electricity, *etc*.

Indicator: Annualized operational embodied energy used for building facilities, E_o [MJ/m^2/y].

Assessment method: The greatest influence on energy efficiency is related to the building envelope. The foundation, roof, walls and fenestration must have high R-values (thermal resistance) in order to assure energy efficiency beyond the minimum values imposed by ASHRAE or other national standards. The HVAC systems also play a great role, as they can contribute to an efficient use of the energy sources.

In order to calculate this parameter in the design phase, a whole building energy simulation must be conducted, using an adequate energy certifying software. Beyond the components of the envelope, the simulation must include data on all mechanical equipment and services, including boilers, coolers, ventilation systems, temperature set points, electrical devices, but also the number of occupants and water demands. In case of existing buildings, of at least 3 years old, the parameters should be calculated based on the energy bills, including winter and summer periods.

Benchmarks: E_o = 1100MJ/m^2/y – **0p**;
E_o = 450MJ/m^2/y – **5p**.

The final score is obtained by linear interpolation.

En 3. Non-renewable embodied energy in construction materials used for maintenance, renovation and replacement works

Scope: To minimize the operational non-renewable embodied energy in materials for maintenance, renovations and replacements.

Indicator: Annualized embodied non-renewable energy in materials for maintenance and replacement of interior or exterior structural and non-structural elements, E_R [MJ/m^2/y].

Assessment method: Regardless of the chosen constructive system, a building needs maintenance and renovation works during its life cycle. These works could be of different types and, depending on this, it could be more or less expensive and it represents a very important part of the building life-cycle. The integration of maintenance works, renovations and replacements for a structure is difficult to estimate, because the predictions that could be made in advance may not correspond to reality. In general, the maintenance scenario for a residential building includes minor works, as the changes of internal and external decorations, or major replacements as the change of heating system, roof and exterior thermo-system. Based on the maintenance scenarios, the embodied energy can be calculated using LCA software or manually, using proper datasets.

The final value of the criterion is the sum of the energy sources, normalized to the gross floor area of the building and annualized over the designed life span.
Benchmarks: E_R = 40MJ/m^2/y – **0p**;
E_R = 15MJ/m^2/y – **5p**.
The final score is obtained by linear interpolation

En 4. Embodied non-renewable energy in building materials after end of life
Scope: To minimize the embodied non-renewable energy in the disposal of building materials after end of life.
Indicator: Annualized embodied non-renewable energy in the disposal of demolished construction elements E_D [MJ/m^2/y].
Assessment method: It is certain that the building process is not complete without an end-of-life scenario for the materials and structural elements if considering the life-cycle approach. Normally, the final destination of waste building materials represents a problem in every country. There are materials that could be reused in their original form for the same purpose (ballast for example), some that could be reused for other less important purposes (e.g. crushed concrete as street bed-layer), some that need waste treatment (incineration) or used simply as land-fill. Based on scenarios for disposal or recycling of construction waste after the end of their life span, the embodied energy can be calculated using LCA software or manually, with proper datasets.

The final value of the criterion is the sum of the energy sources, normalized to the gross floor area of the building and annualized over the designed life span. It is to note that landfill scenarios result in low embodied energy, but lead to low score at other criteria.
Benchmarks: E_D = 35MJ/m^2/y – **0p**;
E_D = 10MJ/m^2/y – **5p**.
The final score is obtained by linear interpolation

En 5. Use of renewable energy sources
Scope: To encourage the use of renewable energy sources as solar, wind, geothermal, *etc*., in order to supply a part of the non-renewable energy. In this way environmental and economic impacts related to fossil fuel energy sources can be reduced.
Indicator: Percentage of renewable energy supply per total energy demand RE [%].
Assessment method: Represents the ratio between the annually produced renewable energy and the predicted annual energy demand. The amount of renewable energy can be calculated in function of the energy source, while the annual energy demand results from the whole building energy simulation performed for En 2.
Benchmarks: RE = 0% - **0p**
RE = 25% - **5p**
The final score is obtained by linear interpolation.

GHG Emissions (G)
G 1. Initial GHG emissions
Scope: To minimize the amount of $CO_{2\text{-eq}}$. emissions resulting from the burning of fossil fuels during the extraction, fabrication and transportation of building materials and components.

Indicator: Annualized CO_2-eq. emissions related to the extraction, fabrication, transportation and construction of the materials for structure, envelope and major interior components G_i [kg $CO_{2\text{-eq}}$/m^2/y].

Assessment method: The assessment method for this parameter is similar to the procedure used at En 1. The same input values are required, while the outputs result from the same datasets.

The final value of the criterion is the sum of the emissions, normalized to the gross floor area of the building and annualized over the designed life span.

Benchmarks: G_i = 20.6 kg/m^2/y - **0p**

G_i = 6.2 kg/m^2/y - **5p**

The final score is obtained by linear interpolation.

G 2. GHG emissions from all facilities in the building operation (HVAC)

Scope: To minimize the amount of CO_2-eq. emissions from building utilities (HVAC).

Indicator: CO_2-eq. emissions annualized according to the predicted lifespan of the building arising from the building facilities G_o [kg CO_2-eq/m^2/y].

Assessment method: This parameter is strictly related to the power generation mix of the energy source used for the HVAC systems. This parameter can be taken directly from the energy simulation software, or it can be calculated manually using the emission factors of the energy source mixes. It is supposed that the annual energy demand is already calculated.

Benchmarks: G_o = 93 kg/m^2/y - **0p**

G_o = 40 kg/m^2/y - **5p**

The final score is obtained by linear interpolation.

G 3. GHG emissions from construction materials used for maintenance, renovation and replacement works

Scope: To minimize the amount of $CO_{2\text{-eq}}$. emissions related to maintenance, renovation and replacement works.

Indicator: CO_2-eq. emissions annualized according to the predicted lifespan of the building arising from maintenance, renovation and replacement works G_R [kg CO_2-eq/m^2/y].

Assessment method: The assessment method is similar with the procedure used at En 3. GHG emissions results from the same datasets, for the same predicted maintenance scenarios.

The final value of the criterion is the sum of the emissions, normalized to the gross floor area of the building and annualized over the designed life span.

Benchmarks: G_R = 3 kg/m^2/y - **0p**

G_R = 0.8 kg/m^2/y - **5p**

The final score is obtained by linear interpolation.

G 4. End of life GHG emissions

Scope: To minimize the amount of $CO_{2\text{-eq}}$. emissions arising from the disposal, recycling or re-use of the initial building materials.

Indicator: CO_2-eq. emissions annualized according to the predicted lifespan of the building arising from disposal, recycling or re-use of the building elements G_D [kg CO_2-eq/m^2/y].

Assessment method: The assessment method is similar to En 4. Emissions are determined either by the LCA software or manually, using proper datasets, based on end-of life scenarios.

Benchmarks: G_D = 1.9 kg/m^2/y - **0p**

G_D = 0.6 kg/m^2/y - **5p**

The final score is obtained by linear interpolation.

G 5. Heat island effect of the roof

Scope: To reduce the effect of the heat island, caused by dark surfaces on roofs, that absorb the heat from the sun and rise the temperature in the surrounding area.

Indicator: Average solar reflectance index of the roof area, Avg. SRI.

Assessment method: The solution to reduce heat island effect is to use roofing materials that supply a high solar reflective index. Roofs with a slope of less or equal than 16% (low sloped) must provide a minimum average solar reflectance index Avg SRI of 78, while roofs with a slope greater than 16% (steef sloped) a minimum of 29.

Within the developed model this parameter can be calculated using the SRI for a large variety of roofing materials taken from [55], [56], [57], [58]. If the roof has a single slope, using one type of material, the value of SRI results from the database, else an average SRI is calculated with equation (3.2):

$$Avg.SRI = \frac{\sum SRI_i \times A_i}{\sum A_i} \tag{3.2}$$

Where:

Avg. SRI – Average Solar Reflectance Index;

SRI_i – Solar Reflectance Index of the roofing material

A_i – Area of the roof.

Benchmarks: *Avg. SRI* = 29 – **0p** – low sloped;
Avg. SRI = 8 – **0p** – Steef sloped;
Avg. SRI = 95 – **5p**

Materials and Resources (MR)

MR 1. Re-use of existing materials, products and structural elements, if available

Scope: The aim is to reduce the consumption of new materials, by re-using part of existing structures.

Indicator: The percentage, by area, of the assessed building that is made out of materials or elements from existing structures on site, where the structures are in usable condition.

Assessment method: If there is an existing structure on site, the basis of evaluation should be a report that provides a structural, functional and economic assessment of the existing structure. The parameter represents the ratio between the building area made of reused elements and the total built area.

Benchmarks: MR1 = 0% - **0p**;
MR1 = 50% - **5p**.

MR 2. Material efficiency

Scope: The aim is to assess the extent to which structural and building envelope components make efficient use of physical resources.

Indicator: The combined weight in [kg] of building structural and building envelope components relative to the gross volume of the structure, M [kg/m^3].

Assessment method: Calculation of material weights, in [kg] based on the project documentation. Within the developed model, this parameter is calculated based on the introduced material quantities and the geometrical data.

Benchmarks: M = 2000kg/ m^3 – **0p**;
M = 900kg/ m^3 – **5p**.

MR 3. Use of materials with recycled content
Scope: To encourage the use of materials with recycled content, in order to reduce the consumption of virgin materials and to minimize the embodied energy and emissions during the manufacturing of virgin materials.
Indicator: The estimated percentage of materials with recycled content used for the building M_{Rec}, [%].
Assessment method: The review of the design plans and material declarations. The greatest contributions may have concrete made with high percentage of cement replacement materials and recycled concrete aggregates, use of recycled steel products, *etc*. Within the developed model, this parameter is obtained in percentage by the ratio between the mass of materials with recycled content and the total mass.
Benchmarks: M_{Rec} = 0% - **0p**;
M_{Rec} = 30% - **5p**.

MR 4. Use of local resources
Scope: To encourage the use of local resources, in order to reduce impacts related to transport.
Indicator: The average transport distance of the building materials, D_{avg} [km].
Assessment method: The evaluation of the transportation distances of the building materials, [tkm/total mass]. Within the developed model, when introducing the material quantity, the transport distance is also required. The average distance results from the sum of the mass-transport product per total mass. It is recommended to purchase materials from the surrounding area.
Benchmarks: D_{avg} = 30km - **0p**;
D_{avg} = 5km - **5p**
The final score is obtained by linear interpolation.

Construction site (CS)
CS 1. Waste from construction and demolition process sent off the site
Scope: To minimize the amount of waste sent off the site by encouraging the development and implementation of a construction waste management program, by sorting, re-using and recycling measures.
Indicator: The percentage by weight of building materials, that will be recycled, re-used on or off site (Wa), according to the waste management plan.
Assessment method: The waste from the construction and demolition process is divided into seven categories: steel profiles, steel tiled sheets; steel-reinforcement; wooden elements, ballast and excavated land; concrete, mortar, bricks; other inert materials, other combustible materials [59]. For these categories a waste management plan should be developed. According to local practices, the percentage of reused/ recycled and burned/ landfilled materials is established.

Within the developed model, the input requirements are: material quantities, grouped into the seven categories and the recycling, re-use and disposal conditions. The end-of-life scenario of integrated materials is in accordance to present conditions in Romania for recycling, reuse and disposal, taken from [60]. The values are summarized in Table 3.3. These scenarios can be modified and adapted to other conditions. The burning and landfill of materials are considered unsustainable, so these practices are accounted as insufficient.

Table 3.3. End-of-life scenario for construction materials in Romania

Material categories	% Recycled/ reused	%Burned/ landfill
Steel profiles, steel tiled sheets	100	0
Steel-reinforcement	80	20
Wooden elements	35	65
Ballast and excavated land	70	30
Concrete, mortar, bricks	0	100
Other inert materials	0	100
Other combustible materials	0	100

Benchmarks: Wa = 5% - **0p**;
Wa = 50% - **5p**.

CS 2. Dust produced during construction

Scope: To minimize the sources of dust and PM10 (Particle matter <10μm) emissions arising from construction activities but also from construction equipment, vehicle exhaust, on-site machinery, *etc*.

Indicator: Completing of a checklist with protection measures taken on site to reduce dust emissions and to protect neighbourhood, P.

Assessment method: Verification of the fulfilment of the protection measures mentioned in the checklist. Within the developed model, the following checklist has been elaborated [61] (Table 3.4):

Table 3.4. Checklist with protection measures for dust control on construction site

Categories	Protection measures	Max points
Site Planning and preparation	Are effective barriers erected around dusty activities or the site boundary?	1
	Are bonfires used for site preparation?	1
	Are machinery and dust causing activities located away from sensitive receptors	1
	Are the vegetation and cover removed in section and not all at once	1
	Are earthworks, excavation and digging activities kept damp?	1
	Is the storage of the removed vegetation protected?	1
	Is mud or water runoff present?	1
Traffic on construction site	Are the engines turned off for vehicles while waiting?	1
	Are the vehicles cleaned before leaving the site if close to sensitive receptors?	1
	Are the loads covered, which enter or leave the site?	1
	Is the road to construction site paved?	1
	Are the material delivery trucks limited in speed?	1
	Is the drop height of the materials loading controlled?	1
Materials handling, mixing, storage and disposal	Are fine, dry materials protected from the wind?	1
	Are fine particle materials damped down during loading?	1
	Is concrete mixed on site?	2
	Are mortar and plaster mixed on site?	2

	Is construction waste disposed correctly?	1
	Is residual waste cleaned up regularly?	1

A sum of 21 points can be achieved if all measures and recommendations are followed, while the final score represents the ratio between available and achieved points, expressed in percentage.
Benchmarks: P = 20% - **0p**;
P = 100% - **5p**.

CS 3. Noise produced during construction
Scope: To minimize the noise arising from construction activities, in order to avoid the disturbance of the neighbourhood and to protect the health of the workers.
Indicator: The average sound level at the ear of the workers during a working day and the sound level at the neighbourhood property line, measured in decibel (L_s).
Assessment method: The site plans and time schedules indicate the position and utilisation period of different equipment. The input parameters are: emission source (equipment), distance to the target worker and neighbourhood property line, as indicated in Figure 3.5, and the daily use of the equipment.

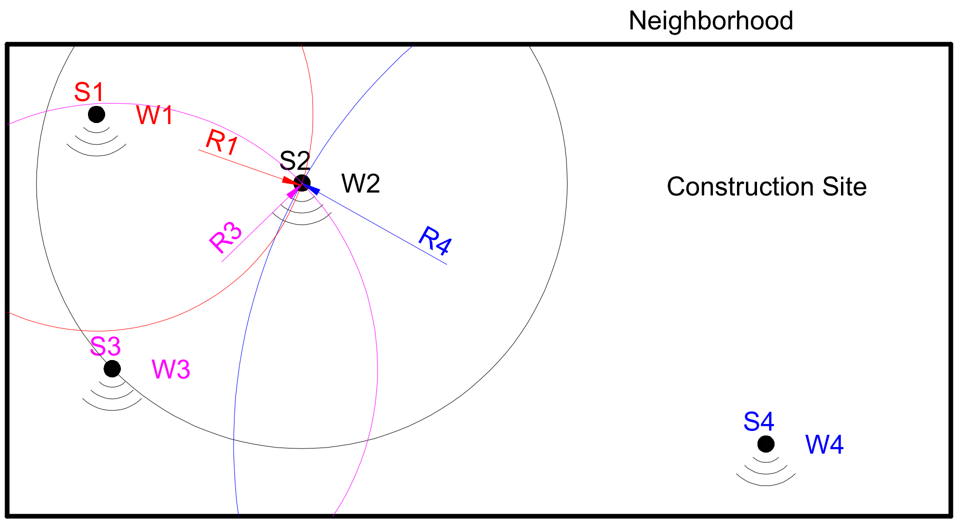


Figure 3.5. Position of the noise sources on site with their relative distances to each other and to the neighbourhood property line

The output parameters are: average daily sound level at workers ear and at neighbourhood. Sound level at a certain distance is calculated with equation (3.3) [62].

$$L_S = L_0 - 20 \times Log(r_2/r_1), [dB] \tag{3.3}$$

Where:
L_s – sound level at specific distance;
L_0 – Initial sound level;
r_1 – reference distance from sound level (r_1=1m)
r_2 – distance to target.

The final values of the parameters for both average sound levels at workers ear and at neighbourhood property line are obtained with equation 3.4.

$$L_{savg.} = \frac{\sum L_{si} \times h_i}{h_d}, [dB] \quad (3.4)$$

Where:

L_{savg} – average sound level;
L_{si} – sound level at specific distance for equipment i;
h_i – number of hours in use of equipment i;
h_d – daily number of working hours.

The sound levels of different construction equipment and the admissible daily sound levels for workers and the surrounding neighbourhood has been taken from [63]. If the conditions are not achieved, special protection measures should be taken to protect the workers and to limit sound propagation outside the construction site.

Benchmarks: Workers ear: L_{savg} = 105dB – **0p**;
L_{savg} = 70 dB – **5p**;
Neighbourhood: L_{savg} = 80dB – **0p**;
L_{savg} = 45dB – **5p**.

Land Use and Water Consumption (LW)

LW 1. Construction on contaminated land

Scope: To encourage the use of sites that may have environmental contamination caused by prior occupants. Such lands should be preferentially developed, since this will reduce pressures to use more valuable lands for development.
Indicator: Documentation on the land.
Assessment method: Report of geotechnical studies whether the site is documented as being contaminated or if it is defined as such by governmental agency.
Benchmarks:

The site is documented as having no sub-surface contamination	**0p**
The site is documented as having little sub-surface contamination	**3p**
The site is documented as having moderate sub-surface contamination	**5p**

LW 2. Ground occupancy percentage

Scope: To fulfill the urbanity criteria of the zone where the building will be situated, regarding the allowed ground to build on.
Indicator: The ground occupancy percentage for the proposed or existing building, GOP.
Assessment method: Comparison of the calculated ground occupancy percentage to the admissible value, reported to the building location. GOP is the ratio between the built ground area and the total property area. Within the model, the values for admissible GOP are according to the Romanian regulations [64], but can be adapted to other legislation.
Benchmarks: If the GOP criterion is fulfilled, **5p** are accorded.

LW 3. Potable water consumption by building occupants

Scope: To minimize the amount of potable water consumption by building occupants for indoor and outdoor utilities.
Indicator: The amount of potable water consumed, W_c in [l/p/d].

Assessment method: The estimation of daily water consumption is very difficult, because it is mainly depending on the user's habits. In the design phase, the evaluation implies a series of assumptions, based on the review of sanitary fixtures and on the average values for routine activities as hand washing, use of toilets, showers, outdoor equipment, irrigation, *etc*. In the case of existing buildings, the water consumptions results from the analysis of water meter records.

Within the developed model, this parameter can be calculated, introducing user specific information and details on the sanitary fixtures. Average values for routine activities are indicated, taken from literature [65], [66], which can be changed.

Benchmarks: W_c = 180 l/p/d – **0p**;
W_c = 90 l/p/d – **5p**.

LW 3. Use of grey and rain water

Scope: To reduce the consumption of potable water for outdoor use, by collecting rainwater, using grey water, or other non-potable water sources.

Indicator: The percentage of water savings, due to rain, grey or other non-potable water sources, W_s.

Assessment method: Verification of special arranged areas for rainwater collection, grey water systems, or other water sources.

Within the developed model, together with the water consumption calculator tool, this parameter can also be calculated. The required input parameters are: demand for grey-/ rainwater, percentage of recycled grey water, rain water collection area and annual average rainfall.

Benchmarks: W_s = 0% - **0p**;
W_s = 30% - **5p**.

Economic

Cost (C)

C 1. Initial cost

Scope: To assess the initial investments of the building. Higher initial costs may result in lower operational costs and vice-versa, so a life cycle cost analysis must be performed for a correct evaluation, including the structure, finishing, installations and all costs related to the project.

Indicator: Represents the initial costs per unit of gross area C_i.

Assessment method: Review of cost analysis. The initial costs include land acquisition, ground studies, construction itself, approvals, technical assistance and other unforeseen costs.

Benchmarks: C_i = 650 Euro/ m^2 – **0p**;
C_i = 300 Euro/ m^2 – **5p**.

C 2. Operational cost

Scope: To assess the operational cost related to the building's utilities, including heating, cooling, air conditioning, water consumption, lighting.

Indicator: Represents the annualized operational costs per unit of gross area, C_o.

Assessment method: Review of cost analysis. The greatest impact on operational cost is related to heating, but also to water consumption. A higher initial investment in thermal insulation and efficient HVAC systems may result in lower operational costs.

It is difficult to estimate the present value of an annually recurring cost, because it is expected to change from year to year at a constant rate of change (escalation rate) over the study period. Within the developed model, the operational costs can be calculated with equation (3.5), on a maximum period of 25 years, using the actualization factors presented in [67] and [68].

$$P_7 = A_0 \times \left(\frac{1+e}{d-e}\right)\left[1-\left(\frac{1+e}{1+d}\right)^N\right] \quad (3.5)$$

Where:

A_0 - annually recurring cost at base-date prices;
d – discount rate;
e – escalation rate;
N - number of time periods (years) over which A_0 recurs;
P_7 - present value of future cost after N years, with d and escalation rate e.

In the design phase, the estimation of the base-date prices are based on the annual energy, electricity and water demands, calculated previously for other parameters. The heating costs are strongly dependent on the heating system fuel source. A caloric conversion is performed if the source is different from electricity, to obtain equivalent prices for 1kWh, as indicated by energy demand simulations (Table 3.5). The current prices in Romania are used, but they can be adapted to other conditions, changing the values in the database with fuel prices.

Table 3.5. Caloric conversion factors of fuel sources

Fuel source	**Unit**	**Caloric conversion factor**
Electricity	1kWh	1 kWh
Coal (weighted average)	1t	7500 kWh
Industrial wood	1t	3806 kWh
Fuel oil	1l	11.85 kWh
LPG	1l	7.08 kWh
Gas/ diesel oil	1l	10.89 kWh
Burning oil	1l	10.32 kWh
Petrol	1l	9.42 kWh
Natural gas	$1m^3$	10.5 kWh

In situations where the building is at least 3 years old, the base-date price for building operation can be obtained by the analysis of the bills.

Benchmarks: C_o = 40 Euro/m^2/y - **0p**;
C_o = 5 Euro/m^2/y – **5p**.

C 3. Maintenance and Repair Cost

Scope: To assess the costs for future replacements, minor and major refurbishments, maintenance, *etc*.

Indicator: Represents the annualized costs per unit of gross area, C_R.

Assessment method: Review of cost analysis. As in the case of embodied energy and GHG emissions, the estimation of this parameter is based on different maintenance scenarios. Future replacements and refurbishments may or may not appear as assumed at present time. Another aspect that should be taken again in consideration is to estimate the present value of the future cost.

Within the developed model this parameter is divided in three parts: Repair and replacement costs, that include the capital and current repair (these are non-annually recurring costs) and maintenance costs, which recurs annually. To find the present value of these future costs, equation (3.6) and (3.7), taken from [67], [68] has been applied, on a maximum period of 25 years.

$$P_2 = C_t \times \frac{1}{(1+d)^t} \tag{3.6}$$

Where:

P_2 – present value of future cost;
C_t – future cost occurring in year t;
t – number of time periods (years) between the present time and the time the cost is incurred;
d – discount rate;

$$P_4 = A \times \frac{(1+d)^N - 1}{d(1+d)^N} \tag{3.7}$$

Where:

A – annually recurring cost;
N – number of time periods (years) over which A recurs

Within the developed model, the actual value of the repair, replacement and routine maintenance costs has been obtained by a general estimation, suggested by [68], which said: capital repair represents about 15% of the initial investments, the current repair represents about 20% from the total of the capital repair and occurs periodically, while maintenance costs can represent about 50% from the current repair. For the current economic situation of Romania, the discount rate d can be taken as 10%, while the escalation rate e is around 6%. All these base values can be changed and adapted to other conditions, if it is necessary.

Benchmarks: C_R = 15 Euro/m^2/y – **0p**;
C_R = 3 Euro/m^2/y – **5p**.

Construction process (CP)

CP 1. Erection time

Scope: To shorter the erection time of the building, but without compromising its quality or costs.

Indicator: Represents the effective workload per square meter of erected building, t, [man*hour/m^2].

Assessment method: Review of construction process planning.

Benchmarks: t=120 man*hour/m^2 – **0p**;
t=55 man*hour/m^2 – **5p**.

CP 2. Production rate

Scope: To raise the production efficiency of the construction work.

Indicator: Production rate expressed in Euro/hour of each worker, PR.

Assessment method: Review of effective workload, working time and costs.

Within the developed model, to calculate this parameter the total initial investment and workload are needed. The ratio between them represents the production rate of one worker. This parameter might be very useful because it shows how efficient the team has been working. The production rate can be calculated in the design phase, based on cost analysis, or after construction, based on the real situation.

Benchmarks: PR = 6 Euro/h – **0p**;
PR = 15 Euro/h – **5p**.

CP 3. Construction Schedules

Scope: The aim is to match the resources of equipment, materials and labour with the project work tasks over time, eliminating problems on site.

Indicator: Applatization factor.

Assessment method: Review of construction schedules made according to specialized methods. One of the most widely used scheduling technique is the critical path method. This method calculates the minimum completion time for a project along with the possible start and finish times for the project activities. In completion to this, a graphical representation is helpful for the visualization of the plan and to ensure that the mathematical requirements are met. The Gantt chart illustration is very useful, because it shows the scheduled time, duration, and resources for each activity. The applatization factor is calculated with equation (3.8):

$$C_a = \frac{W}{D \times R} \tag{3.8}$$

Where:

C_a – Applatization factor;
W – Total workload in [man*hours];
D – total duration of the construction work in [hours];
R_{max} – maximum number of workers on site, at the same time.

Benchmarks: C_a = 0.4 – **0p**;
C_a = 0.9 – **5p**;

Project Management (PM)

PM 1. Initial documents

Scope: The aim is to assure a high project quality and to encourage the implementation of sustainability issues still in the development phase of the project, offering alternative solutions.

Indicator: Beside the mandatory documents for the authorizations, additional documents should be available which underline the quality of the project.

Assessment method: A series of documents will be verified and evaluated using a checklist.

Within the developed model a checklist has been prepared which contains the documents that a project should contain in order to gain additional sustainability points. These documents and their scores are presented in Table 3.6.

Table 3.6. Checklist with necessary initial documents to gain sustainability points for criteria PM 1

Project documents	**Points**
For the design phase	
Mandatory documents:	
Documents to obtain authorization to proceed with construction	3
Optional documents or verifications:	
Evidence of sustainability issues in the bid contest	1
Feasibility Studies	1

Energy Certification	1
Health and Safety plan	1
Documentation for water consumption and use of rain water	1
Waste management plan	1
Comparison of different alternatives	1
For existing buildings	
Mandatory documents:	
Documents to obtain authorization to proceed with construction	3
Documents for the execution of the construction works	2
Documents for the finalization of the construction	
Optional documents or verifications:	2
Detailed design documentation and calculations of the building that match the actual building conditions	2
The constructor has been selected based on sustainability aspects	2
The sustainability aspects from the design plans were incorporated in the execution	2

Benchmarks: For both the design phase and the existing building, mandatory documents must be provided in order to continue the assessment. Otherwise the following message will appear: „Missing documents". If the condition is fulfilled, the points are accorded based on the achieved checkpoints, as follows:

For design phase: P = 3 – **0p**;
P = 10 – **5p**;
For existing buildings: P = 7 – **0p**;
P = 13 – **5p**.

PM 2. Documents of maintenance and operation

Scope: The aim is to ensure optimized use and operation of the building, by comprehensive documentations for maintenance, regular inspections, minor refurbishments and a user's guide with relevant information on the building's utilities.

Indicator: Verification of the checklist with the available documents.

Assessment method: Review of project documentation.

Benchmarks:

No explicit plan exists for future maintenance and efficient operation of the building.	**0p**
An explicit plan exists for future maintenance and efficient operation of the building, providing specific and relevant information about various technical building systems. It also explains the special characteristics of individual building parts and components and their replacements over at least a 15-year period.	**3p**
An explicit plan exists for future maintenance and efficient operation of the building, providing specific and relevant information about various technical building systems. It also explains the special characteristics of individual building parts and components and their replacements over at least a 25-year period.	**5p**

PM 3. Monitoring of performances

Scope: To ensure the on-going optimization of building energy and water consumption, air quality and thermal comfort, over time.

Indicator: The provision of monitoring systems, according to design documentation.
Assessment method: Review of project documentation.
Benchmarks:

No monitoring system will be provided for any building utility.	**0p**
Monitoring system for the reporting of thermal comfort and air quality will be provided.	**2p**
Monitoring system for the reporting of thermal comfort, air quality and energy consumption will be provided.	**3p**
Monitoring system for the reporting of thermal comfort, air quality, energy and water consumption will be provided.	**4p**
Monitoring systems for all major building utilities will be provided	**5p**

Efficiency (Ef)
Ef 1. Long service life
Scope: To ensure a long service life for building, without any necessary investments in major renovations or rehabilitations of the load bearing structure.
Indicator: Designed service life, SL.
Assessment method: Review of project documentation.
Benchmarks: SL = 25 years – **0p**;
SL = 75 years – **5p**.

Ef 2. Area efficiency
Scope: To ensure the efficient utilization of built space within the building.
Indicator: The ratio of usable floor area to gross floor area, A_{ef}.
Assessment method: Review of design plans.
Benchmarks: A_{ef} = 70% - **0p**;
A_{ef} = 95% - **5p**.

Ef 3. Controllability
Scope: To ensure that a building management control system is provided to optimize the operational efficiency of building systems, such as HVAC and lighting.
Indicator: The presence of a control system, which is capable of managing the control of the building utilities.
Assessment method: Review of design plans.
Benchmarks:

No control system is available.	**0p**
Control system, capable of ensuring normal operation of the HVAC system is available.	**3p**
Control system capable of ensuring that building technical systems operate at peak efficiency during all operating conditions.	**5p**

Social

Comfort (Cf)
Cf 1. Thermal Comfort
Scope: To assure an adequate thermal comfort for occupants during summer and winter.
Indicator: Predicted mean vote PMV and Predicted percentage of dissatisfied PPD.
Assessment method: Based on ISO 7730, BSR/ASHRAE Standard 55P or other national standards.

Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment. There are large variations, both physiological and psychological, from person to person, which make it difficult to satisfy everybody in a space. The environmental conditions required for comfort are not the same for everyone. However, extensive laboratory and field data have been collected. Those are the ones that provide the necessary statistical data to define conditions that a specified percentage of occupants will find thermally comfortable [69].

Within the developed model the computer model method has been used to determine PMV and PPD, for general indoor conditions (metabolic rates between 1 met and 2 met, and clothing provide no more than 1.5 clo of thermal insulation.

The input parameters are:

- clothing CLO – thermal insulation provided by garments and clothing ensembles, [CLO], 1CLO=0.155 $m^2/\ ^0C/W$;
- air temperature TA – the temperature of the air surrounding the occupant, [^0C];
- mean radiant temperature TR – the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space, [^0C];
- activity (Metabolic rate) – Rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, [met];
- air speed – the rate of air movement at a point, without regard to direction, [m/s];
- relative humidity – the ratio of the partial pressure (or density) of the water vapour in the air to the saturation pressure (or density) of water vapour at the same temperature and the same total pressure, [%].

The output parameters are:

- operative temperature – the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment, [^0C];
- PMV – is an index that predicts the mean value of the thermal sensation votes of a large group of persons on a 7-point scale;
- PPD – is an index that predicts the percentage of a large group likely to feel thermally dissatisfied for the body as a whole, determined from PMV, [%].

The graphical representation of the two indexes within the model is shown in Figure 3.6.

The computer code for the calculation of PMV and PPD has been taken from ISO 7730 [70].

Benchmarks:

Comfort Class	**PPD**	**PMV**	**Points**
A	<6	-2<PMV<2	5
B	<10	-0.5<PMV<0.5	4
C	<15	-0.7<PMV<0.7	3

If the user defined comfort class, specified in the initial page, is not achieved improvements on the environmental conditions have to be done.

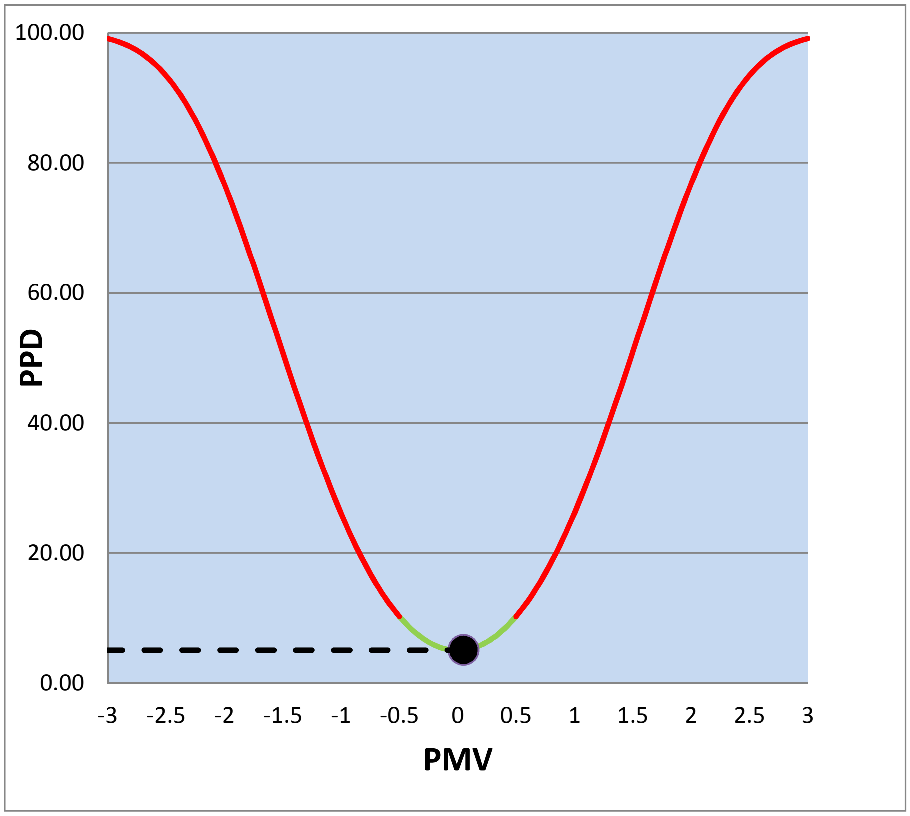


Figure 3.6 Predicted percentage dissatisfied (PPD) as a function of predicted mean vote (PMV)

Cf 2. Noise and acoustic comfort

Scope: To create proper indoor conditions assuring a low level of interference and background noise; to ensure that noise attenuation through the wall facing the noisiest site boundary is adequate to provide interior noise levels that will not interfere with normal tasks.

Indicator: Reverberation time (RT60), Airborne sound insulation, Impact sound insulation.

Assessment method: Calculation of the parameters for the main building elements.

The reverberation time RT60 is the time required for the sound level to decrease by 60 dB. It is calculated using Sabine's equation, in relation to the room volume and total absorption [71]:

$$RT60 = k \times V \,/\, Sa, [s] \tag{3.9}$$

Where:

k – is a constant that equals 0.161;

V – volume of the room;

Sa – is the total surface absorption of a room expressed in Sabin's. It is a sum of all the surface areas in the room multiplied by their respective absorption coefficients. The absorption coefficients express the absorption factor of materials at given frequencies.

Within the model, a tool has been developed, which permits the calculation of this parameter. The required input parameters are: height of the room, area and the material of all room surfaces. The outputs are: volume, total surface absorption and reverberation time. The absorption coefficients of the common materials were taken from [72], [73].

Airborne sound insulation represents the insulation against noise originating in air: voices, music, motor traffic, wind, *etc*. The ideal material for good sound insulation has a very high mass and low stiffness but some of the most convenient building materials have low mass and relatively high stiffness.

Within the developed model, airborne sound insulation of single partitions can be calculated using the mass law, a simplified, but generally accepted method. The rule stating that sound insulation for a single wall is determined almost wholly by its weight per unit area means, that doubling the weight of the partition increases the insulation by 5 decibels. Airborne sound insulation is calculated with equation (3.10):

$$D_n = R + 10\,log\left(\frac{A_0}{S}\right), [dB] \tag{3.10}$$

Where:

D_n – normalized airborne sound insulation;
R – Sound reduction index;
A_0 – reference area=10m^2;
S – sum of all room surfaces.

$$R = 10 \times log\left(\frac{1}{T}\right), [dB] \tag{3.11}$$

Where:

T – Sound transmission coefficient.

$$T = \left(\frac{\rho_0 \times c}{\pi \times f \times m}\right)^2 \tag{3.12}$$

Where:

$\rho_0 \times c$ – acoustic impedance ≈420 Ns/m^3;
n – number of surface parts
f – frequency, [Hz];
m – mass per unit area of the partition, [kg/m^2].

For the composite partitions of n numbers of surface parts, the average transmission coefficient T_{AV} can be calculated from the following equation:

$$T_{AV} \times A = \sum_{i=1}^{n} T_i \times A_i \tag{3.13}$$

Where:

T_i – transmission coefficient of the ith part;
A_i – area of the ith part, [m^2];
A – total area of partition, [m^2].

Impact Sound Insulation represents the insulation against noise originating directly on a structure by blows or vibration: footsteps above, furniture being moved, drilling and hammering the structure, *etc*.

Within the developed model, the level of sound pressure caused by footsteps, measured on the finished floor slab $L_{n,w}$, can be calculated. For design purposes, there is a mathematical model, also based on the mass per unit area law that may be used to calculate the theoretical value [74]:

$$L_{n,w} = L_{nweq} - \Delta L_w + K, [dB] \tag{3.14}$$

Where:

$L_{n,w}$ – level of sound pressure caused by footsteps measured on the finished floor slab;

L_{nweq} – level of sound pressure caused by footsteps measured on the naked floor slab;

ΔL_w - reduction in noise caused by footsteps after installing a finishing;

K – correction factor for the lateral transmission of noise;

The value depends on the surface mass of the naked slab and the surface mass of the vertical walls.

$$L_{nweq} = 164 - 35 \times \log(m), [dB] \tag{3.15}$$

Where:

m – is the surface mass of the slab, [kg/m^2]

Benchmarks: The desirable reverberation time for residential buildings is difficult to find. The optimum reverberation time of a room depends upon it's intend to use. Around 1 or 2 seconds is a desirable value for the general purpose room.

The values for airborne sound insulation:	D_n = 35dB – **0p**;
	D_n = 47dB – **5p**;
The values for impact sound insulation:	$L_{n,w}$ = 70dB – **0p**;
	$L_{n,w}$ = 58dB – **5p**.

Cf 3. Visual Comfort

Scope: To ensure a good visual comfort, by letting natural light inside the building. In this way the monotony of the indoor environment can be disrupted and the consumption of electricity for lighting systems can also be reduced.

Indicator: The predicted Daylight Factor in the living area of a dwelling unit located on the ground floor, as indicated by drawings and specifications.

Assessment method: Based on drawings. The average daylight factor represents the average indoor luminance (from daylight) on the working plane within a room, expressed as a percentage of the simultaneous outdoor luminance on a horizontal plane under an unobstructed sky. The average daylight factor can be calculated using the following equation [75]:

$$ADF = \frac{M \times A_W \times \theta \times T}{A \times (1 - R^2)}, [\%] \tag{3.16}$$

Where:

A_w – total glazed area of windows or roof lights;

M – a correction factor for dirt;

θ – angle of visible sky

T – glass transmission factor;

R – area-weighted average reflectance of the room surfaces;

A – total area of all room surfaces.

Guide values for a typical dwelling with light-coloured walls are as follows:

R = 0.5

M = 1.0 (vertical glazing that can be cleaned easily)
0.8 (sloping glazing)
0.7 (horizontal glazing)

T = 0.7 (double glazing)
0.6 (double glazing with low emissivity coating)
0.6 (triple glazing)

$$\theta = 90^0 - arctan\frac{H}{D} - arctan\frac{T_w}{H_w} \tag{3.17}$$

Where:

H_w – Height of window;
T_w – Thickness of the wall;
H – Height of the obstruction above the mid height of the window;
D – Distance from the window to the obstruction.

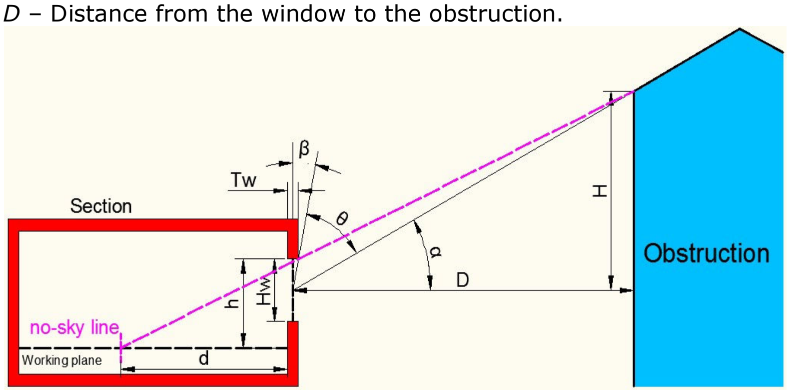


Figure 3.7 Scheme for the determination of the angle of visible sky

Benchmark: *ADF = 0.5% - **0p**;*
*ADF = 3% - **5p**.*

Indoor air quality (IAQ)

IAQ 1. VOC concentration in indoor air

Scope: To ensure that occupants are not exposed to harmful levels of volatile organic compounds (VOCs), resulting from building materials as carpets, adhesives, paints, *etc*.

Indicator: The total amount of VOCs (TVOCs) resulting from building materials.

Assessment method: Volatile organic compounds or VOCs are organic chemical compounds whose composition makes it possible for them to evaporate under normal indoor atmospheric conditions of temperature and pressure. According to [76], the TVOC content in a product after 3 days must be ≤ 10mg/m^3, while in order to satisfy the long-term condition, the TVOC content in a product must be ≤ 1mg/m^3 after 28 days.

Within the developed model, this parameter is evaluated based on the review of product documentations.

Benchmarks:

Option	Points
VOC content in paints, adhesives, etc. is over limit value.	0
VOC content in paints, adhesives, etc. is below limit value.	2
VOC content in paints, adhesives, etc. is at 25% below limit value.	3
VOC content in paints, adhesives, etc. is at 50% below limit values.	4
There is no VOC content in paints, adhesives, etc.	5

IAQ 2. CO concentration in indoor air

Scope: To ensure that carbon monoxide concentrations stay below acceptable levels in typical primary occupancy areas.

Indicator: Measures taken for HVAC systems according to ASHRAE, CIBSE or other acceptable protocol.

Assessment method: Carbon monoxide is an odourless, colourless and toxic gas. Because it is impossible to see, taste or smell, the toxic fumes can kill you before you are aware it is in your home. At lower levels of exposure, CO causes mild effects that are often mistaken for the flu. These symptoms include headaches, dizziness, disorientation, nausea and fatigue. The effects of CO exposure can vary greatly from person to person depending on age, overall health and the concentration and length of exposure. Average levels in homes without gas stoves vary from 0.5 to 5 parts per million (ppm). Levels near properly adjusted gas stoves are often 5 to 15 ppm and those near poorly adjusted stoves may be 30 ppm or higher [77].

Within the developed model, this parameter is assessed by the review of mechanical systems and evaluation of the checklist, as presented in Table 3.7.

Table 3.7. Checklist with measure to prevent CO exposure risk

Measures to prevent CO exposure risk	Points
Home without any gas equipment.	5
Purchasing gas equipment, carrying the seal of a national testing agency.	2
Exhaust fan are installed and used over all gas appliances to avoid that CO builds up in the home.	0.75
Yearly service of heating system, water heater and any other gas, oil, or coal burning appliances by qualified technician.	0.75
Yearly inspection and cleaning of the flues and chimney.	0.5
Flues and vents are open when gas appliance is in use.	0.5
Battery-operated CO detector is installed in the home.	0.5

Benchmarks: If the home is without any gas equipment **5 points** are accorded, else it is the sum of the points accorded for the completion of each measure.

IAQ 3. Effectiveness of ventilation in natural or mechanical ventilated spaces

Scope: To ensure that the building occupants are provided with a high quality air and sufficient ventilation, either by natural or mechanical ventilation.

Indicator: The predicted or measured air change rate in an occupancy area.

Assessment method: Review of documents and mechanical system.

Benchmark: ach=0.3 – **0p**;
ach=0.8 – **5p**.

Safety (Sa)

Sa 1. Protection against earthquake

Scope: To assure structural safety against earthquake, protecting the building occupants and reducing damages.

Indicator: Classification in earthquake risk classes, based on the calculation of the three parameters R1, R2, R3 according to EN 1998/2004 or P100-3/2005.

Assessment method: Construction and evaluation measures, according to EN 1998/ 2004 or/and P 100-1:2006. If new constructions are designed according to actual standards, they do not need any further assessment. Old buildings must be evaluated which implies the following steps: collection of information about the characteristics of the existing building regarding infrastructure, structural skeleton, finishing, etc.; determination of the material properties; identification of the degree of physical and chemical degradations; fixing of performance objectives, in order to establish the seismic action; establishment of the calculation and evaluation methodology; qualitative and quantitative assessment of the construction (R_1, R_2, R_3); classification of the construction in seismic risk classes based on the obtained parameters.

The classification in risk classes is based on the following parameters [78]:

- R_1 – degree for the fulfilment of rules for seismic detailing;
- R_2 – degree of structural degradation caused by seismic or other actions;
- R_3 – degree of structural seismic protection, defined as the ratio between seismic resistance and seismic effect.

The risk classes are as follows:

- R_s I – includes constructions with high risk of collapse in case of earthquake;
- R_s II – includes constructions which suffer major structural degradations at seismic actions, but the loss of stability is less probable;
- R_s III – includes constructions, which under seismic actions can present structural degradation, which have minor effects on the structural safety, but causes important non-structural damages;
- R_s IV – includes constructions which have a similar response to seismic actions as constructions designed according to rules in force.

Benchmarks:

Option		**Points**
New buildings designed according to EN 1998/2004 or other national standards.		5
Earthquake risk classes of existing buildings (before 2004)	R_s I	0
	R_s II	2
	R_s III	3
	R_s IV	4

Sa 2. Protection against flood

Scope: To discourage the selection of land for a building that presents substantial risk of flood appearance.

Indicator: The height of the minimum elevation of the site above the elevation of the 100-year flood plain, H_f, [mm].

Assessment method: Review of site analysis report, defined in official documentation or assessment by competent authorities.

Benchmarks: H_f=1000mm – **0p**;
H_f=6000mm – **5p**.

Sa 3. Protection against fire

Scope: To ensure that the building and its structural elements can assure fire resistance until a specific time.

Indicator: Fire resistance class, obtained according to the combustibility class of the materials and fire endurance class of the building element.

Assessment method: The fire resistance time and combustibility class of the main building elements are assessed according to the European and National codes.

Within the developed model the fire endurance class can be established for masonry, concrete and wooden structures.

The fire behaviour of masonry walls is assessed according to Eurocode 6 [79], and depends on:

- the masonry unit material – clay, calcium silicate, autoclaved aerated concrete or dense/lightweight aggregate concrete, manufactured stone;
- the type of unit – solid or hollow (type of holes, percentage of formed voids), shell and web thickness;
- the type of mortar – general purpose, thin layer or lightweight mortar;
- the relationship of the design load to the design resistance of the wall;
- the slenderness of the wall;
- the eccentricity of loading;
- the density of units;
- the type of wall construction;
- the type and nature of any applied surface finishes.

The period of fire resistance $t_{fi,d}$, for a given thickness of a masonry wall, t_F, may be taken from the tabulated data for the relevant wall and loading situations.

The fire behaviour of RC structures is assessed according to Eurocode 2 [80] using tabulated data for major structural elements: columns, walls, beams and slabs. For situations where no tabulated data can be used, the calculation methods in EC 2 must be followed.

The fire endurance assessment of wooden elements, applied within the model, is based on the concept, that at a fire exposure time t, the initial width, B, and height, H, are reduced to b and h, respectively, as illustrated in Figure 3.8.

A section, smaller than the original section, is capable of supporting the design load, because of the margin of safety provided in the cold design. The original section is stressed only to a fraction of the maximum capacity. Failure occurs when the remaining cross section is stressed beyond the maximum capacity [81].

Within the developed model beams and columns are calculated separately, due to their different failure mode, but in both cases it is assumed that the charring rate β is identical in every direction and the remaining cross section is rectangular.

Beams and decks are assumed to fail when the reduction in cross section results in a critical value for the section modulus *S*. The critical section is obtained by formula 3.18.

$$\frac{B \cdot H^2}{6} = k \cdot \frac{b \cdot h^2}{6} \tag{3.18}$$

Where:

B, H – Initial dimensions;

b, h – dimensions in function of the exposure time t, and charring rate, β;

k – safety factor, that takes in consideration the ratio between design and ultimate strength.

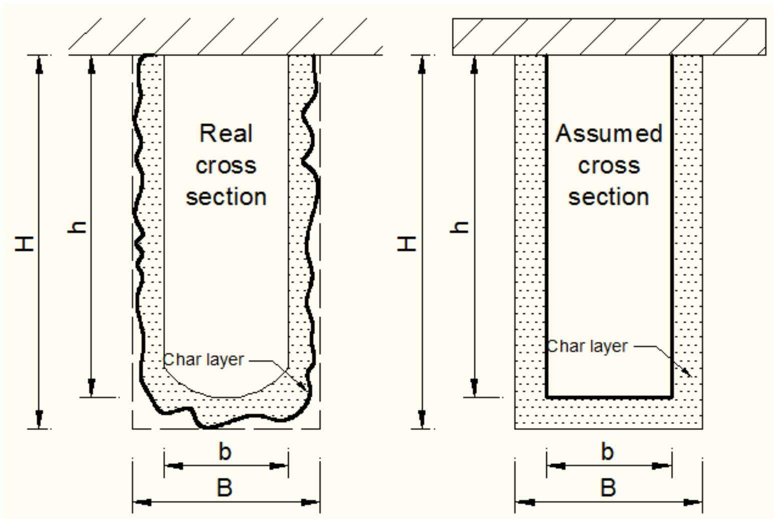


Figure 3.8. Scheme for the real and assumed cross section dimensions of a wood element exposed on three surfaces

Given the initial dimensions *B* (width), *H* (Height), safety factor *k*, number of exposed surfaces *n* and charring rate *β*, the endurance time can be calculated by solving the resulting equations for *t*. The charring rates for a large variety of wooden materials are given in Eurocode 5 [82].

For *n*=1

$$\frac{B \cdot H^2}{6} = k \cdot \frac{B \cdot (H - \beta \cdot t)^2}{6} \tag{3.19}$$

For *n*=2

$$\frac{B \cdot H^2}{6} = k \cdot \frac{B \cdot (H - 2 \cdot \beta \cdot t)^2}{6} \tag{3.20}$$

For *n*=3

$$\frac{B \cdot H^2}{6} = k \cdot \frac{(B - 2 \cdot \beta \cdot t) \cdot (H - \beta \cdot t)^2}{6} \tag{3.21}$$

For *n*=4

$$\frac{B \cdot H^2}{6} = k \cdot \frac{(B - 2 \cdot \beta \cdot t) \cdot (H - 2 \cdot \beta \cdot t)^2}{6} \tag{3.22}$$

The resulting endurance times for the different exposure conditions are expressed in minutes and are available for an unprotected surface. The endurance time for surfaces of beams and decks, initially protected from fire exposure, is increased with the charring time t_{ch}, which represents the period until the protective cladding layer is destroyed. This value is calculated according to [82] in function of the protection layer.

The column and wall failure mode depends on the slenderness ratio. Long columns fail when the reduction in cross section reaches a critical value for moment of inertia *I*. In this case the critical section is determined by formula 3.23.

$$\frac{B \cdot H^3}{12} = k \cdot \frac{b \cdot h^3}{12} \tag{3.23}$$

H is considered the narrowest dimension of the column and buckling is assumed to occur in the weakest direction. Again given the initial dimensions *B* (width), *H* (Height), safety factor *k*, number of exposed surfaces *n* (n=4) and charring rate *β*, the endurance time can be calculated by solving the resulting equations for *t.*

For *n*=4

$$\frac{B \cdot H^3}{12} = k \cdot \frac{(B - 2\beta \cdot t) \cdot (H - 2\beta \cdot t)^3}{12} \tag{3.24}$$

As in the case of the beams and decks, if protection layers are available, the calculated exposure time is increased with the charring time t_{ch} of the layer.

All equations can be solved within the model, using „Excel Equation Solver", following the steps from Figure 3.9.

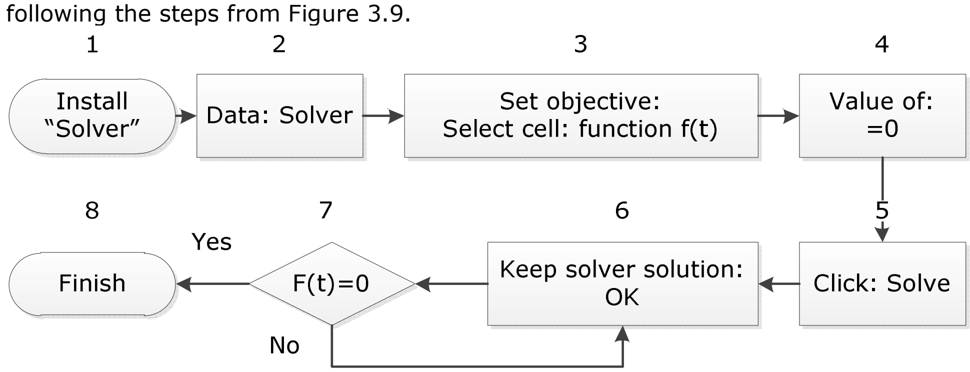


Figure 3.9. Scheme with the required steps to determine *t*, using „Excel Solver"

The equations can be solved one at a time, so in order to determine the exposure time for different elements having different number of exposure surfaces, the calculation procedure must be repeated every time (excluding the first step).

The fire resistance class of an entire building can be obtained if its major elements fulfill the minimum criteria with regards to combustibility class and fire endurance time, according to [83].

Benchmarks: Class 5 – **0p**;
Class 1 – **5p**

Accessibility and Adaptability (AA)

AA 1. Access to public transport systems and proximity to user specific facilities.

Scope: To reduce pollution and traffic flow generated by private cars, which are used for relative short distances in order to reach user specific facilities.

Indicator: The walking distance to the nearest means of public transport system and to personal usage facilities.

Assessment method: During assessment the distances to public transportation systems, their connections and the presence of the user specific facilities shall be evaluated in terms of walking minutes.

The traffic connection with various means of transportation belongs to the mandatory criterion of a good site. On the other hand it should contribute to the user's quality of life, offering a large variety of facilities for daily necessities such as food shops, medical centres, outdoor open access public area, banks, schools, *etc.*, situated at short walking distances.

Benchmarks:

	Time [Minutes]	Points
Avg. distance to public transport.	30	0
	5	5
Avg. Distance to user specific facilities	50	0
	10	5

AA 2. Lifetime homes

Scope: To encourage the construction of buildings that are accessible and easily adaptable to meet the changing need of current and future occupants.

Indicator: Checklist of the 16 design criteria imposed by lifetime homes standards.

Assessment method: Verification of the checklist with the 16 criteria.

„Lifetime Homes" was developed by the Habinteg Housing Association, the Helen Hamlyn Foundation and the Joseph Rowntree Foundation in the early 1990s. The scheme involves the incorporation of 16 design features that together create a flexible blueprint for accessible and adaptable housing in any setting [84]. The 16 criteria are presented below.

Access:

1. Car parking place potentially 3.3m width. The general provision for a car parking space is 2400mm width. If an additional 900mm width is not provided at the outset, there must be provision (e.g. a grass verge) for enlarging the overall width to 3300mm at a later date;
2. The distance from the car parking space to the home should be kept to a minimum and should be levelled or gently sloped;
3. The approach to all entrances should be levelled or gently sloped;
4. All entrances should be illuminated, should have level access over the threshold and should have a covered main entrance;
5. Communal stairs should provide easy access and in the cases where the homes are reached by a lift, it should be fully accessible.

Inside the home:

6. The width of the doorways and hallways should conform to the specifications: front door 800mm, internal door 750mm;
7. There should be space for turning a wheelchair in dining areas and living rooms and adequate circulation space elsewhere. A turning circle of 1500mm diameter or a1700mmx1400mm ellipse is required [in dining areas and living rooms];
8. The living room should be at entrance level;
9. In houses of two or more storeys, there should be space on the entrance level, that could be used as a convenient bed-space;
10. There should be a wheelchair accessible entrance level WC, with drainage provision enabling a shower to be fitted in the future;

11. Walls in bathrooms and toilets should be capable of taking adaptations such as handrails. Wall reinforcements should be located between 300 and 1500mm from the floor;

12. The design should incorporate the provision of a stair lift or a suitably identified space for a through-the-floor lift;

13. The design should provide a reasonable route for a potential hoist from a main bedroom to the bathroom. Most timber trusses today are capable of taking a hoist and tracking. Technological advances in hoist design mean that a straight run is no longer a requirement;

14. The bathroom should be designed to incorporate ease of access to the bath, WC and wash basin. Although there is not a requirement for a turning circle in bathrooms, sufficient space should be provided so that a wheelchair user can use the bathroom.

Fixtures and Fittings

15. Living room window glazing should begin at 800mm or lower and windows should be easy to open/operate. People should be able to see out of the window whilst seated. Wheelchair users should be able to operate at least one window in each room;

16. Switches, sockets, ventilation and service controls should be at a height usable by all (i.e. between 450 and 1200mm from the floor).

For the fulfilment of a criterion, 1 point is granted, so 16 points can be earned if all criteria are fulfilled.

Benchmarks: Fulfilment of criteria: 3 – **0p**;
Fulfilment of criteria: 15 – **5p**

AA 3. Adaptability constraints imposed by structure

Scope: To ensure that the structural system offer a degree of adaptability for new purposes.

Indicator: Structural system, including floor-to floor height, load-bearing structure, separating walls and foundations.

Assessment method: Review of design documents.

Benchmarks:

Adapting the building to new purposes is not possible, because the structure is unsuitable for the new occupancy.	**0p**
Adapting the building to new purposes is possible, but with major modifications of the structural system.	**2p**
Adapting the building to new purposes is possible, but requires the strengthening of some structural elements.	**3p**
Adapting the building to new purposes is possible, but requires the modification of the envelope.	**4p**
Adapting the building to new purposes is possible without any modification of the structural system.	**5p**

AA 4. Adaptability to future changes in type of energy supply

Scope: To ensure that the building can be adapted in the future to run on a different fuel from that which was originally anticipated, or on renewable energy sources.

Indicator: The ease or difficulty in installing heating or cooling equipment that require different fuel, or to install renewable energy systems.

Assessment method: Review of design plans.

Benchmarks:

Adapting the building to a new fuel source or installing photovoltaic will not be possible without major renovations.	**0p**
Adapting the building to a new fuel source will be easy, and installing photovoltaic will require only a minor level of renovations.	**3p**
Adapting the building to a new fuel source or installing photovoltaic will require only minor adjustments to architectural, HVAC or electrical systems.	**5p**

3.1.4. Results and ranking

The global model results in a Building Sustainability Index BSI in the interval between 0 and 5. Based on the calculated BSI, the building can be ranked as shown in Table 3.8.

Table 3.8. Rating benchmarks of the global model

Global Model Rating	Score BSI
Very Good	> 4.0
Good	3.0-4.0
Acceptable	2.0-3.0
Insufficient	<2.0

The result worksheet offers the following information:

- centralization of the active weights and achieved weighted scores for each sustainability category;
- numerical and graphical representation of the dimension and category scores, offering a clear visualization of the building's strengths and weaknesses (Figure 3.10 and 3.11);
- the achieved Building Sustainability Index BSI and the final ranking;
- number of active criteria;
- the total percentage of quantifiable parameters, by resuming the values and weights of these parameters.

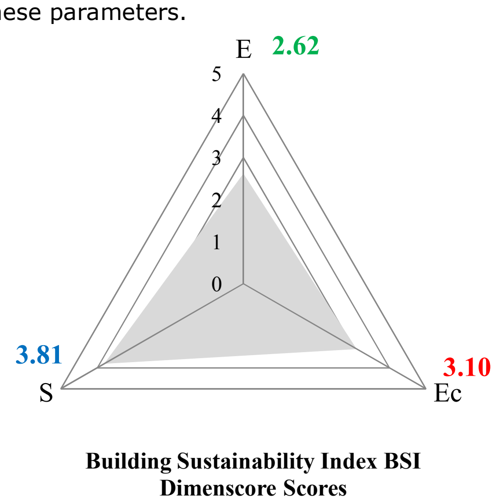


Figure 3.10. Graphical representation of the three sustainability dimension scores

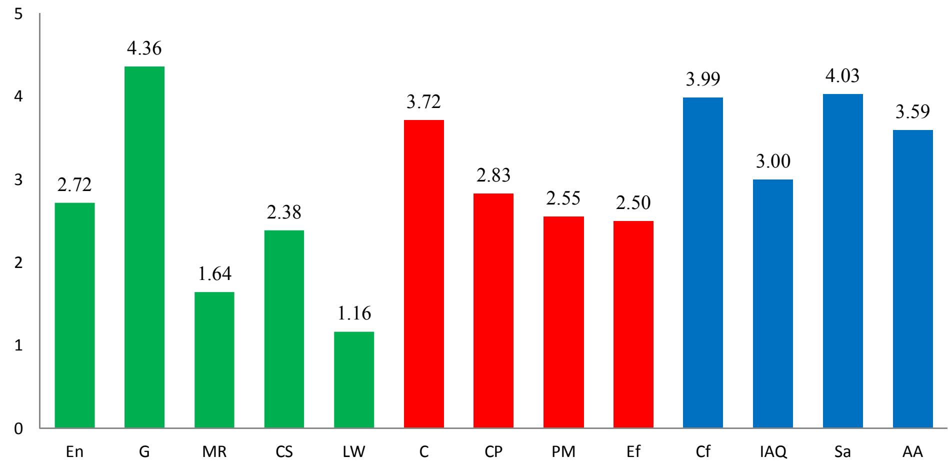


Figure 3.11. Graphical representation of the category scores

3.1.5. Utilization procedure of the global model for the assessment and certification of the construction work

The global model is materialised by a calculation software made in Microsoft Excel. The assessment procedure of the Excel spread sheet is based on the successive proceeding of the calculation steps. Each of these steps require the completion of input data that are necessary for the calculation tools implemented in the program.

The first step in the assessment procedure is the presentation of general information about the studied building. The Worksheet „*Initial Data*" requires the following information:

- building phase: Existing or Design;
- building type: Family house;
- desired location of the building: central, commercial, mixt, exclusive residential for buildings with G, G+1, G+2, residential for buildings with over 3 storeys or predominantly residential zone;
- general information about the building: project name, address, owner, architect, designer, constructor; description of the structure and building services;
- geometrical information: number of storeys, usable floor area, gross floor area, built area on ground, total property area; gross volume, heated floor area;
- technical information: designed life time, number of occupants; average daily use time; indoor air temperature, air change per hour, renewable energy supply, the height of the minimum elevation of the site above the elevation of the 100-year flood plain.

Some of the above presented data has only an informative role, while others represent important input values for the calculation off different parameters.

The next steps, namely the definition of benchmarks, establishing of the weightings and compilation of the material database, are of key importance, as they can have a major influence on the final result. The model contains default benchmarks, weightings and a comprehensive material database, which have been developed for a traditional family house. These values can be modified for building specific cases. A schematic representation of these steps is shown in Figure 3.12.

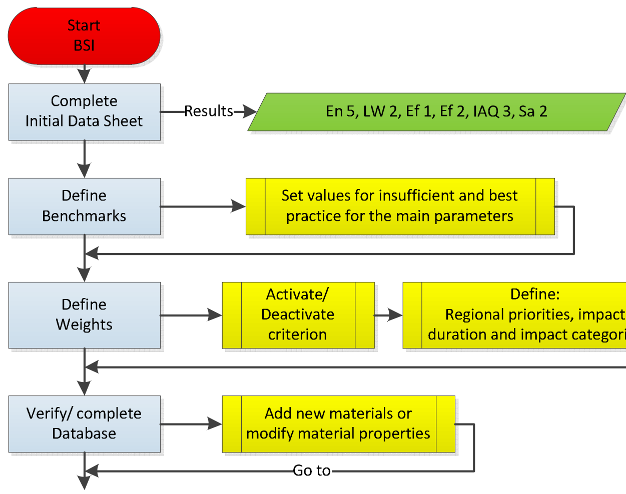


Figure 3.12. Procedure to define the initial conditions

The procedure continues with the assessment of the environmental, economic and social parameters according to the calculation steps in Figures 3.13, 3.14, 3.15.

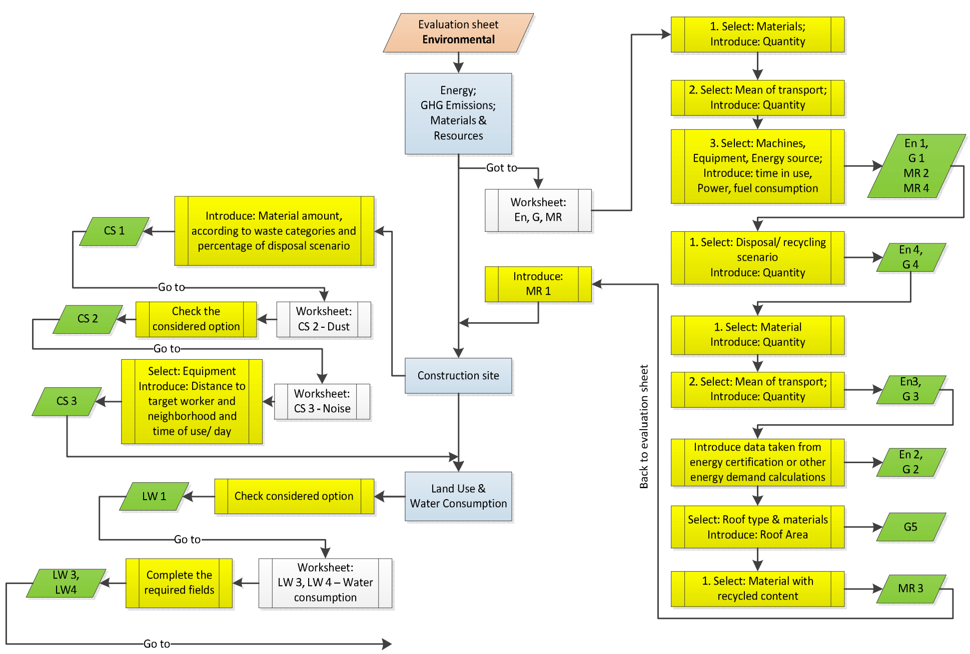


Figure 3.13. Assessment procedure of the environmental parameters

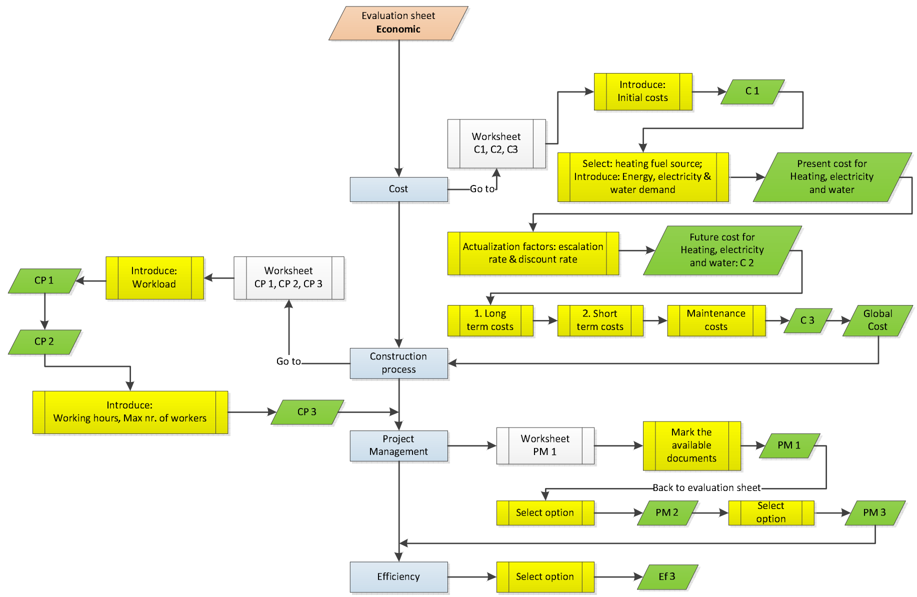


Figure 3.14. Assessment procedure of the economic parameters

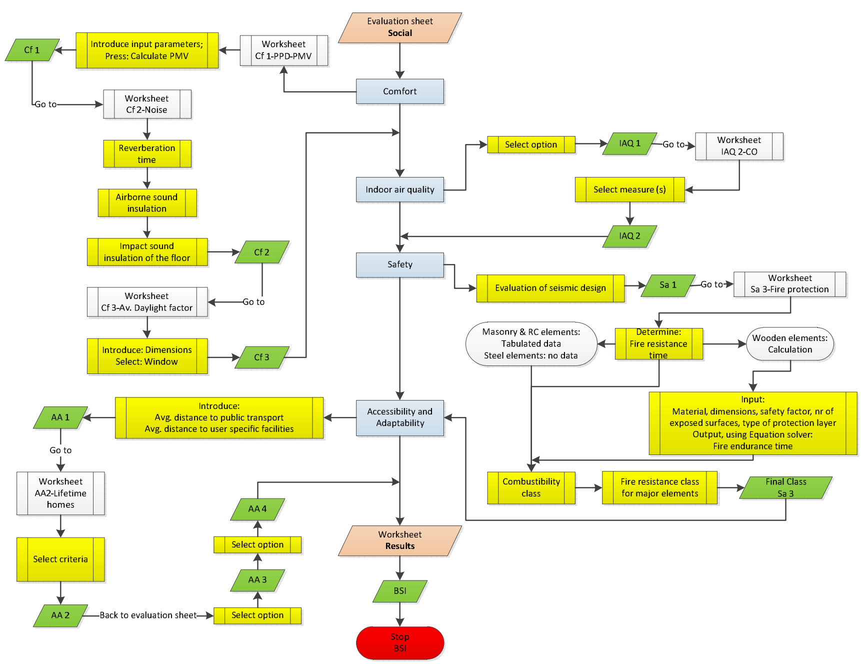


Figure 3.15. Assessment procedure of the social parameters and final results

3.2. Specific model

Most of the existing rating tools which evaluate the sustainability performances of construction works are very comprehensive with high applicability but also show some disadvantages:

- some of the tools do not cover all three dimensions;
- they include a great number of criteria and many of them are difficult or impossible to quantify;
- the tools are focused mainly on entire buildings and they can be applied with some difficulties on other types of construction works and activities;

Taking into consideration the disadvantages of the existing tools a new assessment method has been developed, the specific model. The model has the aim to help engineers to assess the sustainability performances of different construction works. The main advantages of this method are:

- covers the three dimensions of sustainability;
- high degree of applicability;
- includes only quantitative parameters.

3.2.1. System boundaries

The specific model is a flexible and target oriented evaluation method, which was developed for the sustainability assessment of construction works. It has a larger applicability than the global models and can be used for:

- partial building works;
- production of building materials;
- rehabilitation works;
- transport of prefabricated elements;
- construction technologies *etc*.

A similar approach has been suggested by Grace D. [14], but it was only a general proposal, without any practical applications.

The time boundary of the specific model is difficult to define, because it depends on the type of construction work and on the parameters which have been considered for the assessment. For example, if a construction element made out of different materials is assessed, a life cycle approach is indicated, while for the assessment of some means of transport, this approach would be useless.

The main purpose of the model application is to compare different solutions, considering parameters from all sustainability issues, in order to choose the most suitable one. In this case a relative value of each solution is obtained. The absolute value can be obtained by a self-assessment, if correct reference values are available.

3.2.2. Selection, weighting and quantification of the parameters

Different from the global models, where the parameters are clearly defined, the selection of parameters in the developed specific model is very case sensitive. Depending on the type and scale of the construction works, parameters are carefully selected and evaluated. This occurs in order to permit a correct and objective assessment of each proposed solution, but in same time to respect the principles of sustainability. The selected parameters must cover all major issues of environmental, economic and social dimensions of sustainability. The number of parameters is not limited, but they should include all the important characteristics of the assessed construction work.

The weights for each parameter are established through the estimation of their impact on a micro and macro level, as in the case of the global one. Independent of the importance of each parameter, the weighting system respects the definition of sustainability, so environmental issues contribute with 40%, while economic and social issues each add 30% to the final score.

The quantification of the parameters is very laborious and requires many information sources. Most of them are calculated using national or international standards, comprehensive material datasets or other available and legal data sources. It is advised to use the same data source for all proposed solution, in order to avoid an erroneous value of the final result.

3.2.3. Calculation procedure and results

The specific model is based on simple mathematical equations, which combine the results of the quantified parameters in a rational way, obtaining finally a Sustainability Index *SI*.

$$SI = S_{env} + S_{eco} + S_{soc} \tag{3.25}$$

$$S_{env} = \sum_{i=1}^{n} \alpha_i \times \frac{P_i^{Renv}}{P_i^{env}};\, S_{eco} = \sum_{i=1}^{n} \beta_i \times \frac{P_i^{Reco}}{P_i^{eco}};\, S_{soc} = \sum_{i=1}^{n} \gamma_i \times \frac{P_i^{Rsoc}}{P_i^{soc}} \tag{3.26}$$

Where:

SI – Sustainability Index;
S_{env}, S_{eco}, S_{soc} – sustainability indexes for the environmental, economic and social dimensions;
α_i – weighting factor of each parameter of the environmental dimension;
β_i – weighting factor of each parameter of the economic dimension;
γ_i – weighting factor of each parameter of the social dimension;
$P_i^{env}, P_i^{eco}, P_i^{soc}$ – the calculated value for each parameter;
$P_i^{Renv}, P_i^{Reco}, P_i^{Rsoc}$ – the reference value for each parameter.

In case of a comparison between different solutions, the reference values can be taken as the best values of the parameters from each solution; in case of a self-assessment the best available practices are taken as reference values.

For those situations, where the higher value of a parameter is considered more sustainable, the ratios of these parameters in Equation 3.26 become P_i / P_i^R.

Diaz-Balteiro & Romero [85] also intended to solve the problem that for some parameter "higher is better", while for other "lower is better". Disadvantages of this model are that it takes into account three values for a single parameter: calculated value, standard value and best practice, which are difficult or impossible to be found for some applications. For cases where "higher is better" the model gives not proper results.

The final result of the developed specific model is a Sustainability Index *SI*, with a dimensionless value between 0 and 1, where 1 is the best and 0 the worst value [86]. Based on this index the most sustainable solution can be identified. Although in some cases the most sustainable solution is not always the best solution, because due to some technical reasons, it cannot be applied.

The schematic calculation procedure of the specific model is presented in Figure 3.16.

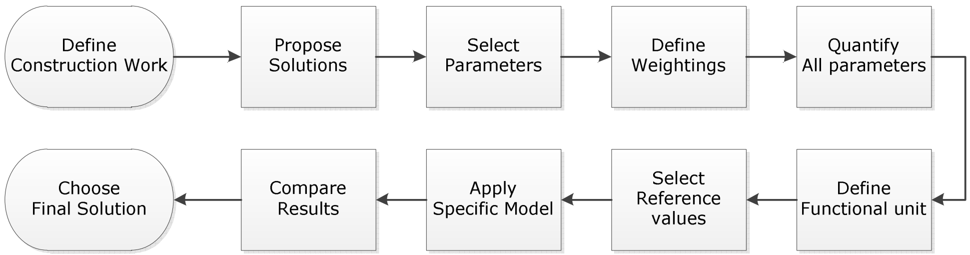


Figure 3.16. Calculation steps using the specific model

4. CASE STUDIES

4.1. Application of the global model

The global model has been first applied and calibrated on a typical family house. The studied construction work is an existing, two storey residential building, situated near to Timisoara in a rural zone (Figure 4.1. and Figure 4.2).

Figure 4.1. Front view of the studied building

Figure 4.2. Back view of the studied building

The structural skeleton consists of masonry, with load-bearing walls of vertical hollow ceramic blocks, confined by RC columns and belts. The infrastructure is composed of continues RC foundations under the walls. Both ground floor and slab are made of RC, while the roofing system is made of a timber structure. The usable floor area is 122.2 m^2, gross floor area is 162.88m^2, built area on ground is 80.81m^2 and total property area is 300m^2, while the gross volume is 407m^3. Currently no renewable energy sources are available [87].

The sustainability evaluation has followed the procedure described in the previous chapter. Using the project documentation, completed with on-site inspections, the parameters have been calculated successively. In the first phase general data regarding building characteristics, geometry and site location have been introduced. In the second phase the weightings and benchmarks have been calibrated, and the datasets have been verified and completed. The most time and work intensive part represented the quantification and scoring of the parameters. Table 4.1 presents summarily the results of the evaluation.

Table 4.1. Results, benchmarks and scoring of the parameters

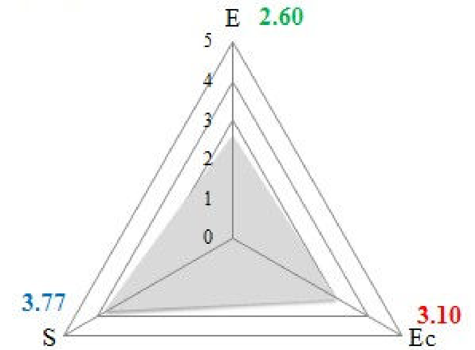
Parameter	**Value**	**Unit**	**Benchmark**		**Score**
			0p	**5p**	
En 1. Initial embodied non-renewable energy in original construction materials	118.14	MJ/m^2/y	150	60	1.77
En 2. Non-renewable embodied energy in all facilities of building operation (HVAC)	671.04	MJ/m^2/y	1048	450	3.15
En 3. Non-renewable embodied energy in construction materials used for maintenance, renovation and replacement works	24.75	MJ/m^2/y	60	20	4.41
En 4. Embodied non-renewable energy in building materials after end of life	13.71	MJ/m^2/y	35	10	4.26
En 5. Use of renewable energy sources	0.00	%	0	15	0
G 1. Initial GHG emissions	9.52	kg CO_2-eq/m^2/y	15.4	6.2	3.19
G 2. GHG emissions from all facilities in the building operation (HVAC)	57.60	kg CO_2-eq/m^2/y	93	40	3.34
G 3. GHG emissions from construction materials used for maintenance, renovations and replacements	1.04	kg CO_2-eq/m^2/y	3.3	1.1	5
G 4. End of life GHG emissions	0.65	kg CO_2-eq/m^2/y	1.9	0.6	4.66
G 5. Heat island effect of the roof	17	%	29	95	0
MR 1. Re-use of existing materials, products and structural elements, if available	0.00	%	0	50	0
MR 2. Material efficiency	963.97	kg/m^3	2000	900	4.71
MR 3. Use of materials with recycled content	1.36	%	0	30	0.23
MR 4. Use of local resources	12.32	km	60	5	4.06
CS 1. Waste from construction and demolition process sent off the site	9.63	%	5	70	0.36
CS 3. Noise produced during construction	82	dB	20	100	2.96
	58	dB	105	70	1.92
LW 1. Construction on contaminated land	Checklist				3
LW 2. Ground occupancy percentage	26.94	%	>30	30	5
LW 3. Potable water consumption by building occupants	174	l/p/d	180	90	0.34
LW 4. Use of grey and rain water	0.00	%	0	30	0

C 1. Initial cost		388.62	Euro/m^2	650	300	3.7
C 2. Operational cost		14.90	Euro/m^2 /y	40	10	4.18
C 3. Maintenance and Repair Cost		4.54	Euro/m^2 /y	25	5	5
CP 1. Erection time		64	man*hr /m^2	120	55	4.3
CP 2. Production rate		6.12	Euro/hr	6	15	0.1
CP 3. Construction Schedules		0.83	-	0.4	0.9	4.3
PM 1. Initial documents		Checklist				2
PM 2. Documents of maintenance and operation		Checklist				0
PM 3. Monitoring of performances		Checklist				3
Ef 1. Long service life		50	Years	25	75	2.5
Ef 2. Area efficiency		75.0	%	70	95	1
Cf 1. Thermal Comfort		5.05	PPD	<15	<6	5
		0.05	PMV	[-7,7]	[-2,2]	5
Cf 2. Noise and acoustic Comfort	RT(60)	1.41	s	>5	[1,2]	5
	Dn,T	37	dB	35	47	1.34
	Ln,w	66	dB	70	58	0.78
Cf 3. Visual Comfort		2.61	%	0.5	3	4.21
IAQ 1. VOC concentration in indoor air		Checklist				3
IAQ 2. CO concentration in indoor air		Checklist				4.5
IAQ 3. Effectiveness of ventilation in natural or mechanical ventilated spaces		0.50	ach	0.3	0.8	2
Sa 1. Protection against earthquake		New building				5
Sa 2. Protection against flood		5500	mm	1000	6000	4.5
AA 1. Access to public transport systems and proximity to user specific facilities.		25	Minutes	30	5	1
		25		50	10	3.13
AA 2. Lifetime homes		Checklist				4.17
AA 3. Adaptability constraints imposed by structure		Checklist				3
AA 4. Adaptability to future changes in type of energy supply		Checklist				3

The results are represented in a very suggestive way, which offer the possibility to identify the strengths and weaknesses of the studied building (Figure 4.3)

Building Sustainability Index BSI
Result Worksheet

	Sustainability categories	Active Weights	Achieved weighted scores
E	**Environmental**	**40.00%**	**2.60**
En	Energy	14.01%	2.72
G	GHG Emissions	9.12%	4.30
MR	Materials and Resources	5.73%	1.64
CS	Construction site	3.65%	2.38
LW	Land Use and Water Consumption	7.49%	1.16
Ec	**Economic**	**30.00%**	**3.10**
C	Cost	13.01%	3.72
CP	Construction process	5.96%	2.83
PM	Project Management	5.96%	2.55
Ef	Efficiency	5.07%	2.50
S	**Social**	**30.00%**	**3.77**
Cf	Comfort	7.07%	3.99
IAQ	Indoor air quality	3.95%	3.00
Sa	Safety	13.15%	4.03
AA	Accessibility and Adaptability	5.84%	3.46



Building Sustainability Index BSI Dimension Scores

BSI ≥ 4 = Very Good
BSI = 3 – 4 = Good
BSI = 2 – 3 = Acceptable
BSI <2 = Insufficient

Building Sustainability Index BSI **3.10** **Good Practice**

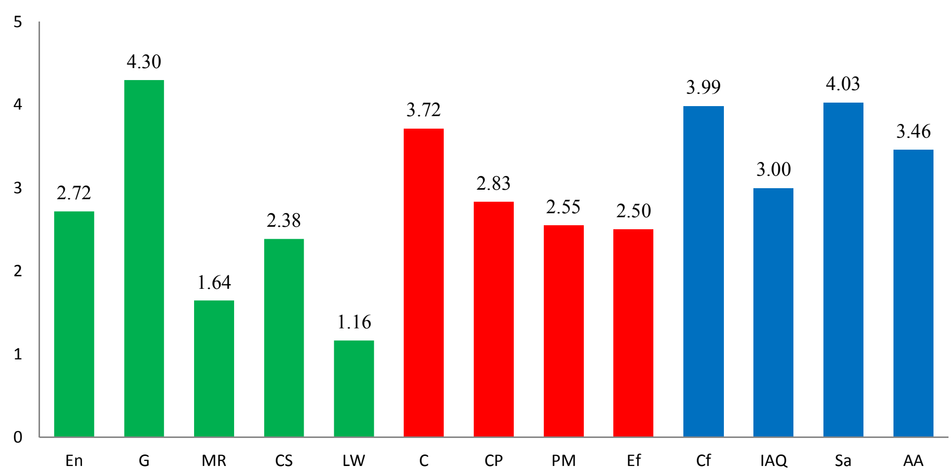


Figure 4.3. Result worksheet of the global model

The Building Sustainability Index of the dwelling is 3.1, which corresponds to a good practice. A total of 46 criteria were used, with about 80% of quantifiable parameters, which contributed to a high degree of objectivism. Evaluating the sustainability performances of the building with the developed global model the following conclusions were drawn:

- low life cycle cost, due to a good thermal insulation of the envelope, which reduces the costs for heating and cooling;
- high comfort resulting from good indoor environment, large surfaces of windows, which permit the access of daylight, and good sound insulation due to the high mass of the walls and slabs;
- high safety because the building respects all prescriptions regarding the design to exceptional loads;
- no re-use or recycling of existing elements or materials;
- no special protection measures on site to limit dust and sound emissions;
- high water consumption, which can be caused either by impropriate sanitary fixtures or by the occupants' usage;
- only mandatory documents were available, without the implementation of any sustainability issues, or alternative solutions;

4.2. Application of the specific model

4.2.1. Rehabilitation of the Western University of Timisoara, Romania

The Western University of Timisoara, built in 1962-1963, has many buildings, among them the „Main Building" that is used as administrative part as well as classrooms for students. The RC structure consists of:

- transversal and longitudinal frames with eight stores and two spans of 5.6 m and eleven bays of 3.8m;
- floors with girder mesh in two directions and a slab of 100mm;
- foundation with a thick slab and deep beams in two directions.

From the visual examination and non-destructive measurements no important damages of the RC structure were observed. Performing a structural analysis, including seismic action at present-day level, the following issues were noticed:

- the drift limitation conditions are not within the admissible limits at the ground store;
- weakness of reinforcement and insufficient anchorage of beam-positive reinforcement at the beam-column joint, especially in longitudinal direction.

Rehabilitation solutions consist in strengthening of the columns located at the ground storey. Some columns were strengthened in 1999 to prevent local damages due to reinforcement corrosion, while the others were rehabilitated in 2004 for decreasing the lateral displacement and for homogeneous column stiffness at the ground storey [88].

Different solutions have been proposed for the strengthening of the columns: coating with steel profiles, reinforced concrete jacketing, and composites based on CFRP (lamellas and sheets). Details of the solutions are presented in Figure 4.4.

Analysing the characteristics of the solutions, several parameters from each dimension of sustainability have been selected for evaluation, the ones which were considered the most representative for a correct comparison. These parameters are the following: CO_2 emissions arising from the manufacturing, transport and execution of the building materials, total cost, consolidating time (workload), inscrease of the capable bending moment and stiffness of the consolidated element. To quantify the parameters, different databases, codes and bulletins have been used [53], [54], [89], [90], [91].

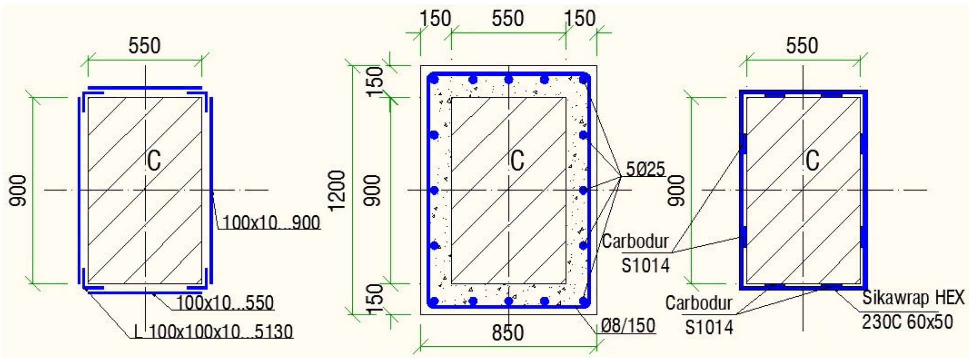


Figure 4.4. Strengthening solutions using steel profiles, RC jacketing and CFRP

Adjusting eq. (3.26) the sustainability index resulted from:

$$SI = 0.4 \times \frac{G^R}{G} + 0.2 \times \frac{C^R}{C} + 0.1 \times \frac{W^R}{W} + 0.1 \times \frac{\Delta B}{\Delta B^R} + 0.2 \times \frac{K}{K^R} \tag{4.1}$$

Where G, G^R, C, C^R, W, W^R, ΔB, ΔB^R, K, K^R are given in Table 4.2.

Table 4.2. Rehabilitation of the Western University using different solutions

Western University of Timisoara				
Rehabilitation solution / **Parameters**	**Steel Profiles**	**RC Jacketing**	**CFRP**	**Reference**
CO_2 , G, Emissions [kg/m^2]	41.70	93.1	25.47	25.47
Cost, C, [Euro/m^2]	91.66	68.4	155.70	68.4
Workload, W, [man-hour/m^2]	4.29	5.9	1.86	1.9
Increase of bending moment, ΔB, [kNm/m^2]	62.37	57.2	58.26	62.37
Stiffness, K, [kNm/m^2]	241.61	292.6	169.13	292.62
Sustainability Index SI	0.702	0.633	0.797	1

Each solution showed advantages and disadvantages: coating with CFRP had by far the lowest CO_2 emissions and shortest consolidating time, but without assuring the drift limitation conditions, which was the main objective of the rehabilitation. Furthermore, it was very expensive; RC jacketing resulted in a good stiffness, relative good price, but high workload in comparison to coating with steel profiles. By applying the specific model, the most sustainable solution proved to be the CFRP procedure; RC jacketing and steel profiles have comparably *SI*, but as final solution the coating with steel profiles has been applied due to its stiffness.

4.2.2. Rehabilitation of the Timisoreana Brewery, Romania

The Timisoreana Brewery is a reinforced concrete framed structure, with one section composed of five storeys and a tower of nine storeys. The brewery and the tower were built in 1961 and the extension in 1971.

The industrial building's vertical structure is a spatial frame, while the foundation system consists of isolated RC foundations under columns. The RC monolithic floors are made of main girders, secondary beams and a one way reinforced slab.

From the visual examination and non-destructive on site assessment several problems have been identified at slabs, main girders, secondary beams and columns:

- concrete cover spalled over large surface;
- complete corrosion of many stirrups and deep corrosion of main reinforcement;
- some broken reinforcement;
- dangerous inclined cracks;

The damages were mainly produced by concrete carbonation and chloride ion penetrations, favoured by high RH (≈80%) and temperature (over 40°C).

By performing a structural analysis, including seismic action at present-day level, the following were noticed:

- high vulnerability to seismic actions due to structural irregularities;
- some elements were characterized by inadequate longitudinal reinforcement (column) and shear reinforcement (beams).

The necessary rehabilitation of the RC structure was adopted for all types of damages and has been performed in two steps. First, in 1999 the main girders, secondary beams and the columns were strengthened for both local damage and inadequate reinforcement, by jacketing with reinforced concrete.

In 2003 due to continues operation and subsequent damage of the structure, a new assessment was required. It was found that some beams and one column were characterized by inadequate longitudinal reinforcement and shear reinforcement as well as corrosion of many stirrups at beams. The strengthening solution adopted was based on CFRP composites [92].

As in the case of the Western University of Timisoara, different rehabilitation solutions were proposed. Details of the solutions are presented in Figure 4.5 and Figure 4.6.

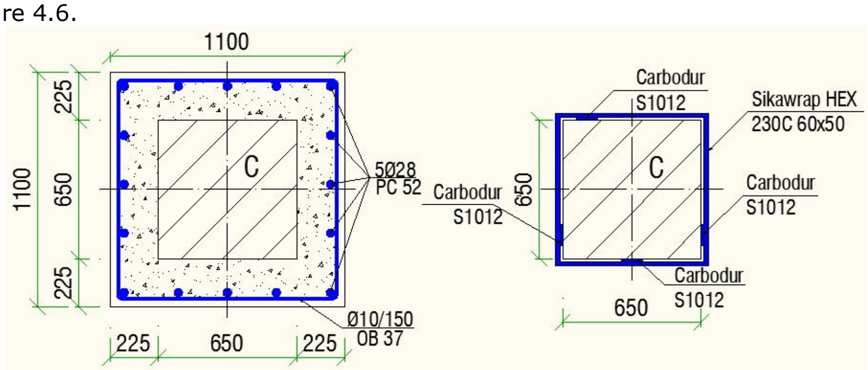


Figure 4.5. Strengthening of the column by RC Jacketing and CFRP composites

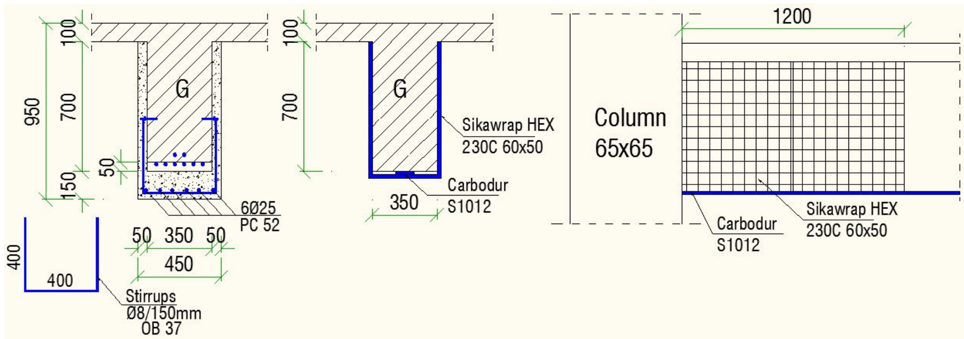


Figure 4.6. Strengthening of the girder by RC Jacketing and CFRP composites

The calculation procedure of the sustainability index has been similar to the previous example but with slight modifications (structural stiffness was not a problem of vulnerability). The results are summarized in Table 4.3, separately for column and girder.

Table 4.3. Rehabilitation of the Timisoreana Brewery using different solutions

Timisoreana Brewery						
Rehabilitation solution	**Column**			**Girder**		
Parameters	**RC Jacketing**	**CFRP**	**Ref.**	**RC Jacketing**	**CFRP**	**Ref.**
CO_2 Emissions, G, [kg/m^2]	141.19	14.88	14.88	25.32	7.75	7.75
Cost, C, [euro/m^2]	92.20	85.23	85.23	36.77	40.73	36.77
Workload, W, [man-hour/m^2]	8.58	1.84	1.84	32.34	9.19	9.19
Increase of bending moment, ΔB, [kNm/m^2]	55.07	11.65	55.07	64.03	20	64.03
Sustainability Index SI	0.548	0.763	1	0.751	0.774	1

For both elements, the most sustainable solution was proved to be the coating with CFRP. In 1999 the solution with RC has been chosen due to the lack of experience of the authors in the field of CFRP at that time. In 2003 the sustainable solution has been applied fulfilling all technical and technological requirements.

4.2.3. Transportation of prefabricated RC elements

The aim of this example is to demonstrate the applicability of the specific model also on other types of construction activities. An industrial hall made of prefabricated reinforced concrete elements has to be transported from Timisoara to Galati (690km on road). The structure consists of 97 elements (beams and columns), weighting 450t. Due to the great mass, four transport opportunities have been evaluated: on road by trucks, on railway by train, on inland water (Danube River) by barge and a combined solution by truck and barge, because in many situations there is no direct access on inland water (like in case of Timisoara).

For the sustainability evaluation of each transport method different parameters have been assessed. The most important were the CO_2 emissions, costs, transport duration, emissions of dust and noise. To calculate the sustainability index the following scenarios have been considered:

Scenario 1 – The transport on road is done by trucks with cargo capacity of 20t. The distance is 690km. The elements are handled using ones at loading and ones at downloading. Noise is considered as the highest level of sound produced by the convoy of trucks [93].

Scenario 2 – The transport on railway is done by freight trains with cars up to 50t loading capacity on a distance of 720km. Having rail access to the manufacturer, the elements are loaded directly into the cars, skipping supplementary handling. At the final destination the elements will be handled twice. The noise level of the train has been considered at a speed of 70km/h [94].

Scenario 3 – The combined transport is necessary because Timisoara has no direct access on the Danube River. The elements are transported on road by trucks to Moldova Noua (150km), from there to Galati on barges (950km), repeating the load and download process two times. The noise level of trucks has been considered in this scenario.

Scenario 4 – This scenario considers that the entire transport is done on water, with two processes of loading and downloading. Because barges have no disturbing effect on settlements, the minimum noise level imposed by standards has been considered.

For all scenarios, the values for specific CO_2 and dust emissions, costs and duration were taken from different databases and catalogues [95] [96] [97] [98], [99], [100]. All specific values were obtained for a cargo of 450t and the minimum distance of 690km.

Adjusting eq. (3.26) the sustainability index resulted from:

$$SI = 0.4 \times \frac{G^R}{G} + 0.2 \times \frac{C^R}{C} + 0.1 \times \frac{D^R}{D} + 0.1 \times \frac{PM^R}{PM} + 0.2 \times \frac{N^R}{N} \qquad (4.2)$$

The results are summarized in Table 4.4.

Table 4.4. Transportation of prefabricated RC elements by different means

Transport of prefabricated RC elements Timisoara - Galati						
Transport solution	**Truck 690km**	**Train 720km**	**Combined**		**Only Barge 1100km**	**Ref.**
Parameters			**Truck 150km**	**Barge 950km**		
CO_2 Emissions, G, kg/1000tkm]	123.13	24	46.14		22.43	22.43
Cost, C, [Euro/1000tkm]	39.4	56.04	35.26		0.04	0.04
Duration, D, [hour/1000tkm]	0.11	0.12	0.30		0.31	0.11
Dust (PM10+VOC), PM, [g/1000tkm]	0.13	0.04	0.06		0.04	0.04
Noise, N, [dB]	90	110	90		50	50
Sustainability Index SI	0.305	0.689	0.412		0.931	1

Each mean of transport shows advantages and disadvantages. Transportation on water is by far the most sustainable solution, even if the duration time takes longer than for other cases. But its main disadvantage represents it's applicability. Barges need ports and access to water, which is not possible in all situations. Like in the case of Timisoara – Galati, a combined alternative was proposed. Transport by trucks to the nearest port and then further on water. Due to great CO_2 and dust emissions of the trucks this alternative resulted to be the less sustainable solution. Transport by freight trains resulted to be the most viable solution in this situation. Transport by trucks is suitable for smaller cargos and for places where none of the above mentioned means can be applied, due to the lack of infrastructure.

5. SPECIAL ASPECTS OF CONCRETE STRUCTURES. CO_2 UPTAKE THROUGH CONCRETE CARBONATION

5.1. Theoretical background

5.1.1. Cement and concrete chemistry

The most important constituant of concrete is cement. The main mineral compounds of Portland cement clinker are [101]:

- Tricalcium silicate: $3CaO.SiO_2$ – C_3S – Alit
- Dicalcium silicate: $2CaO.SiO_2$ – C_2S – Belit

} = 75%

- Tetracalcium aluminoferrite: $4CaO.Al_2O_3.Fe_2O_3$ – C_4AF – Celit I
- Tricalcium aluminate: $3CaO.Al_2O_3$ – C_3A – Celit II
- Gypsum: $CaSO_4.2H_2O$

} = 25%

The cement clinker also contains free CaO and MgO, but only in limited quantities.

Alite constitutes the largest part and is the most important phase in strength development up to 28 days. Belite makes up 15-30% of the cement clinker mass and it is important in later strength development, typically after 28 days, as it reacts slowly with water. Ferrite, which constitutes about 5-15% of cement clinker, reacts very quickly with water but this can be rather variable due to the ratio of iron and aluminium present in the phase. The fourth major mineral compound, Aluminate, ranges between 5-10% in Portland cement clinker and it reacts very quickly with water so it can cause very fast setting. This is the reason why gypsum is added to cement in order to controll the setting of the aluminate phase.

The binding quality of portland cement paste is due to the chemical reaction between the cement and water, called hydration. The hydration of these compounds contributes to the formation of products which are involved and responsible for carbonation and recarbonation. The hydrated cement in concrete has a complex chemistry and physical structure. The reactions involved are more complex than the simple conversion of anhydrous compounds to their respective hydrates, with full hydration taking a long time to achieve [102]. Cement chemistry reactions are therefore written as sums of their oxide composition [103]:

$$3CaO \cdot SiO_2 + mH_2O \rightarrow xCaO \cdot SiO_2 \cdot pH_2O + (3-x)Ca(OH)_2 \quad (5.1)$$

$$2CaO \cdot SiO_2 + nH_2O \rightarrow xCaO \cdot SiO_2 \cdot pH_2O + (2-x)Ca(OH)_2 \quad (5.2)$$

$$3CaO \cdot Al_2O_3 \cdot Fe_2O_3 + 3CaSO_4 + nH_2O \rightarrow 3CaO \cdot Al_2O_3.Fe_2O_3 \cdot CaSO_4.pH_2O \quad (5.3)$$

$$3CaO \cdot Al_2O_3 \cdot +3CaSO_4 + 26H_2O \rightarrow 3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O \quad (5.4)$$

Summarised, the four main products of cement hydration are:

- $Ca(OH)_2$ – Calcium hydroxide *(CH)* (Portlandite);
- $CaO \cdot SiO_2 \cdot pH_2O$ – Calcium silicate hydrate (*CSH*);
- $3CaO \cdot Al_2O_3.Fe_2O_3 \cdot CaSO_4.pH_2O$ –Tetracalcium aluminate ferrite monosulfate hydrate (*AFm*);
- $3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$ – Ettringite (*AFt*)

The hydration of the calcium silicate phases are the most important reactions in relation to concrete strength development. The main product of the hydration of C_3S is a nearly amorphous material – Calcium Silicate Hydrate CSH and calcium hydroxide CH. CSH forms up to about 60% by volume of the paste and has the property of a rigid gel. They both play an important role in the re-carbonation process. The hydration of C_2S behaves similarly, but much less CH is formed and the reaction is slower. The hydration of C_4AF forms very few stable structures. It combines initially with gypsum and lime to form high-sulfate sulfoaluminate and sulfoferrite. Once all the sulfate has been consumed it undergoes a similar transition to C_3A and transforms into the low-sulfate aluminoferrite solid solution and a more intricate solid solution phase where the sulfate ion is replaced by a hydroxyl ion. Both the hydration of aluminate and ferrite has been shown to be retarded by both gypsum and CH [104].

5.1.2. Mechanism of carbonation and re-carbonation

Understanding the chemistry and mechanism of concrete carbonation is very important in order to appreciate the re-carbonation process and inclusive the uptake capacity of concrete. As a general definition, carbonation is the natural reverse process of the decarbonisation. The deliberated CO_2 in the atmosphere reacts with the hydration products of the hardened cement to form limestone ($CaCO_3$) (Eq. 5.5).

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (5.5)$$

For the formation of calcium carbonate three components are necessary: carbon dioxide, calcium phases and water. The first component is present in the atmosphere, however, it cannot react directly with the hydrates of the cement paste. Thus the CO_2 gas must first dissolve in water and form carbonate ions that in turn will react with the calcium ions of the pore water [105]. The other components are obtained by the hydration of cement during the mixing of concrete.

When CO_2 comes into contact with water at neutrality it forms bicarbonate. Inside concrete, the pH is high and as a result, the bicarbonate dissociates and forms carbonate ions. Thus in the carbonated layer bicarbonate forms, but closer to the uncarbonated cement paste the carbonate ions form (due to higher pH) and precipitate calcium carbonate crystals (CC). The sequential mechanism that takes place during the carbonation of cementious materials are illustrated in Figure 5.1. The individual steps of the sequences and the chemical process which take place are [105], [106], [107], [108]:

1. Diffusion of CO_2 in air;
2. Permeation of CO_2 through the solid;
3. Solvation of $CO_{2(gas)}$ to $CO_{2(aquatic)}$;

4. $CO_{2(aq)}$ dissolvation in the pore water, forming carbonic acid (H_2CO_3)
5. Ionisation of carbonic acid, which can react with the calcium ions of the pore solution; this occurs almost instantaneously, making the pH fall by approximately 3 units, typically from 11 to 8.

$$CO_2 + H_2O \rightarrow H_2CO_3 = HCO_3^- \text{ (bicarbonate ion)} + H^+ \tag{5.6}$$

$$HCO_3^- = CO_3^{2-} \text{(carbonate ion)} + H^+ \tag{5.7}$$

6. Dissolution of cementitious phases C_3S and C_2S. Because the process is cyclic, this step is rapid and extensive and generates a considerable exotherm reaction. The calcium silicate grains are covered by a loose layer of calcium silicate hydrate gel, which is quickly dissolved.

$$Ca^{2+} + CO_3^{2-} = CaCO_3 \tag{5.8}$$

$$H_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2H_2O \tag{5.9}$$

7. Nucleation of $CaCO_3$, CSH. The nucleation is favoured by slightly high temperatures and the presence of finely divided material, which acts like heterogeneous nuclei.

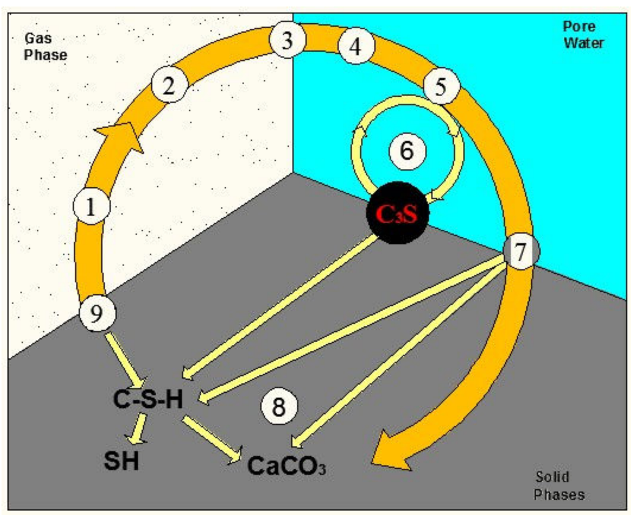


Figure 5.1. Carbonation reaction mechanism
Adapted from [107], [108].

8. The dissolution of solid calcium hydroxide, with the solubility of $9.95\text{x}10^{-4}$ and the precipitation of Ca^{2+} with CO_3^{2-} forming $CaCO_3$ with a solubility of $0.99\text{x}10^{-8}$, followed by the reaction with silicates and aluminates. At the beginning, vaterite and aragonite can be formed, but these polymorphs of $CaCO_3$ ultimately revert to calcite. Amorphous calcium carbonate can be found in the final product.

$$Ca(OH)_2 = Ca^{2+} + 2OH^- \quad (5.10)$$

$$3CaO \cdot 2SiO_2 \cdot 3H_2O + 3CO_2 \rightarrow 3CaCO_3 + 2SiO_2 + 3H_2O \quad (5.11)$$

$$4CaO \cdot Al_2O_3 \cdot 13H_2O + 4CO_2 \rightarrow 4CaCO_3 + 2Al(OH)_3 + 10H_2O \quad (5.12)$$

9. Secondary carbonation. CSH gel forms and is progressively decalcified, converting ultimately to SH and $CaCO_3$

Because calcium carbonate has a much lower solubility than calcium hydroxide, it will dissolve so calcium carbonate will precipitate and the process will continue until all of the CH is consumed. This process drops the pH which assured the equilibrium between CH, CSH, AFm and Aft. So when the CH is consumed, CSH will dissolve congruently, followed by the monosulphate and ettringite. The release of calcium ions from the CSH will form more CH that will undergo recarbonation. Once recarbonated, CSH yield CC and silica gel. Most of the calcium from CSH will be bound to CC, but some will always remain in silica gel [105].

Adapted from [105], [109], [110] the phase changes in the hydration products can be described according to Figure 5.2.

pH	Calcium hydroxide; $Ca(OH)_2$	Calcium Silicate Hydrate; $\alpha 2CaO.SiO_2.nH_2O$; $\alpha > 1.5$		Monosulphate hydrate; $3CaO(Al,Fe)_2O_3CaSO_4$ $12H_2O$	Ettringite: 3CaO $Al_2O_3.SO_3 32H_2O$
12.5	CH (solubility $9.95x10^{-4}$)	CSH(1)	CaO/SiO_2 1.65	AFm	AFt
12 / 11.6	CC: $CaCO_3$ (solubility $0.99x10^{-8}$	CSH(1); CC	1.65	AFm	AFt
11 / 10.5	CC	CSH(2); CC	0.9-1.45	AFt/$Fe(OH)_3$; CC	AFt
10 / 9.54	CC	CSH(3); CC	0.8 <0.5 0.11	$Fe(OH)_3$; $Al(OH)_3$; CC	$Al(OH)_3$; CC
9	pH=9.54 upper range of phenolphthalein colour change				

Cement stone components

Figure 5.2. Phase changes of hydration products at different pH values

At a pH level of above 12.5, where the concrete is not carbonated, the solid phase assemblage consists of CH, CSH, AFm and Aft. The CSH phase of non-carbonated concrete has a Ca/Si ratio in the range of 1.5-1.8 [104]. At around a pH of 11.6 the AFm (monosulphate) will decompose into ettringite and aluminate compounds. At around 10.5 Aft (ettringite) will decompose resulting in sulphate ions and aluminium hydroxide compounds.

Chen et al. [109] showed that the Ca/Si-ratio of CSH decreased with decreasing pH from values around 1.5 down to 0.11 at pH of 9.54. A pH of 9.54 is in the upper range of the phenolphthalein colour change interval, suggesting that the Ca/Si-ratio of CSH in carbonated paste is even lower than 1.5. Stronach and Glasser [111], based on thermodynamic modelling of the $CaO–SiO_2–CaCO_3–H_2O$ system at 25°C, found an invariant point at pH 10.17. At this pH, CSH, calcite and amorphous SiO_2 were found to coexist with the CSH having a Ca/Si ratio of 0.8. At a pH of 9.15, another invariant point was found with the presence of only amorphous silica and calcite [112].

Carbonation gives rise to volume and mass. The transformation of CH to calcite gives a volume change of 11%, while to metastable vaterite an increase of 14%. The volume change in the transformation of the CSH is, however, more uncertain and depends on the water content of the silica gel. The volume changes affect the porosity in the carbonated layer and thus the speed of diffusion. It is known that the volume changes do not affect the mechanical stability of the carbonated layer, which is stable and hard. This indicates that, normally, the surplus volume of calcite precipitation mainly fills empty space in the capillary system and thus densifies the cement paste. [105].

5.1.3. Rate of carbonation

Carbonation of cement-based materials is a natural process, which starts from the surface subjected to air and moves inwards. Concrete carbonates whenever carbon dioxide and water are available, although the rate of carbonation depends mainly on how fast the carbon dioxide ions can difuse in the concrete and how the cement hydration products can react with them. Adapted from [107] Figure 5.3. shows the factors which have an influence on the carbonation rate.

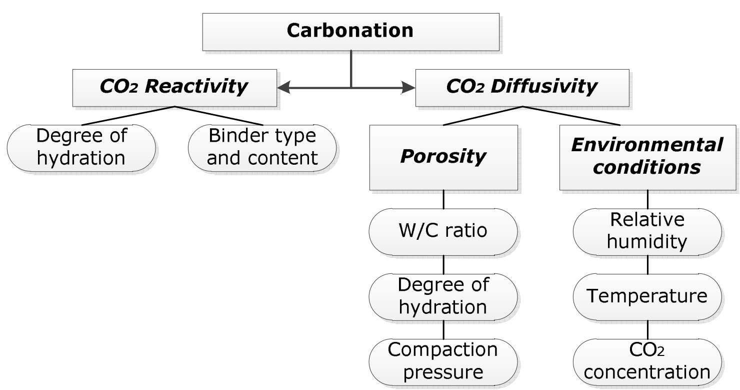


Figure 5.3. Factors which influence the rate of carbonation

Carbonation is a mass transport process which can be controlled by the law of diffusion. Concrete carbonation models are generally based on Fick's first law of diffusion, according to which the carbonation depth can be described by Eq. (5.13),

$$d = k \cdot \sqrt{t} \tag{5.13}$$

where *d* is the carbonation depth, *k* represents the rate constant, while *t* is the exposure time [103].

The carbonation rate constant has been treated by several authors, considering a variety of concrete compositions and environmental conditions [113], [114], [115], [116], [117]. Bob in [116] has first proposed a useful and practical calculation method of the carbonation depth in normal environmental conditions, which took into account the compressive strength of concrete f_c, but also other important factors as the effect of different cement types *c* and the relative humidity in different exposure conditions *k*. Later it has been modified based on the tests in [117] and [118] for accelerated carbonation of different CO_2 content *d*, according to Eq. (5.14).

$$\bar{x} = \frac{150 \cdot c \cdot k \cdot d}{f_c} \cdot \sqrt{t}\,[mm] \tag{5.14}$$

For concretes of identical exposure conditions and degree of hydration, the rate of carbonation is determined mainly by the capillary porosity and permeation properties, which define the concrete strength. Lower water/cement or water/binder ratio and high degree of hydration result in denser concrete with less connective porosity. It will also result in denser carbonate products and consequently will slow down carbonation in all environments.

Categorized after compressive strength, the carbonation rate constants in normal exposure conditions, using pure Portland cement (CEM I 42.5), can be chosen from Table 5.1 [116], [117]. As it is visible in Table 5.1, the rate constant varies from 3.3 to 15, which underlines the importance of concrete quality on carbonation.

Table 5.1. Carbonation rate constants for various concrete strengths

CEM I 42.5, CO_2=0.03%, Indoors	Compressive strength (MPa)								
	12	16	20	25	30	35	40	45	>45
	$(mm/\sqrt{year})$								
	12.5	9.4	7.5	6.0	5.0	4.3	3.75	3.3	3.0

The estimated carbonation rate constants presented in Table 5.1 are valid for concrete made of CEM I 42.5 cement (95% clinker), exposed indoors and under normal CO_2 concentration level. The carbonation rate may be affected by different factors and so the rate constant needs to be corrected. The correction factors proposed in [116], [117] and [118] are presented in Table 5.2.

Table 5.2. Correction factor for different cement types, RH and CO_2 concentrations to be multiplied by the rate constant provided in Table 5.1

Cement type	**c**	**Exposure Conditions**	**k**	**CO_2 Concentration**	**d**
CEM I 52.5	0.8	Indoors	1	0.07	1.05
CEM II A	1.2	Sheltered	0.7	0.1	1.1
CEM II B	1.4	Exposed	0.5	0.15	1.2
CEM III A	2	Wet/ Buried	0.3	50	2.7

Lagerblad [105], based on literature review, also suggested various carbonation rate constants for concrete of different strengths and exposure conditions, as shown in Table 5.3 and Table 5.4.

Table 5.3. Carbonation rate constant for different concrete strengths and exposure conditions

Environment	**Cylinder compressive strength (MPa)**			
	<15	15-20	25-35	>35
	$k = mm / \sqrt{year}$			
Wet/Submerged	2.0	1.0	0.75	0.5
Buried	3.0	1.5	1.0	0.75
Exposed	5.0	2.5	1.5	1.0
Sheltered	10.0	6.0	4.0	2.5
Indoors	15.0	9.0	6.0	3.5

Table 5.4. Correction factors for binder type and concrete surface cover

Binder wt. %	<10	10-20	20-30	30-40	40-60	60-80	**Concrete Surface cover**	
Limestone		1.05	1.10					
Silica fume	1.05	1.10					Indoor	0.7
Fly ash		1.05		1.10			Outdoor	0.9
GBFS	1.05	1.10	1.15	1.20	1.25	1.30	Infrastructure	1.0

The binder type has a great influence on the carbonation rate. If the concrete is prepared with other cement type, the rate constant may be affected either positively or negatively. Using a higher quality of cement (CEM I 52.5) leads to a better binding capacity, which slows down the carbonation mechanism. Ordinary Portland Cement (CEM I) has been the most common type used, but the addition of cement replacement materials in order to obtain blended cement became an important practice. The most common additives are limestone, granulated blast furnace slag GBFS, fly ash, silica fume and volcanic ash, as listed in EN 197 [119]. These additives can be divided into inert mineral fillers, latent hydraulic binders and pozzolanas.

Portland cement with limestone addition (CEM II/L, CEM II/LL) contains ultrafine grinded calcite particles, accounting for about 10% to 20%. This blended cement develops the same strength as CEM I, because the ultrafine particles become an integrated part of the cement paste [120]. The proportion between the different hydrate phases is the same as in CEM I, so it can be assumed that in the same environmental conditions, concrete with this blended cement may present a similar carbonation rate.

Portland cement mixed with blast granulated furnace slag (GBFS) of different proportions (CEM II/A-S – 20%, CEM II/B-S – 35%, CEM III – 35%–95%) contains less CH and more CSH. Thus the carbonation process and the structure of the carbonated paste will be different. According to [111], Portland cement combined with this latent hydraulic binder results in a faster carbonation process, mainly due to the fact that the carbonated concrete forms a coarser pore structure, which enhances the speed of the diffusion. On the other hand, [121] stated that the carbonation is faster only in the beginning, but the rate is similar to OPC in old concrete.

Fly ash and silica fume are both pozzolana, which can be added to cement either at the factory or mixed with Portland cement directly in concrete. The amount added to the cement can vary, also becoming major component of the cement (CEM III and CEM IV). As every pozzolana, fly ash and silica fume are leading to the consumption of CH, while the amount of CSH increases. They both change the mode and rate of carbonation, and also the structure of the carbonated layer. Silica fume is the most efficient pozzolana and it reacts early on in the hydration process while fly ash will react with already formed CH. The experimental studies found in the specialized literature showed that concrete containing fly ash or silica fume has an increased rate of carbonation, depending on the amount of additive. The amount of calcium ions to be carbonated is less in cement with pozzolana thus, the carbonate ions can penetrate to a greater depth, leading to an increased carbonation rate and therefore to an increased CO_2 sequestration, proportional with the amount of replaced cement [114], [122], [123], [124], [125].

In general the additives are reducing the clinker content per united volume of concrete, which reduces the amount of hydration products that can carbonate. On the other hand the higher the amount of additives, the higher the carbonation rate.

The effects of the atmospheric conditions on carbonation rate, in terms of temperature, humidity and carbon dioxide pressure, must also be taken into consideration. The rate of diffusion and rate of the carbonation reaction are increasing with temperature. Thus indoor climate or exposure in warmer regions will lead to faster carbonation, if all the other factors remain constant [126], [127].

It is known that water is needed for the carbonation process to occur. Gas diffusion in a dry capillary system is rapid but the carbonation mechanism demands formation of carbonate ions, which in turn demands water [105]. On the other hand concrete that is wet or submerged in water has a slow carbonation rate. Pores are saturated and gaseous CO_2 has difficulties in the diffusion process. These considerations led to the interval of relative humidity RH, where the carbonation rate is at maximum level. The most favorable RH for carbonation is between 50 and 70%, which corresponds mainly to indoor conditions [128]. For sheltered, exposed and wet concrete the carbonation rates may be reduced.

Also the CO_2 content in the atmosphere has a great influence on carbonation. The effect of a higher carbon dioxide concentration is an increased carbonation rate, as it can be seen in the correction factors from Table 5.2.

5.2. CO_2 cycle in concrete structures

In its plain, reinforced or prestressed form, concrete is the most widely applied building material worldwide. It is essential to our modern society as it provides a cost-effective and durable material to nearly all types of infrastructural installations (e.g. bridges, tunnels, dams, *etc*.), buildings and houses.

The life cycle of RC structures can be divided into primary and secondary life. The primary life starts with the extraction and manufacturing of the raw materials for cement and concrete production and ends with the demolition of the built structure. The secondary life commences when the demolished concrete is recycled and re-used in different applications in the form of recycled concrete aggregate, road base, *etc*. It ends when the newly built construction reaches the end of its service life.

Like most other construction works, the execution of concrete structures implies a great amount of CO_2 emissions into the atmosphere which are mainly related to the manufacturing and transport of the component materials, but also to construction related processes. On the other hand in some stages during its life cycle, carbon dioxide can be saved through the use of cement replacements or slowly absorbed by concrete through carbonation. Figure 5.4 presents summarized the carbon life cycle of a typical RC structure.

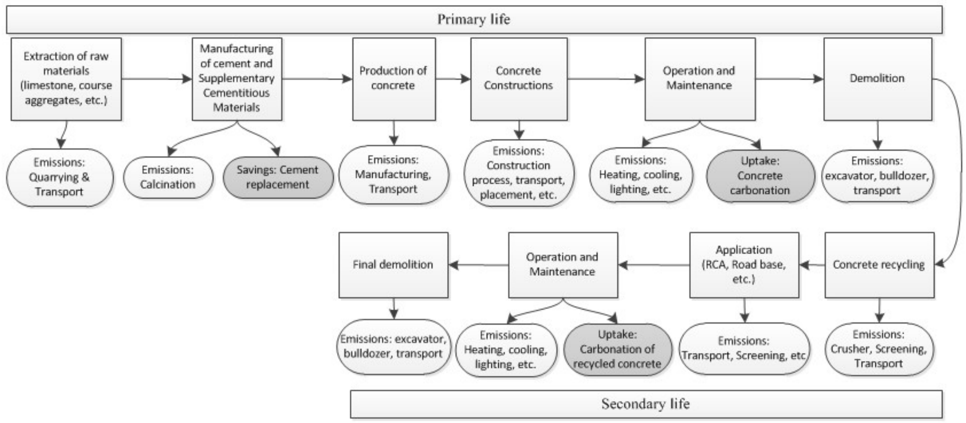


Figure 5.4. Life cycle consideration of CO_2 emissions and uptake in RC structures
Adapted from [129]

5.2.1. Manufacturing of raw materials

Limestone, granite, marble, natural sand and gravel are mined in quarries and are further processed for different construction utilities. The main CO_2 emissions are arising from the combustion of fuels consumed by machineries for quarrying and transportation and from the electricity needed for further processing of the materials: washing, drying, screening, crushing, sorting, *etc*. The final products are used either as raw material for cement production or as bulk of concrete mixture, in form of fine and course aggregates.

The major part of the CO_2 emission resulting from concrete production is related to the manufacturing of the cement. Cement is a hydraulic and clinkerization binder which has the property to harden when it is mixed up with water. The main component of cement clinker is limestone, for about 95%, but also some correction addititives are used, like: gypsum, bauxit, roasted pyrite, *etc*.

In order to produce cement, the components are ground together either wet or dry. The obtained raw material, called raw meal, is introduced in a cement kiln. This is a rotary calciner kiln, with a length of 50-150m, a diameter of 2.5-3.5m, an inclination of 2-3 grade and with 1-2 rotations/minute. The raw meal is burned at 1400-1450^{0}C. In this heating process CO_2 is released from the limestone to obtain the cement clinker. The resulted product consists of mineral residue containing calcium oxide (CaO), together or without iron (Fe), aluminium (Al), or silicor (Si). Finally the cement clinker is ground together with gypsum, in order to prolong the binding time of cement [130].

The decarbonisation begins at 600^{0}C and continues till the temperature reaches around 908^{0}C, when the decarbonisation is complete. The chemical process of the decarbonisation is:

$$CaCO_3 + (600\text{-}908^0C) \rightarrow CaO + CO_2 \qquad (5.15)$$

In modern cement production the total CO_2 emission per produced metric ton of clinker is normally 800-900 kg. Average cement clinker contains about 63%-64% CaO. So the production of 1 metric ton of clinker results in about 495 kg of deliberated CO_2 from calcination. The remaining emissions are arising from thermal energy, the burning of fossil fuels, electricity and transportation.

The cement can be partly substituted by supplementary cementitious materials, such as ground granulated blast furnace slag, a waste by-product from steelmaking, and fly ash, a fine waste residue that is collected from the emissions liberated by coal burning power stations. These materials can reduce significantly the emissions of CO_2, as they replace a part of the cement with waste by-products, whose processing contribute to much lesser emissions.

5.2.2. Concrete production, construction stage, demolition and recycling activities

Concrete is a composite construction material, which is produced by mixing together cement with fine aggregates (sand), course aggregates (gravel or crushed stone) and water. Small amounts of chemical admixtures can be added to improve workability in the fresh state. The properties of concrete in the fresh and the hardened state, as well as the environmental impacts, are determined by the type of cement (OPC or blended cement), the additives and the overall proportions (the mix design) of the components. The major source of emissions originates from cement. The contribution of concrete preparation and construction process related activities to the overall emissions is relative small, counting for about 13-24% [129]. Of course, the emissions can vary depending on transportation distances. The CO_2 sources originate from concrete mixing, transportation, placement and curing. Further emissions can occur if temporary structures (supports, form works, *etc*.) are needed. So the CO_2 emissions can range from 112 kg/m^3 for a 20-MPa concrete with 50% slag cement to 313 kg/m^3 for a 35-MPa concrete [7].

After the expiration of the service life, the structure is demolished and the concrete rubble can be recycled. The demolished concrete is processed to recycled concrete aggregate RCA, which can replace natural or crushed aggregates in road applications or other concrete production. The crushing, screening and storage of RCA can be made in plants or on site, using mobile pneumatic breakers and other portable equipment. The CO_2 emission sources due to demolition and recycling originate mainly form the combustions used by the machineries and equipment for demolishing, crushing, screening, loading and transportation of the RCA. The contribution of this life cycle stage to the overall environmental impact is similar to the impact from the construction stage [131], or can be even negligible [129].

5.2.3. CO_2 uptake through carbonation during primary and secondary life

Concrete has a documented ability to chemically react with carbon dioxide through carbonation. In order to calculate the uptake, the following input data are required:

- concrete composition and properties: cement type and dosage, compressive strength;
- exposed surface area, treatment and cover;
- environmental conditions of the exposed surface;
- carbonation rate;
- degree of carbonation.

If all parameters are available, the uptake during primary life can be calculated using the formula presented in [105], [131].

The uptake in secondary life is considerably higher. RCAs have a significantly larger surface than the original structure and thus the carbonation takes place much faster. The additional data required for the calculation of the uptake are the amount of concrete rubble processed to RCA and the size and distribution of the crushed particles. The depth of carbonation is based on the same principle as in service life, while the differences are related to the consideration of the surface areas and volume of carbonated concrete, as presented in [131], [132].

In [131] the carbon dioxide balance is exemplified on 1m^2 of typical roof tile with a weight of 42kg and service life of 50 years. It is an outdoor element, with a strength class of >35MPa. After demolition it is assumed that 90% of the material is reused as recycled concrete aggregate (RCA). The balance has been calculated with a special developed calculation tool. The result is presented in Figure 5.5.

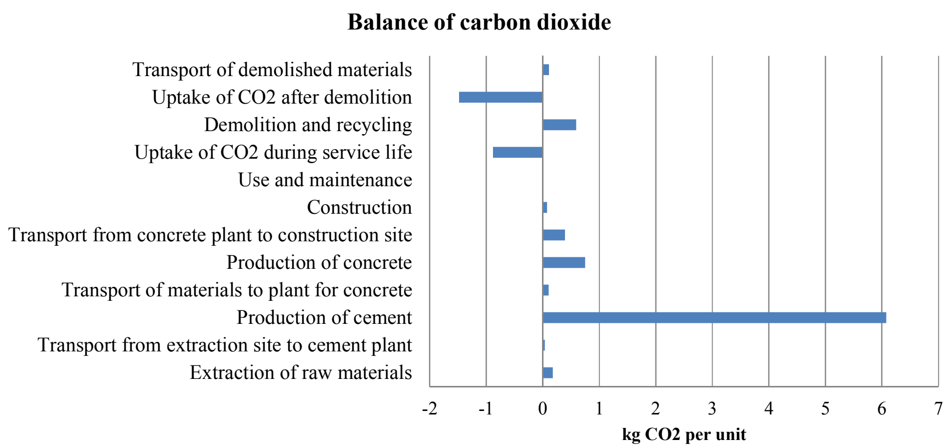


Figure 5.5. Example of CO_2 balance for 1m^2 of typical roof tile [131]

5.3. Existing researches regarding CO_2 uptake

5.3.1. CO_2 balance of RC structures

The balance between CO_2 emissions and CO_2 re-absorption (uptake) represents a relatively new subject which has been approached only in few studies. One of the most comprehensive studies regarded to CO_2 – uptake has been realized by the research institutes and cement industries from Denmark, Sweden, Norway and Iceland [105], [131], [132], [133], [134]. These works focused on the CO_2 absorption capacity of cement based products throughout their life cycle, considering structures of 100 years in total life, with 70 of service life and 30 of secondary life. The project results showed that the net CO_2 uptake during a realistic lifetime is depending on the type of the concrete, its application and the percentage of concrete rubble generated and re-used in these four countries. In countries with the most favourable recycling practices it has been assumed that 86% of the concrete will have carbonated after 100 years taking up approximately 57% from the CO_2 emitted during the calcination.

Engelsen et al. [134] realized a comprehensive study on CO_2 uptake in demolished and crushed concrete, also in the frame of the Nordic Innovation Centre Project. The CO_2 uptake of different crushed concrete types has been measured by conducting extensive accelerated laboratory tests, in order to document any differences in the uptake rate between the different crushed concrete samples. The maximum uptake of CO_2 within reasonable testing time in laboratory was determined. It was found that 60-80% of the CO_2 released during calcination is reabsorbed by the concrete mixtures with w/c = 0.6 or higher, for a grain size of 1-

8 mm, within 20-35 days of exposure. Furthermore, the calculation showed that 60-90% of the total CaO in the same samples was carbonated. Determination of the total carbon content in the carbonated samples by total combustion and CO_2 detection showed reasonable agreement with the measured CO_2 uptake. The w/c ratio was found to be crucial. Thus, it was found that more than 90% of the CO_2 was absorbed within the first 50 hours of exposure, for the mixes with w/c of 0.75 and 0.4 respectively and with a grain size of 1-8 mm. The coarser aggregate samples carbonated significantly slower.

Similar research on recycled and crushed concrete has been set up in New Zealand, with the collaboration between Holcim and Canterbury University, which confirmed that re-carbonation has a major contribution to CO_2 uptake [102]. 20 samples consisting of crushed and in-situ concrete from Auckland and Christchurch localities dated between 0 and 84 years have been analysed by carbon titration and phenolphthalein indicator. While the extent of carbonation is affected by environmental conditions and concrete composition, the post-service demolition and crushing of concrete is considered to be an extremely significant factor in determining CO_2 uptake. According to the test results, up to 83% of the initial CaO can recarbonate in a long period of time.

The CO_2 balance of United States concrete has been estimed by Gajda and Miller in [135] and [136]. Due to lack of sufficient data, but also to simplify the estimations, a series of assumptions were made. The emission sources resulted from the assumption that 50 metric tons of carbon dioxide are liberated from the kiln feed per 100 metric tons of manufactured cement. The emissions from fuel were not considered. The absorption sources relied on the characteristics of average portland cement, supplementary cementitious materials and portland cement concrete. It has been assumed that only CH, formed by the hydration of C_3S and C_2S will carbonate. Based on stochiometric relations, it resulted that 100 metric tons of fully hydrated portland cement can ultimately absorb 19.26 metric tons of carbon dioxide. Because hydration is a time-dependent process, the carbonation rate was combined with the hydration rates from [137], resultsing carbon dioxide absorptions of portland cement at different ages. The use of supplementary cementitious materials has also been taken into consideration. The cement utilization by construction category, including the volume of concrete produced and utilized in the US were based on the survey of the PCA (Portland Cement Association). According to the calculations, in the first year after construction, the concrete is estimated to absorb 200000 metric tons of carbon dioxide, a number relatively small in comparison to total CO_2 released in a typical year by a US cement manufacturer. After 100 years, concrete will absorb nearly 2.1 million metric tons of CO_2, which represents around 7.6% uptake. The study did not consider the carbonation of concrete after demolition.

Jacobsen and Jahren [138] estimated the amount of CO_2 absorbed by concrete in Norway, but without a survey on concrete use. Only a hypothetical concrete element with average properties has been considered for these calculations. Based on these assumptions, 16% CO_2 can be reabsorbed, also taking into account that 10% of the concrete is demolished and recycled.

A study by the British Cement Association on the sustainability benefits of concrete step barriers showed that about 20% of CO_2 can be reabsorbed trough re-carbonation over its entire life cycle. A service life of 60 years and a secondary life of 100 years has been assumed, when the structures will be crushed and recycled as ground works or land reclamation projects. This reduction is an average value, based on the various applications and markets for cement and concrete in the UK. It is also an important factor when considering the environmental impact of cementitious materials [139].

An international research project entitled „The effect of cement concrete as CO_2 sink", involving countries as Korea, Australia, India and USA has been conducted between 2008-2011. The major objectives and methods were:

- quantitative analysis and verification of CO_2 sink capacity of cement paste and mortar through carbonation;
- development of a quantitative analysis approach and prediction model for CO_2 sink of concrete structures in different conditions;
- development of the absorption prediction model for CO_2 dependent on the environment conditions throughout the whole life cycle;

Cement pastes and mortars have been undertaken to accelerated carbonation conditions and powder samples were investigated by XRD and TGA. The outcomes of the projects indicated that the ratio of absorption over emission of CO_2 in Korea was 3.7% after 40 years, 4.5% after 60 years and 5.2% after 80 years for structures with an average concrete compressive strength of 24MPa. The ratio for concrete bridge was smaller 2.5% after 40 years, 3.1% after 60 years and 3.5% after 80 years [140].

A preliminary study on the CO_2 absorption capacity of concrete trough carbonation and recarbonation has been performed in Romania [141]. The first part of the report presented a large theoretical study on concrete carbonation mechanism and CO_2 uptake, while the second part consisted in experimental determination on carbonation depth of a large variety of concrete mix designs. Five cement types were used to prepare concrete mixes with different w/c ratio and cement content. The samples were undertaken to different curing procedures and exposed to natural and to accelerated carbonation. The results offered a great contribution in the determination of the carbonation rate, which is an important and necessary parameter to calculate the CO_2 uptake.

5.3.2. Methods to calculate CO_2 uptake

Beside the traditional experimental techniques as thermogravimetry, quantitative XRD, chemical analysis or infrared spectroscopy, there are other practical methods for the determination of the direct CO_2 uptake capacity of concrete samples.

A very simple and practical method, which defines carbon dioxide uptake is through mass gain. The advantage of this method is, that in comparison to other techniques, where powder samples are neccesary, the mass gain method can be applied on entire specimens. The carbon dioxide uptake can be then expressed as the mass increase in terms of the original amount of binder, as applied by [142]:

$$Mass\ldots gain(\%) = \frac{Mass_{sample,final,driedat60^{\circ}C} - Mass_{sample,initial}}{Mass_{dry,binder}} \tag{5.16}$$

Uncertainities of this procedure related to the deliberated water through carbonation has been eliminated by [143]. They realised a closed system, where the deliberated water during the test has been collected, modifiying relation 5.16 to:

$$Mass...gain(\%) = \frac{(Mass_{final} + Mass_{waterloss}) - Mass_{initial}}{Mass_{dry,binder}} \tag{5.17}$$

Knowing the chemical composition of the binder, Steinour developed a relation between the chemistry of a cementitious material and the maximum amount of CO_2 that can be combined in carbonation. He assumed that all CaO (except that present as $CaSO_4$) converts to CC, all MgO converts to $MgCO_3$ and the alkali oxides convert to alkali bicarbonates [144]:

$$CO_2(\%) \rightarrow 0.785(CaO - 0.7SO_3) + 1.091MgO + 1.420Na_2O + 0.935K_2O \quad (5.18)$$

From relation 5.18 relation results that the maximim CO_2 uptake for OPC with 63% CaO is about 50%. In pure thermodynamic terms, assuming a 100% degree of carbonation, the sequestration potential of one ton of cement would be half a ton carbon dioxide which equals to the amount of CO_2 released from the decomposition of limestone during the production of one ton of cement.

The evaluation of uptake has to be easily accessible for engineers. Therefore it has to use data which are practical and doesn't need suplimentary determinations. In this sense, Lagerblad [105] proposed a practical calculation formula. Formula 5.19 permits the calculation of the amount of CO_2 absorbed per volume of concrete, taking into consideration the binder content, its CaO content and the degree of carbonation:

$$U_{CO_2} = a \cdot C \cdot CaO \cdot \frac{M_{CO_2}}{M_{CaO}}, [kg / m^3] \quad . \quad (5.19)$$

Where:

- a = 0.75 – is the amount of CaO carbonated (degree of carbonation);
- C – is the mass of Portland cement in concrete per m^3;
- CaO – is the amount of CaO in cement (wt - %);
- M – is the molar weight of oxides.

From these components, the cement type and quantity are known from the concrete mix design, the weight percent of CaO is obtained either from a chemical analysis or based on the technical datasheet of the manufacturer. If such data is not available, an average value between 62% – 64% can be estimated. The molar weights are constant values (M_{CO2}=44g/mol, M_{CaO}=56.08g/mol), while the only variable is "a", the degree of carbonation.

This parameter is considered of high importance, since it can lead to major differences in the calculation of the carbon dioxide uptake, when using formula 5.19. The degree of carbonation has been studied by several authors. Either based on theoretical consideration, or on different experimental determinations, the carbonation degree was different, in relation to the cement type, concrete quality, environmental conditions, exposure time or even on the assumptions and measurement methods the studies were based on. For this reason it is difficult to compare the results obtained in different studies but in the same time a general acceptable relation must be found for practical usage.

A PhD project on measurment of carbonation [145] was solely dedicated to quantifying the degree of carbonation, i.e. the extent of reaction by the calcium containing constituents. Möller [145] measured a degree of around 0.75, although he did not obtain a sharp front, but a carbonation profile with a certain slope around the depth of carbonation measured by phenolphthalein indicator [146].

Lagerblad [105] studied the stability of different cement paste hydration products, in terms of carbonation and reached to the conclusion that 100% of the CaO found in CH, AFt and AFm and 50% of the CaO found in CSH can be transformed into calcium carbonate in the carbonated concrete, so about 75 % of the initial CaO content will have carbonated. Therefore he considered that the coefficient “a” is equal to 0.75. This value is a theoretical maximum, which can be reached in a vey long exposure time. Based on the laboratory tests in [134], a carbonation degree of 75% can be considered a realistic level of carbonation, but only when the total uptake of CO_2 is estimated. This means that concrete must be re-used in a crushed form and re-carbonation has to be calculated on a reasonable time scale of 20-50 years.

Other authors, as Gajda and Miller [135] and Jacobsen and Jahren [138], assumed that only the calcium present in CH carbonates, without considering the calcium in CSH, reaching to much lower values of carbonation degree (0.38 resp. 0.32). The percentage of CaO available for carbonation was further reduced to 21% in the study by Gajda [136] in order to account for the presence of pozzolanic material in concrete.

Matsushita in [147] presented a useful concept for the calculation of carbonation degree:

$$D_C(\%) = \frac{C - C_0}{C_{max} - C_0} \times 100 \qquad (5.20)$$

Where:

- D_c – Degree of carbonation;
- C_0 – initial CO_2 content;
- C – final CO_2 content;
- C_{max} – theoretical maximum CO_2 content needed to combine with the total calcium oxide in the sample to form calcium carbonate;

The theoretical maximum uptake C_{max} of a cementitious material is related to the material chemistry and can be calculated using the Steinour formula (5.18). The other neccesary input parameters require further experimental determinations. This concept, combined with other experimental techniques, has been applied in [143], where traditional cementitious materials (Portland cement Type 10, high early strength cement Type 30 and GGBFS) and calcium-rich waste materials (electric arc furnace slag and high carbon fly ash) have been considered for the study of CO_2 uptake potential. The samples where mixtures of binder and water at different ratios, carbonated as bulk powder and compact samples in chambers at 5bar of carbon dioxide gas of 99.5% purity. Carbon content was determined with different methods and combined with the mass gain, to obtain the degree of carbonation. It resulted that the degree of carbonation varied between 15% (for GGBS) and over 45% (for fly ash). But these values do not represent the maximum achievable carbonation level of the analyzed materials, because the test conditions were not the ideal conditions for each of the materials.

Recent researches regarding the carbon dioxide absorption capacity of concrete and other cementitious materials are related to Galan et. all [148]. The quantity of CO_2 absorbed due to carbonation has been studied, considering different concrete mixes, environmental conditions and exposure times. The samples were prismatic and cylindrical specimens of 0.45 and 0.6 w/c ratio, prepared of 12 respectively 15 types of cement. For the concrete mix design with w/c=0.6, 300kg of cement has been used, while for the mix with w/c=0.45, 400kg. The specimens have been dried at indoor temperature for 26 days and then exposed in three different environments: outside-exposed to rain; outside-sheltered from rain and inside. The samples were tested after one year of exposure. Additional specimens were taken from old structures and analysed.

The traditional phenolpthalein test combined with termogravimetry has been used for the determination of the carbonation depth and the quantity of absorbed CO_2. The results, in terms of combined CO_2, showed a great variation, influenced by the different factors. The specimens with a w/c=0.6, exposed inside, showed the lowest degree of carbonation, with values not higher than 13%, while the ones exposed to rain reached values of 33% and those protected from rain absorbed between 12% and 23%. The specimens with w/c=0.45 showed similar tendancies, with some exceptions. These results underlined the importance of the moisture content in combination with CO_2. Generally, with few exception, the concrete specimens with w/c=0.45 absorbed less CO_2 than the other category, which indicated that the concrete quality (porosity) has a higher influnce on the uptake than the available material for carbonation.

Figure 5.6 shows a comparison on the carbonation degree, collected from different authors, obtained both theoreticaly and experimentaly.

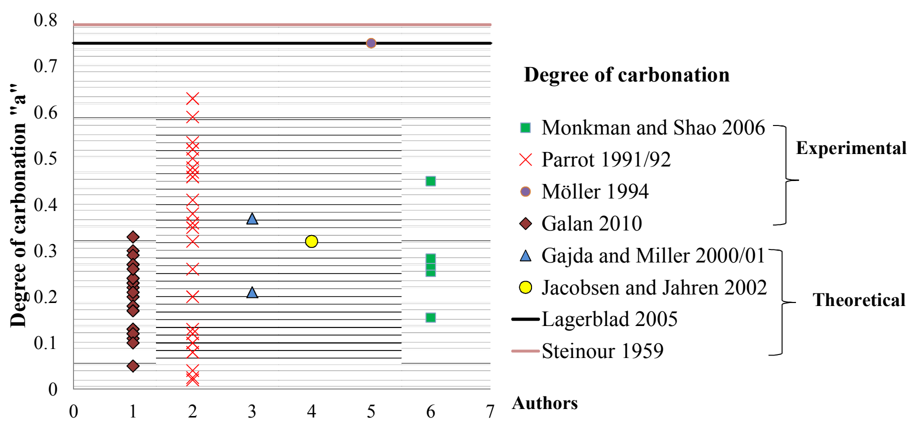


Figure 5.6. Values of carbonation degree obtained by different authors

It is very difficult to make a real comparison as the results are influenced by a series of conditions. The two horizontal lines represent the maximum possible absorption according to the proposals of Steinour [144] and Lagerblad [105], respectively. Where the available data were expressed in different units, some transformations have been made to express the results in the same units.

6. EXPERIMENTAL PROGRAM

6.1. Description of the working procedure

The scope of the experimental program was to determine the CO_2 uptake through carbonation, implicitly the carbonation degree of different concrete mixtures. For these purposes the experimental procedure involved the main steps from Figure 6.1.:

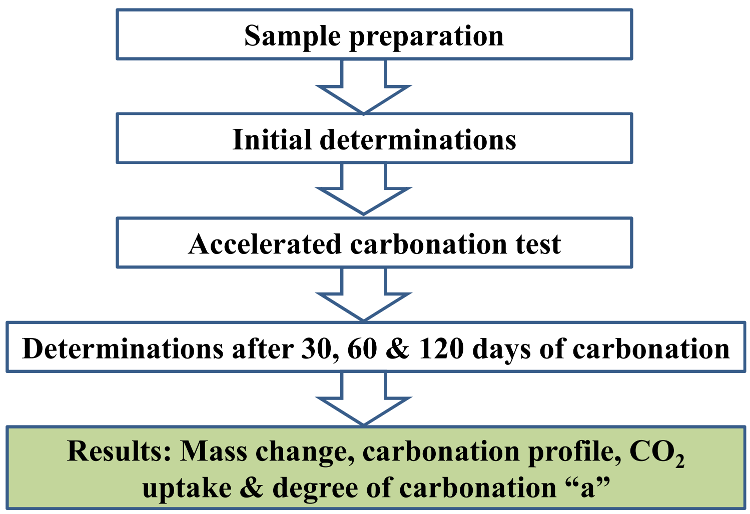


Figure 6.1. Main steps of the experimental program

In the first step of the program different concrete mixtures have been prepared, covering a wide range of usual concrete qualities. To obtain the physical, mechanical and chemical properties of the studied concrete mixtures and their components, initial determinations have been performed.

For the direct determination of the CO_2 uptake an original procedure has been proposed, namely the drying and weighting of the samples before and after carbonation, until they reach a constant mass. This procedure is based on the carbonation mechanism of concrete. When gaseous CO_2 reacts with the hydration products of the cement paste, calcium carbonate precipitates, which is a solid product, and water is unbounded, which can evaporate. The more carbonate ions are absorbed, the more calcium carbonate precipitates. During carbonation 1mol of water is deliberated with every mol of absorbed carbon dioxide. Because the molar weight of carbon dioxide (44g/mol) is higher than the molar weight of water (18g/mol), which becomes evaporable, the concrete gains weight during carbonation [149]. Following this principle, it can be considered that the difference between the constant massess before and after carbonations represents the CO_2 uptake itself.

In this sense, the samples were dried and weighted in their initial phase, to determine the constant mass before carbonation. An accelerated carbonation test followed, where the samples were introduced in chambers with high CO_2 concentration for 30, 60 and 120 days. After each period of time determinations have been conducted to obtain the following parameters: Mass change, carbonation profile, CO_2 uptake and carbonation degree „a".

6.2. Materials, concrete mixtures and curing procedure

The experimental program has been realised in two phases. In the first phase of the project three basic concrete mixtures, while in the second phase four other mixtures have been prepared. The component materials were:

- Cement: CEM I 42.5R and CEM II/A-LL 42.5, offered by Holcim Romania;
- Siliceous river fine and course aggregates with sorts of 0-16 mm (Fig. 6.2);
- No additives

Figure 6.2. Washed and sorted aggregates

The preparation of the concrete samples was realised in laboratory conditions, according to CP 012/1: 2010 [150]. The washed, dried and sorted aggregates were thoroughly mixed with the cement, then water was added gradually and mixed until a uniform paste was obtained. The paste was then cast into lightly oiled moulds, put on a vibrating table and compacted (Fig. 6.3).

Figure 6.3. Preparation of the concrete mixtures

The prepared samples were:

- 7 x 18 cubic specimens of 150x150x150mm → Total: 126;
- 7 x 3 prism specimens of 100x100x300mm → Total: 21;

24 hour after preparation, the samples were demolded and placed in water tank for hydration at 22±2°C. After 7 days of water curing, the samples were covered in polythene foils and kept in laboratory conditions. In this way they were protected from the atmospheric CO_2 until being placed in the carbonation chambers (Fig. 6.4).

Figure 6.4. Curing of the samples in water and covered with polythene foils

Details of the mixture compositions and main characteristics of the studied concretes are shown in Table 6.1 and Table 6.2.

Table 6.1. Mixture compositions of the samples prepared in the first phase

	Mix 1	**Mix 2**	**Mix 3**
Cement type	CEM II/A-LL 42.5R	CEM I 42.5R	
Water to cement ratio W/C	0.6	0.5	0.75
Cement [kg/m^3]	340	340	250
Water [l/m^3]	205	170	188
Aggregate 0/4 [kg/m^3]	712	712	775
Aggregate 4/8 [kg/m^3]	525	525	562
Aggregate 8/16 [kg/m^3]	525	525	538
Apparent density ρ [kg/m^3]	2300	2270	2313
Slump [mm]	S_3 - 140	S_3 – 100	S_1 – 40
Compressive strength at 28 days [MPa]	35.35	38	31.5
Tensile strength [MPa] at 28 days	2.72	3.32	3.0

Table 6.2. Mixture compositions of the samples prepared in the second phase

	Mix 4	**Mix 5**	**Mix 6**	**Mix 7**
Cement type	CEM I 42.5R		CEM II/A-LL 42.5R	
Water to cement ratio W/C	0.55	0.55	0.67	0.58
Cement [kg/m^3]	300	400	300	400
Water [l/m^3]	166	220	203.5	232.5
Aggregate 0/4 [kg/m^3]	770.6	678.8	730.6	663.3
Aggregate 4/8 [kg/m^3]	578.1	507.6	547.95	497.5
Aggregate 8/16 [kg/m^3]	578.1	507.6	547.95	497.5
Apparent density ρ [kg/m^3]	2224	2272	2321	2321
Slump [mm]	S_2 - 50	S_4 - 140	S_3 - 90	S_4 - 140
Compressive strength at 28 days [MPa]	29	42	25	34
Tensile strength [MPa] at 28 days	2.56	3.84	2.45	2.82

6.3. Initial determinations

Different determinations have been performed both on cement and concrete. The greatest influence of cement on CO_2 uptake is given by its chemical and mineralogical composition. In order to determine the chemical composition powdery samples were analysed with Energy-dispersive X-ray spectroscopy (EDAX), which is an analytical technique that uses characteristic x-ray radiation for compositional analysis (Figure 6.5).

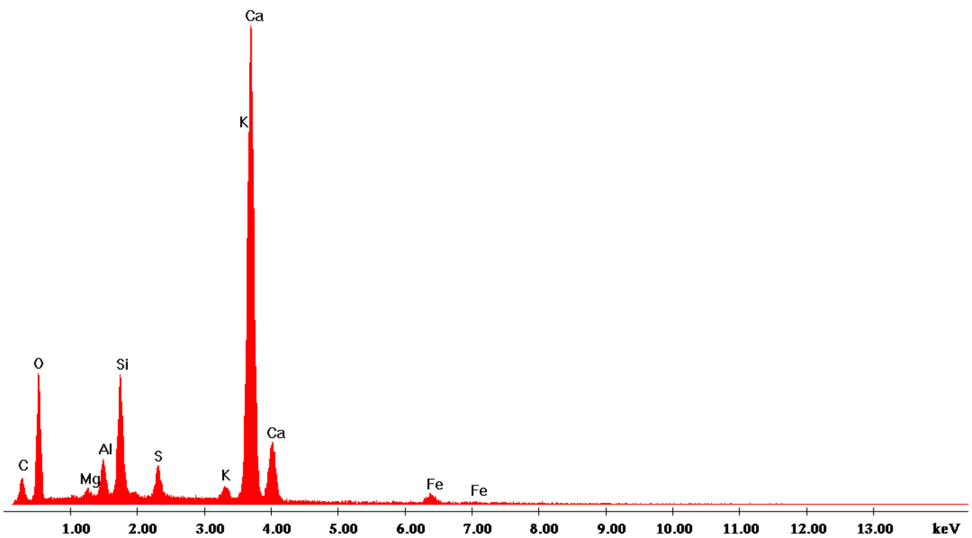


Figure 6.5. Energy-dispersive X-ray spectrum

Combined with the technical data offered by the producer, the chemical compositions of the cements are presented in Table 6.3.

Table 6.3. Cement chemical composition

CEM I 42.5R [%]									
LOI	**IR**	**SIO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**SO_3**	**K_2O**	**Na_2O**
2.98	0.4	19.99	4.89	3.04	64.05	1.3	2.82	0.77	0.2
CEM II/ A-LL 42.5R [%]									
3.1	0.4	20.19	4.62	3.47	62.7	1.24	2.87	0.7	0.24

The main crystalline phases of the cement can be quantified through a complex set of calculations known as the Bogue Formula [151]. Although the result is only approximate, the calculation is an extremely useful and widely-used method in the cement industry. The calculation assumes that the four main clinker phases are pure minerals. The Bogue equations for potential compositions are:

$$\begin{aligned} C_3S &= 4.071CaO - 7.6024SiO_2 - 1.4297Fe_2 - 6.7187Al_2O_3 \\ C_2S &= 8.6024SiO_2 + 1.0785Fe_2O_3 + 5.0683Al_2O_3 - 3.0710CaO \\ C_3A &= 2.6504Al_2O_3 - 1.6920Fe_2O_3 \\ C_4AF &= 3.0432Fe_2O_3 \end{aligned} \qquad (6.1)$$

The results of the Bogue calculation regarding the mineralogical composition of the cement clinker are presented in Table 6.4.

Table 6.4. Mineralogical cement composition

Bogue Calculation									
CEM I 42.5R					**CEM II/ A-LL 42.5R**				
C_3S	C_2S	C_3A	C_4AF	Free CaO	C_3S	C_2S	C_3A	C_4AF	Free CaO
68.97	3.33	7.81	9.25	0.64	63.21	8.29	6.37	10.55	0.62

Scanning Electron Microscopy (SEM) has been done for very high-resolution images of the sample surfaces, revealing details less than 1nm in size (Fig. 6.6).

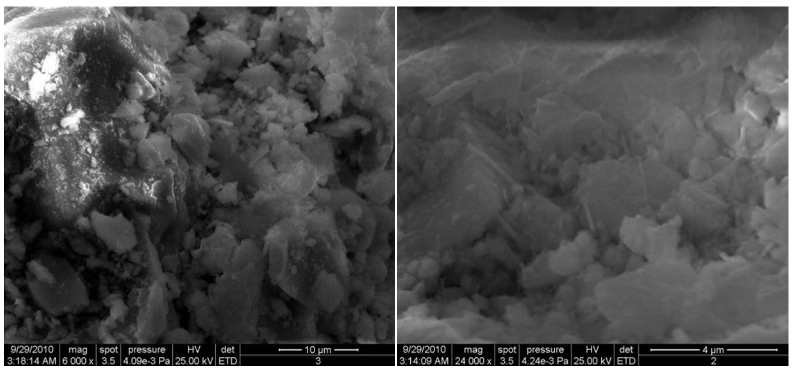


Figure 6.6. SEM image of the cement microstructure

From the mechanical properties of cement, the initial and standard compressive strength has been determined according to SR EN 196-1 [152]. The results are presented in Table 6.5.

Table 6.5. Cement compressive strength

Compressive Strenght	After 2 days [MPa]		After 28 days [MPa]	
Cement:	Exp.	Standard	Exp.	Standard
CEM I 42.5R	25.7	≥ 20	43.5	≥ 42.5
CEM II/ A-LL 42.5R	23.5	≥ 20	42.5	≥ 42.5

To measure the workability of the fresh concrete, the traditional slump test has been used. The utilized apparatus was a metal mould, in the shape of a cone, open at both ends, and provided with a handle, top internal diameter 102mm and bottom internal diameter 203mm with a height of 305mm and a 610mm long bullet nosed metal rod, 16mm in diameter. The cone was placed on a hard non-absorbent surface, filled with fresh concrete in three stages, each time being tamped using the rod. At the end of the third stage, concrete was struck off flush to the top of the mould. The mould was carefully lifted vertically upwards, in a way to not disturb the concrete cone. Concrete subsides, which is termed as slump, and is measured in to the nearest 5mm (Fig. 6.7). In function of the slump, the concrete is assigned to a slump class, according to SR EN 206-1 [153].

At the period of 28 days, samples from each mixture were tested on compressive and tensile strength (Fig. 6.7). The results for the 7 concrete mixtures were presented in Table 6.1 and Table 6.2.

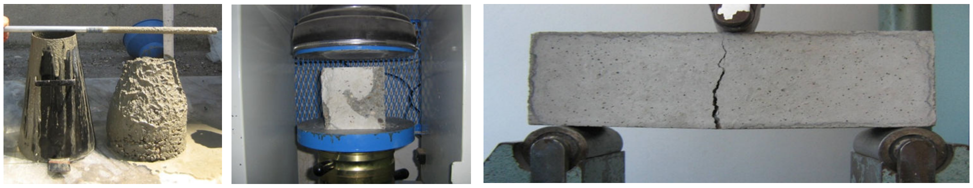


Figure 6.7. Tests on fresh and hardened concrete

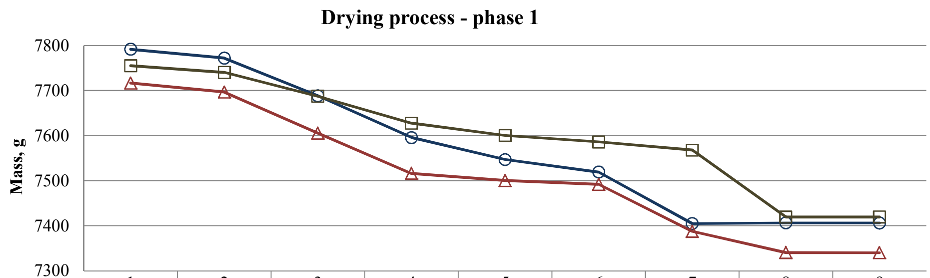
For later chemical investigations, powdery samples have been drawled from the noncarbonated concrete. The powdery samples were kept in airtight bottles (Fig 6.8).

Figure 6.8. Drawling of powdery samples

One of the most important part of the initial determinations, regarding the direct measurment of the CO_2 uptake, represented the obtaining of the constant mass of the noncarbonated concrete samples. All cubic samples have been dried and weighted, until they reached a constant mass, eliminating the free, chemically unbounded water. The results of the initial drying process are presented in Figures 6.9 and 6.10. The dried samples have been then introduced again in water for 24 hour to regain the initital water content, necessary for a favorable carbonation process.

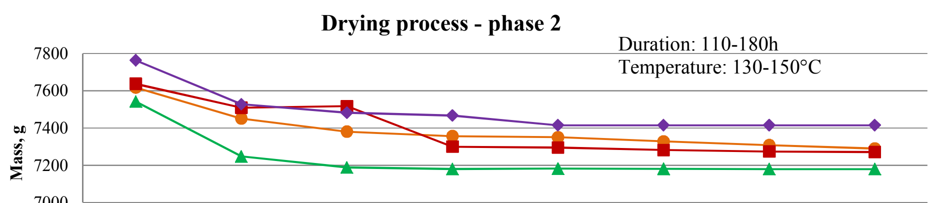
Comparing the initial drying processes in the two phases, it can be observed that the neccessary drying time for the concrete samples in phase 2 is significantly higher than for those in phase 1. This is due to the following causes:

1. At the begining of this procedure, no data was available regarding the necessary drying time or temperature. First, it has been tried at 100°C, but the evaporation of water was very slow, so the drying would have taken weeks of time. The temperature has been raised up to 165-170°C, which permited the evaporation of the water in about 80 hours of effective drying. But this temperature was considered too high, which might unbound also chemical water, so for the rest of the experiment, the drying temperature did not exceed 145-150°C;
2. In the first phase there were 36 cubic samples dried at the same time, while in the second phase 48. The more samples are in the furnace, the more heat is needed, which results in longer drying time.



	1	2	3	4	5	6	7	8	9
Mix 1	7791.5	7771.9	7688.3	7595.6	7546.8	7519.1	7404.7	7406.3	7406.1
Mix 2	7754.9	7740.3	7687.3	7627.4	7600.2	7586	7567.7	7419.2	7419.5
Mix 3	7716.6	7696.5	7605.2	7516	7500.2	7491.8	7387.4	7340.3	7340

Figure 6.9. Weight loss during the drying process in phase 1



	1	2	3	4	5	6	7	8
Mix 4	7617.8	7451.3	7380.8	7356.7	7350.7	7328.7	7308.7	7290
Mix 5	7637.7	7509.1	7517.6	7300.1	7295.6	7282.1	7274.2	7271.3
Mix 6	7542.1	7248.1	7188.6	7180.5	7182.3	7181.2	7180	7180
Mix 7	7763.3	7527.9	7482.1	7467	7415.2	7415	7415	7415

Figure 6.10. Weight loss during the drying process in phase 2

6.4. Accelerated carbonation test

In normal environmental conditions (CO_2 concentration of about 0.03% to 0.1%) the evolution of the carbonation depth, including the CO_2 – uptake would require an extremely long period of time. Therefore in frame of the experimental program an accelerated carbonation test has been conducted, under high CO_2 concentration.

The carbonation setup consisted of three separate chambers, each with a storing capacity of 15 cubes of 150x150x150mm (Fig. 6.11). The chambers were provided with a removable door for access during handling of the samples, a circular hole located on the upper side and a tap, assuring the CO_2 supply from the pressurised bottle. The hole provided access for the probe during the measurements otherwise a rubber stopper was used to close the outlet. The samples were placed on thin supports and spaced at a minimum distance of 20mm apart, to insure that the CO_2 gas could reach unhindered all the surfaces of the cubes.

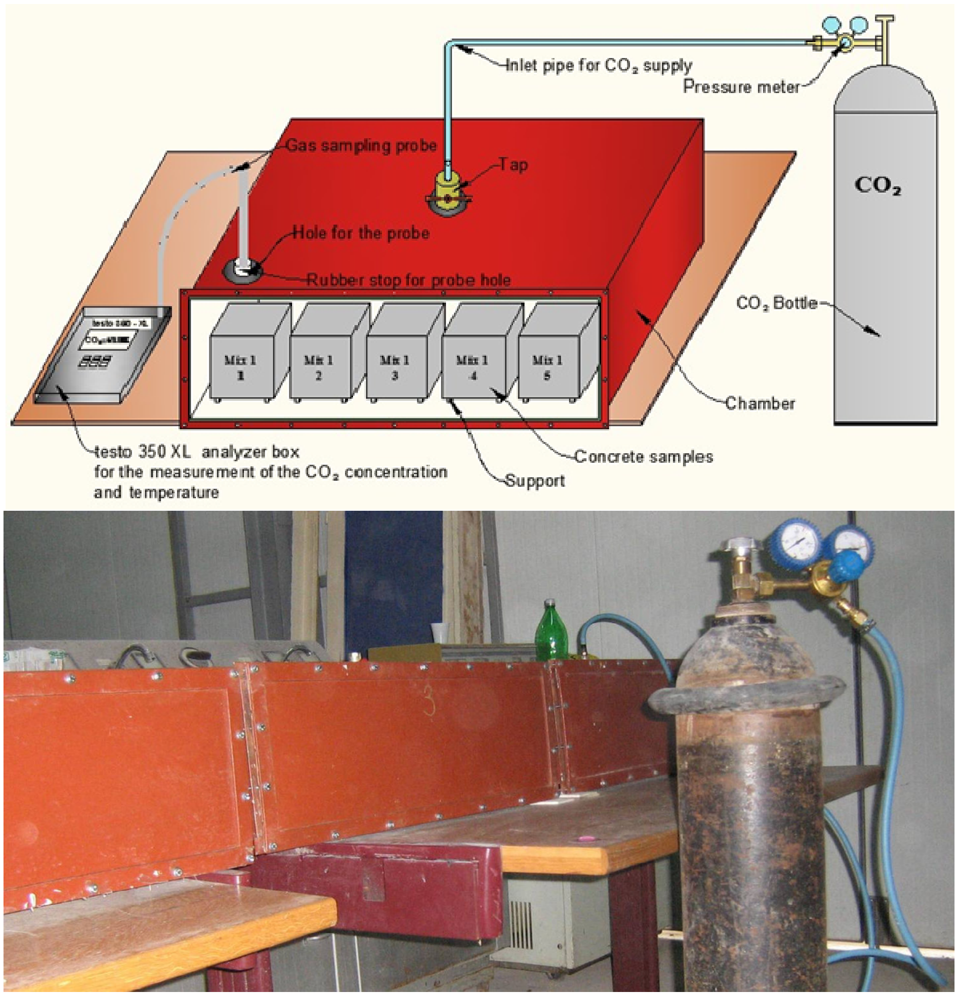


Figure 6.11. Chambers for accelerated carbonation test

For the measurement of the carbon dioxide concentration and the temperature inside the chambers the *testo 350 XL* analyser box has been used. The box is equipped with an electrochemical probe, which can measure CO_2 concentrations up to 50% by volume, with an accuracy of ±0.5% and a resolution of 0.1%. To determine the relative humidity inside the chamber, the *testo 845* with integrated humidity module has been used. The instruments are shown in Figure 6.12. The chambers were kept in a laboratory, at a constant temperature of 15°C±2°C and RH=55%±5%.

After the samples were placed inside, the chambers were closed airthight and filled with CO_2 gas up to 50% by volume. The concentration and temperature were measured and registered two times a day in each chamber. Because of the decrease of CO_2 concentration due to carbonation, but also due to minor leaks, the chambers were refilled with gas after every measurement.

Figure 6.12. Instruments for the measurement of the environmental conditions in the chambers

The strategy to remove samples from the chambers after the defined periods of time differed between the two phases. In the first phase, all of the samples of a mixture were placed in the same chamber. At every determination period, the chambers were opened and three cubes have been removed from each one of them. Then, they were closed again airthight and the accelerated carbonation continued until the next defined period. This procedure showed some disadvantages:

- supplimentary work to open and close all the chambers at each defined carbonation period;
- the opened chambers came in contact with the exterior environment, which may have influenced the environmental conditions inside the chambers over the entire carbonation period, in terms of relative humidity.

For these reasons the removing strategy of the samples has been changed in the second phase. Each chamber was filled with cubes from each mixtures. After the first period of carbonation, all the samples from one chamber have been removed, while the other two continued the carbonation process uninterrupted. In this way the workload has been reduced and the environmental conditions inside the chambers remained constant over the entire process.

The variation of the environmental conditions in chambers, over the entire carbonation process, are shown in Figure 6.13 for both phase 1 and phase 2.

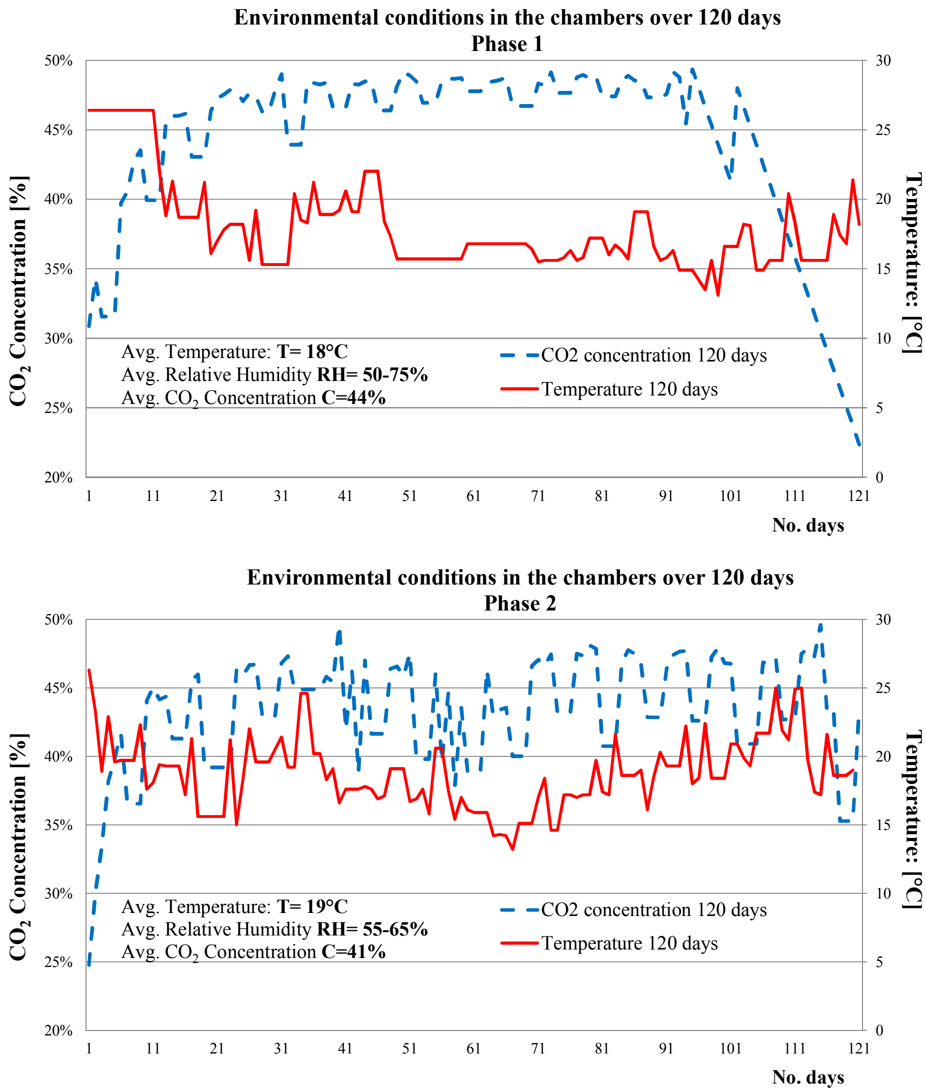


Figure 6.13. Environmental conditions in the chambers

6.5. Determinations after 30, 60 and 120 days of carbonation

6.5.1. Direct mass gain

The experimental procedure for the determination of the CO_2 uptake through direct mass gain, can be considered an original method, because although the principle is theoretically well known, as presented also in [154], [155], few experimental determinations were available for entire concrete specimens [142].

The utilized equipment for this procedure was:

- high precision balance, with an accuracy of ±1g and a resolution of 0.1g;

- electric furnace with resettable program functions;
- press for the splitting of the sample;
- 1% phenolphthalein solution;
- electronic sliding gauge and image processing software for the measurement of the carbonation profile.

The working procedure of this experimental method was as follows. After 30 days of carbonation, three samples from each mix design were removed from the chambers. They were introduced in the electric furnace, warmed up progressively to the specified temperature and then maintained at constant value. After a period of drying (in the beginning longer periods, then shorter periods) each sample was weighted. When after two consecutive weightings the mass loss was almost nothing, the samples were removed from the furnace and so the last value represented the constant mass (Fig. 6.14). The uptake was calculated using formula 6.2.

$$Uptake(g) = Mass_{sample,final,dried} - Mass_{sample,initial,dried} \tag{6.2}$$

The samples were very carefully handled during weighting in order to avoid physical deterioration.

Figure 6.14. Drying and weighting of the samples

In the next phase the carbonation depth and the volume of the carbonated concrete were determined. For a uniform fraction mode, the cubes were loaded through round steel bars in a compression testing machine, in a manner similar to the one used when conducting an indirect tensile splitting test (Fig. 6.15).

Figure 6.15. Splitting of the samples

According to SR CR 12793 [156] a 1% phenolphthalein solution was sprayed uniformly on the freshly broken surface. The phenolphthalein indicator is the traditional method used to measure the carbonation depth of a carbonated sample. The solution leaves the surface colourless when the pH value is less than nine (carbonated) and turns magenta when the pH is above nine (noncarbonated). This procedure offers a good visual representation of the carbonation front, although according to [112], [157] it does not indicate the depth of maximum ingress of CO_2, where $CaCO_3$ can form beyond the purple-red border and it cannot detect the existence of a partially carbonated zone. Furthermore, [103] stated that the phenolphthalein indicates only the pH level, without permitting the distinction between the effect of carbonation or other acid gases, it cannot distinguish the loss of concrete alkalinity resulting from a specific cause.

The carbonation depth was measured on five points on each side, with a precision of 0.5mm, using an electronic sliding gauge. The average carbonation depth is the arithmetical average of the 20 individual values, rounded at the nearest 0.5mm. To choose these points, the edge length was divided in eight equal distances. The five central points were used to fix the carbonation depth (Fig. 6.16).

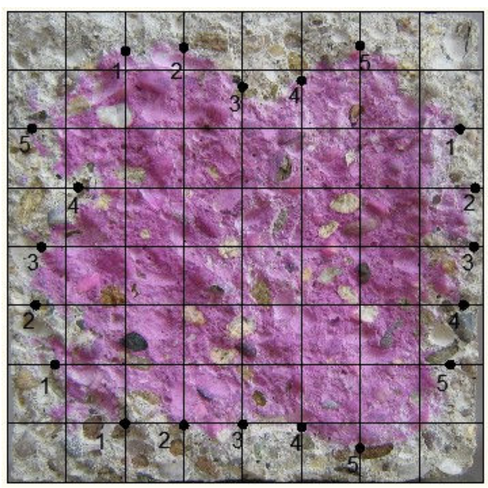


Figure 6.16. Measurement of the carbonation depth using traditional phenolphthalein indicator

In order to determine the carbonated area with a high accuracy, the image of each concrete surface was scaled and edited. Using adequate image editor software, each pixel with the same colour range was detected. The outline of the carbonated zone was drawn and the carbonated area was calculated based on the number of detected versus the total number of pixels. To obtain the volume of carbonated concrete, the average carbonation depth was considered in the perpendicular direction.

The CO_2 uptake capacity of the concrete mix resulted from the correlation of the direct mass gain with the volume of the carbonated concrete, resulting how many kilograms of CO_2 can be absorbed by $1m^3$ of concrete.

The entire procedure has been repeated for the samples removed after 60 days and 120 days of carbonation.

6.5.2. SEM/EDAX

The Scanning Electron Microscopy is a type of electron microscope that images a sample by scanning it with a beam of electrons in a raster scan pattern. The electrons interact with the atoms that make up the sample, producing signals that contain information about the sample's surface topography, composition, and other properties such as electrical conductivity. The image formation is realized by the secondary electrons or back-scattered electrons, which appear due to emitted primary electrons. The SEM can produce very high-resolution images of a sample surface, revealing details less than 1nm in size [158]. Combined with Energy-dispersive X-ray spectroscopy this method can be used as a semi-quantitative analytical technique for the elemental analysis or chemical characterization of the sample.

The SEM image and EDAX spectrum were conducted at the „National Institute of Research and Development for Electrochemistry and Condensed Matter, Timisoara" with the Electronic microscope Inspect, S, FEI Company, Netherland. The analyzed specimens were powdery samples, drawled from the noncarbonated and carbonated concrete. Contrary to the experimental procedure with direct mass gain, the powder samples for this method are not taken after each period of carbonation. The specimens are homogeneous powder mixtures of carbonated concrete, which were taken from different surface points, but only from the carbonated layer, as indicated by the phenolphthalein test. The samples are then focused by charged particles (electrons) and so the interaction with the source of X-ray is analysed. Each element has a unique atomic structure, allowing unique set of peaks on its X-ray spectrum.

The scope for using SEM/EDAX was to identify the quantitative composition of the concrete samples before and after carbonation. The objective was to measure the carbon content in the carbonated sample, in order to see how much CO_2 has been absorbed by the concrete.

6.5.3. X-Ray defraction analysis (XRD)

X-ray diffraction analysis is a common technique for the study of crystal structures and atomic spacing of samples. Although the XRD method does not provide any reliable quantitative information, the technique is very useful for qualitative appreciations. Using an adequate database, the X-ray powder diffraction pattern enables the identification of a large variety of crystalline structures in a sample.

XRD analysis was performed at the „National Institute of Research and Development for Electrochemistry and Condensed Matter, Timisoara". A Philips XRD X'Pert PRO MPD diffractometer was used, with a Cu anode X Ray tube and PixCEL detector, vertical theta-theta goniometer and spinning sample holder with programmed rotation to different sample speeds. High tension generator works at a maximum of 60kV and 55mA.

The analyzed specimens were powdery samples, drawled from the noncarbonated and carbonated concrete. Similar to the SEM/EDAX, the specimens are homogeneous powder mixtures of carbonated concrete, which were taken from different surface points, but only from the carbonated layer, as indicated by the phenolphthalein test.

The XRD method was used to detect the presence of different crystalline structures in the carbonated concrete, which could offer qualitative information regarding the level of carbonation in the sample, compared to the traditional phenolphthalein test.

6.5.4. Termogravimetric analysis

TGA method is a common qualitative technique used for the quantification of portlandite and carbonates resulting from concrete carbonation. TGA involves continuous measurement of the mass of a sample subjected to a variation in temperature. Each chemical component is characterized by its own temperature range of decomposition and a specific mass loss involving gaseous emissions [159]; for example, for portlandite, it is a loss of water and for calcite, it is a loss of CO_2. The lowest temperature of the dissociation range is determinded by the characteristics of the equipment and the heating rate. The maximum temperature of dissociation range is a function of the quantity of the studied phase. The temperature ranges are clearly defined by the edges of the characteristic peaks of the DTG curve.

The thermal analysis was performed at the „Institute of Chemistry Timisoara of Romanian Academy". The thermal analyser was a TGA/ SDTA 851-LF 1100 Mettler, coupled with gas analysis system GSD 320T3, with quart capillary of 1m and mass spectometry "quadrupole" QMC220. Mass domain 1-300 AMU, filament source IR with C-SEM and Faraday detector. It enabled the thermogravimetric curve (TG), the derived thermogravimetric curve (DTG) and the curve from differential thermal analysis (DTA) to be obtained simultaneously on each sample. A powder sample of around 0.110g was taken in a ceramic crucible and heated from room temperature (25°C) to 1000°C at a heating rate of 10°C/ min in a dynamic atmosphere of nitrogen with a flow of $50cm^3$/ min.

TGA method was used to compare the results obtained with the direct mass gain, in terms of CO_2 content and carbonation degree of the different concrete samples.

7. EXPERIMENTAL RESULTS

7.1. Direct mass gain

7.1.1. Relative and absolute mass change

The mass change of the samples has been registered at different steps of the experimental program. The monitored parameters were: initial constant mass, final constant mass, relative weight loss and drying time. Figures 7.1 to 7.3 show the mass variation of the samples at different carbonation periods. The process has been divided into five phases, where measurements have been done:

1. Registration of the initial weight of each sample;
2. Registration of the constant mass, after the first drying process;
3. Registration of the weights after re-wetting;
4. Registration of the weights after 30, 60 and 120 days of carbonation;
5. Registration of the constant weight of the carbonated samples, after the second drying process.

The results are summarized in Table 7.1.

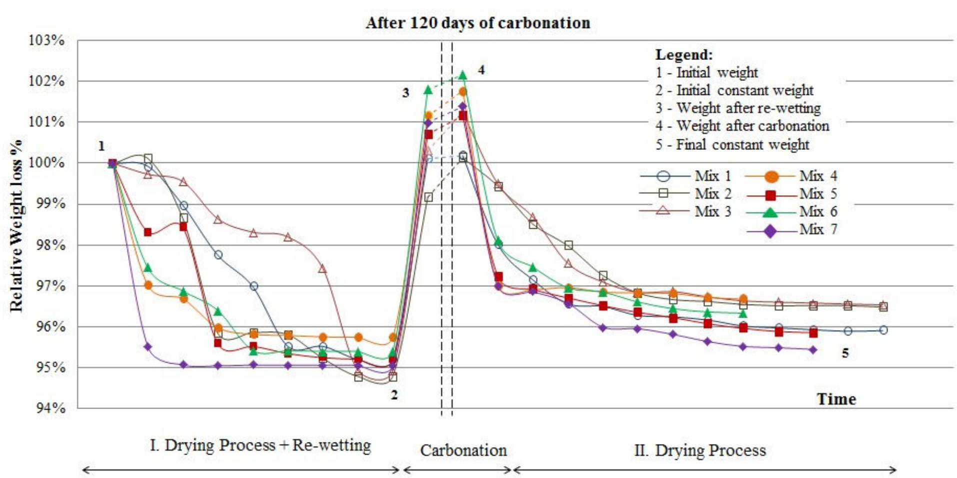


Figure 7.1. Relative weight change of the samples after 120 days of carbonation

Some important observations could be underlined based from the experimental results. The average weight loss of the samples before carbonation was in general higher than after carbonation. The initial drying time for the samples from phase 1 was around 80 hours, while for the samples from the second phase varied between 110 – 180 hours, as presented in the previous chapter. After re-wetting, the samples reached in general at least their initial weight, some of them even exceeded it. During carbonation, which was the most time costing step, a series of processes took place, which influenced the final results. In general, the weight of the samples after different periods of carbonation showed a slight increase, although relevant were their constant mass after the second drying. It could be observed, that the relative mass loss decreased with the carbonation time, as during carbonation water has been released from the samples. The carbonation also influenced the drying time. As seen in Table 7.1, the drying time increased significantly with the carbonation time. In the initial phase, the concrete presented a porous structure, which permitted the evaporation of the free unbounded water relatively fast. After carbonation, the pores in the carbonated area were partially closed, so the surface of the concrete became very dense and almost impermeable.

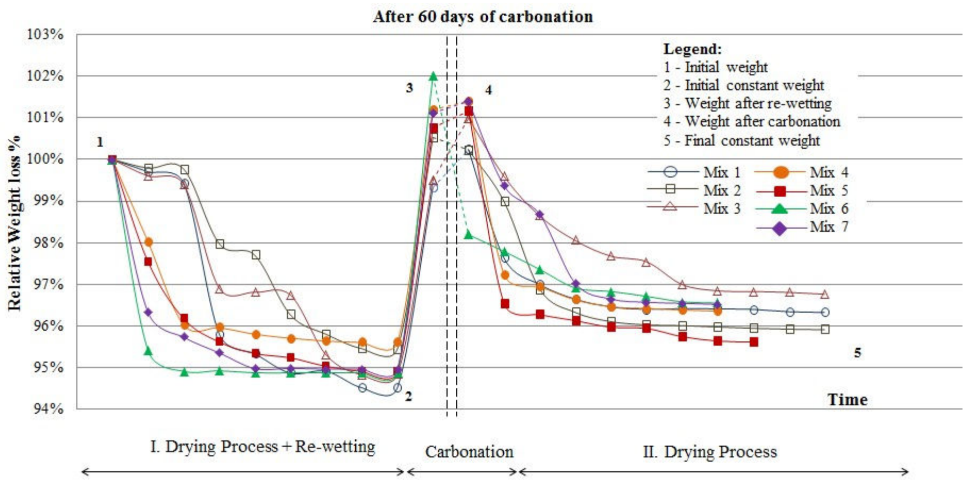


Figure 7.2. Relative weight change of the samples after 60 days of carbonation

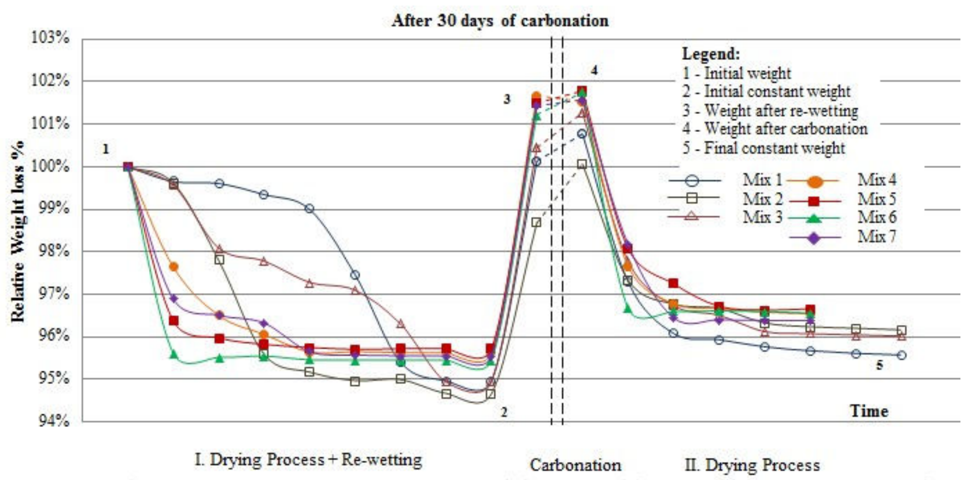


Figure 7.3. Relative weight change of the samples after 30 days of carbonation

In terms of absolute mass gain (uptake), the average values varied from 49g after 30 days of carbonation up to 130g after 120 days carbonation.

Table 7.1. Relative and absolute mass change during the experimental program

Mix	W/C	After 30 d			After 60 d			After 120 d		
		RWL [%]	U [g]	DT [h]	RWL [%]	U [g]	DT [h]	RWL [%]	U [g]	DT [h]
1	0.6	4.7	52.0	96	4.38	74.0	135	4.12	74.0	175
2	0.5	3.4	81.0	96	4.27	72.0	135	2.97	90.0	175
3	0.75	4.14	78.6	96	3.64	88.7	135	2.97	130.0	175
4	0.55	5.04	56.3	120-160	4.55	63.4	130-160	4.40	81.4	160-180
5	0.55	4.93	62.0	120-180	4.89	46.7	130-160	4.99	48.0	160-180
6	0.67	4.61	99.0	120-180	5.41	100.7	130-160	5.15	86.0	160-180
7	0.58	5.15	49.3	120-180	5.26	49.7	130-160	5.39	37.0	160-180

Note: RWL – Relative Weight Loss; U – Uptake; DT – Drying time at 140 - 150°C

7.1.2. Compressive strength and carbonation profile

The possitive influence of carbonation on the compressive strength of concrete is a well known phenomena. The calcium carbonate produced by the process of carbonation precipitates inside the pores of the cement paste matrix. This results in pore refinement of the carbonated cement paste matrix. Pore refinement leads to increased surface hardness, reduced permeability of the carbonated portion of the cement-paste matrix and increased compressive strength of the cement-based product. According to [160], the compressive strength and flexural strength of concrete specimens cured in environment with high CO_2 concentration may increase much higher than the specimens cured in CO_2 free environment.

Figure 7.4 presents the variation of the compressive strength for specimens kept in normal environmental conditions and in chambers with high CO_2 concentration. The typical compressive strength at 28 days has been taken as a reference value. Beside the specimens which were used for the determination of the CO_2 uptake, three samples from each mixture were introduced in accelerated carbonation conditions for 120 days, while other three samples were kept in normal laboratory conditions for this period of time. As shown in Figure 7.4 the samples kept in normal environmental conditions presented an increase in compressive strength varying between 6% and 31%. This is a normal phenomena due to the continues hydration and hardening of the cement matrix. The strength development of the samples at the same age, but kept under high CO_2 concentration, is considerably higher. The effect of carbonation was an increase of the compressive strength with 7% to 15%, additional to the increase under normal conditions. In general the samples prepared in the second phase showed a greater strength development over time, allthough the curing and exposure conditions were similar.

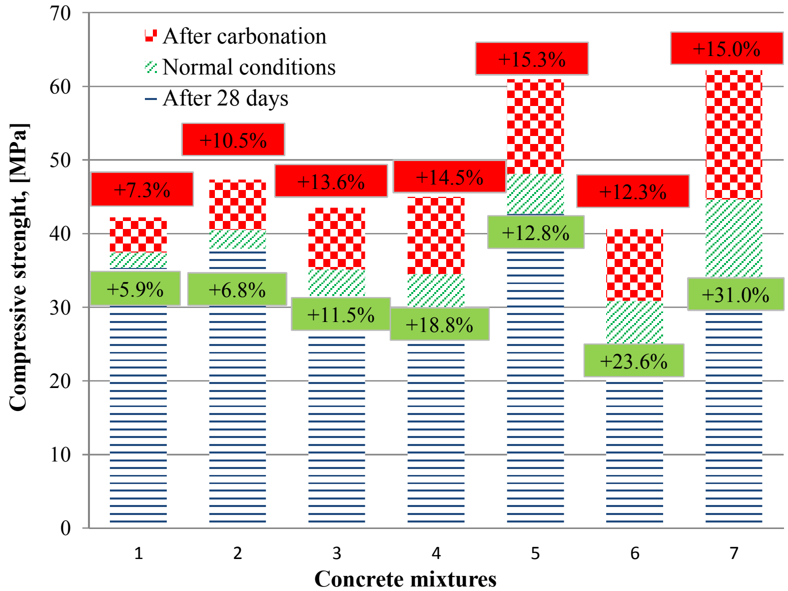


Figure 7.4. Increase of concrete compressive strength due to carbonation

The carbonation depth has been determined according to SR CR 12793 [156], using the traditional phenolphthalein indicator. The samples were split into both directions and the freshly broken surface was sprayed with a 1% phenolphthalein solution. The carbonation depth has been measured in both directions, on five points each side, making the average rounded at the nearest to 0.5mm. Figure 7.5 presents a split and sprayed sample for both casting and perpendicular directions.

Figure 7.5. Split and sprayed sample in casting and perpendicular direction

It can be observed that the casting direction influenced the carbonation profile. At bottom side, the carbonation depth was considerably higher in comparison to the top side, where almost no carbonation was visible. The lateral sides were slightly influenced. Split in perpendicular direction, the samples showed a uniform carbonation profile.

Some of the explanations for this phenomenon to occur could be that during the vibration of the moulded samples, cement matrix ascended to the top side, increasing the quantity of reaction products for carbonation. Practically, the CO_2 could not diffuse into the concrete, because it was already consumed at the surface layer, forming a very compact concrete matrix. At the bottom side, a lower quality of concrete remains, due to segregation, which still contains cementitious components for carbonation, but permits a much better CO_2 penetration.

The carbonation depths over time of the seven concrete mixtures are presented in Figure 7.6 and 7.7 grouped in function of the cement type. The experimental values are compared with the theoretical values calculated with formula 5.14 and the correction factors from Table 5.1 and Table 5.2. The compressive strength at 28 days has been considered for the calculation.

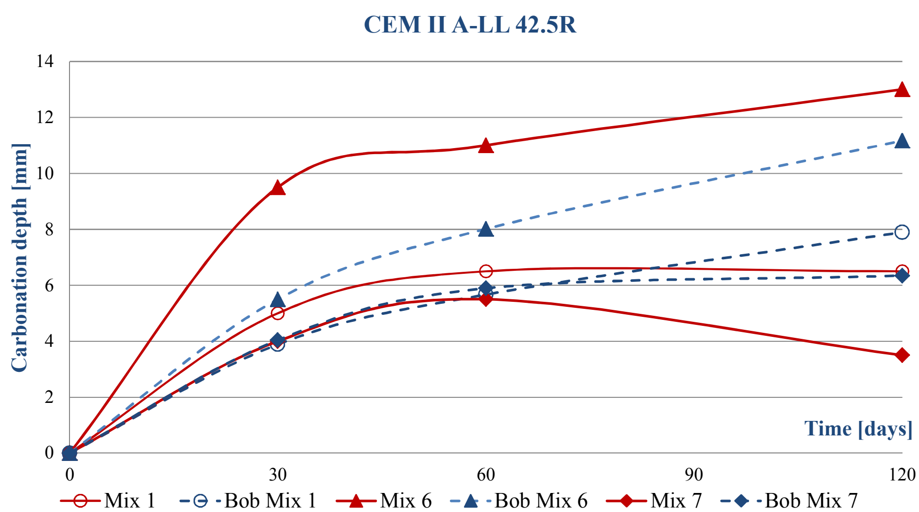


Figure 7.6. Carbonation depth vs time for concrete mixes with CEM II/A-LL 42.5R

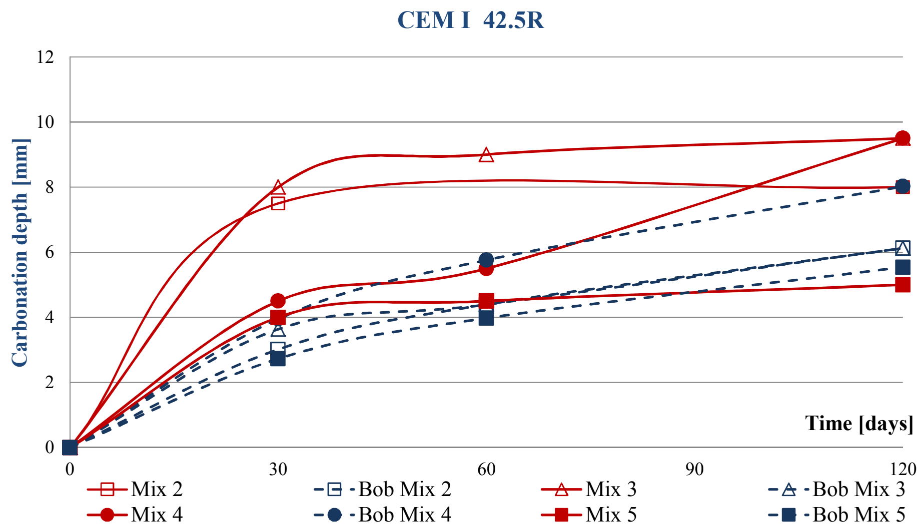


Figure 7.7. Carbonation depth vs time for concrete mixes with CEM I 42.5R

There are certain issues involved with the accelerated carbonation, which need to be taken into consideration for a more precise interpretation of the experimental results performed on concrete exposed to accelerated carbonation conditions. Using higher CO_2 concentrations for carbonation of concrete, may greatly increase internal humidity of concrete, because of water being produced rapidly due to a high rate of carbonation [149]. Due to high saturation of pores in concrete, it may become difficult for CO_2 to diffuse further in the pore network and may result in a reduced penetration rate of carbonation. Even the products of accelerated carbonation of cement may differ from those produced under natural carbonation.

In general there was a good correlation between theoretical and experimental results. The key parameter which influenced the carbonation rate was the concrete compressive strength, as it is shown in Table 7.2. The addition of lime to the cement had minor influence on the carbonation tendency, as no direct effect could be observed on the experimental results.

Table 7.2. Experimental and theoretical carbonation depths

Mix design	Cement type	Compr. strength [MPa]	Exper. carbonation depth [mm]			Theo. carbonation depth [mm]		
			30d	60d	120d	30d	60d	120d
1	II A-LL 42.5	35	5.0	6.5	6.5	3.9	5.7	7.9
2	I 42.5	38	7.5	7.5	8.0	3.0	4.4	6.1
3	I 42.5	31	8.0	9.0	9.5	4.4	3.6	6.1
4	I 42.5	29	4.5	5.5	9.5	4.0	5.8	8.0
5	I 42.5	42	4.0	4.5	5.0	2.8	4.0	5.5
6	II A-LL 42.5	25	9.0	11.0	13.0	5.5	8.0	11.2
7	II A-LL 42.5	44	3.5	5.0	3.5	4.0	5.9	6.35

7.1.3. CO_2 uptake

The experimental procedure through direct mass gain resulted in the quantity of absorbed CO_2 by the samples over different periods of exposure time. In order to determine the CO_2 uptake capacity of $1m^3$ of carbonated concrete, the volume of carbonated concrete is required for each sample. For a more accurate result, image processing, combined with the average carbonation depth has been applied, as shown in Figure 7.8.

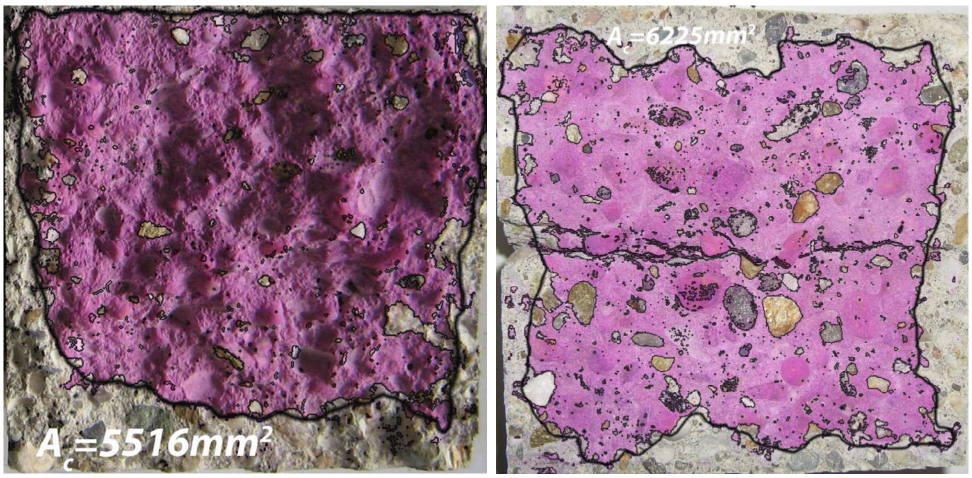


Figure 7.8. Carbonated area obtained by image processing in both directions

The carbonated volume is correlated with the increased mass, resulting the CO_2 uptake capacity of $1m^3$ of carbonated concrete. The values for CO_2 uptake has been determined with the average volume of the carbonated concrete obtained by splitting the samples in both directions. The CO_2 uptake capacity of the seven concrete mixtures determined by direct mass gain are represented in Figure 7.9.

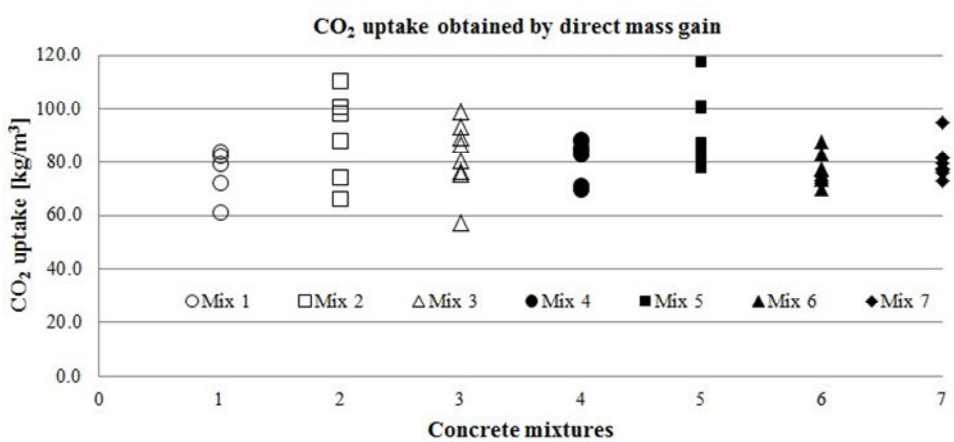


Figure 7.9. Experimental CO_2 uptake obtained by direct mass gain

7.1.4. Degree of carbonation „a”

The degree of carbonation has been calculated by combing the formula proposed by Lagerblad (Eq. 5.19) with the experimental results obtained for direct CO_2 uptake. An analytical and graphical procedure has been used and the results are presented in Figure 7.10 grouped in function of cement type.

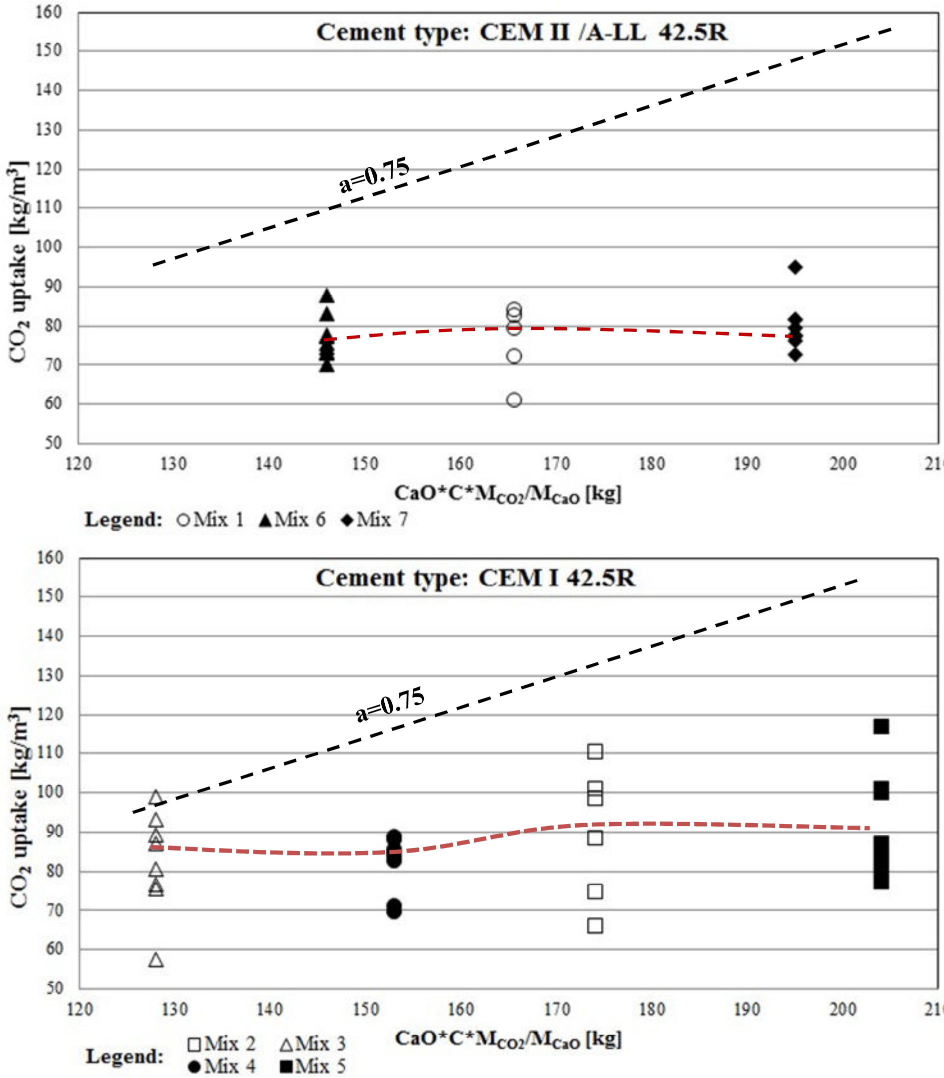


Figure 7.10. Determination of carbonation degree „a” in function of cement type

The experimental uptake is represented on the vertical axis, while the abscissa is the product between cement content, wt% of CaO in the cement and the molar weights. According to Eq. 5.19, for a constant carbonation degree of 75%, the uptake would increase in a linear way with the increase of the of the cement content. The experimental determinations showed that the uptake is almost constant for the different concrete mixes, which underlines the fact, that the carbonation degree is not a constant value. As shown in Figure 7.11 the carbonation degree is mainly depending on the concrete compressive strength. As in the case of carbonation rate, the carbonation degree is higher for low concrete quality and is decreasing for higher concrete classes.

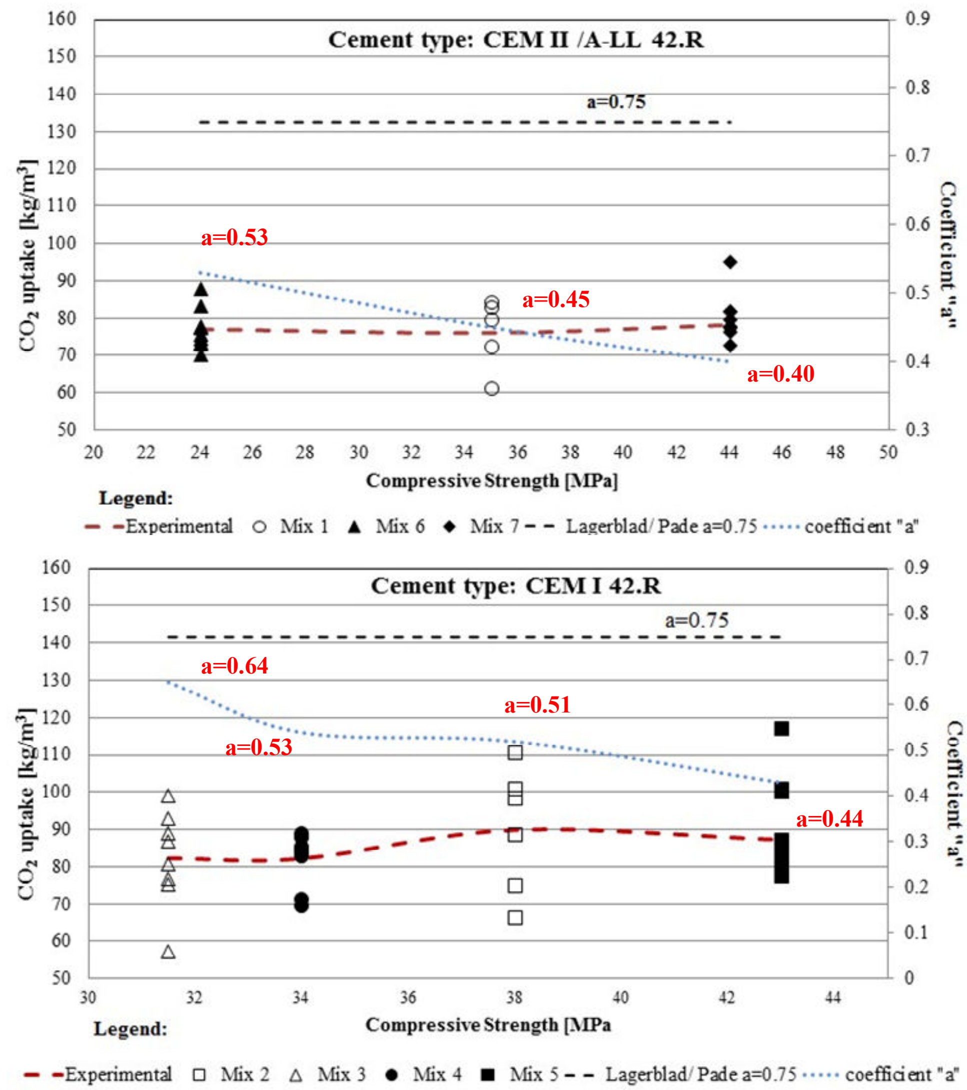


Figure 7.11. Variation of carbonation degree in function of cement type and concrete compressive strength

A new formula has been proposed for the calculation of the CO_2 uptake based on the experimental results, which corrects formula 5.19.

$$U = \frac{1}{e^{c \times f_c / 55}} \times CaO \times C \times \overline{x} \times S_{exp} \times \frac{M_{CO2}}{M_{CaO}} \, [kg] \quad (7.1)$$

Where:

- f_c – concrete compressive strength;
- c – correction factor for binder type, taken from Table 5.2;
- CaO – the amount of CaO in cement (wt %);
- C – Portland cement in concrete (kg/m^3);
- $\overline{x}$ – carbonation depth (mm);
- S_{exp} – exposed surface (m^2);
- M – molar weights of oxides=0.785;

The experimental and theoretical variation of the carbonation degree, related to the concrete compressive strength and the CO_2 uptake capacity of the seven concrete mixtures are shown in Figure 7.12. and 7.13. Formula (7.1) offers a good correleation for the carbonation degree as well, as for the CO_2 uptake. The theoretical CO_2 uptake capacity has been calculated with formula 7.1, but without considering the volume of the carbonated concrete.

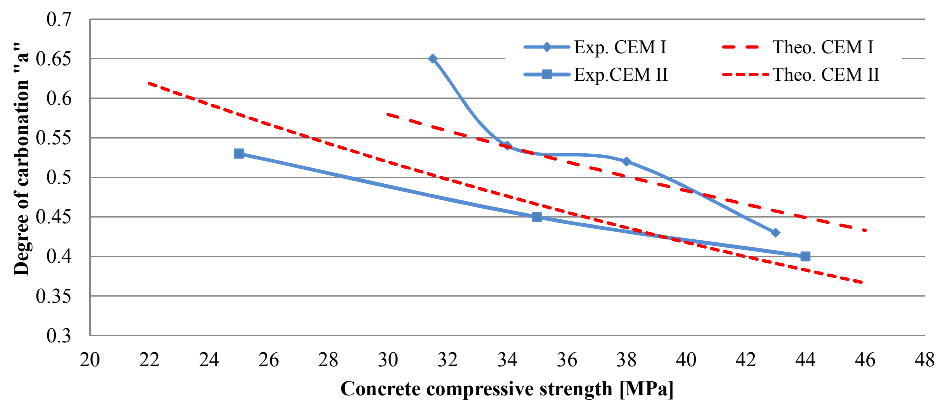


Figure 7.12. Variation of carbonation degree vs concrete compressive strength

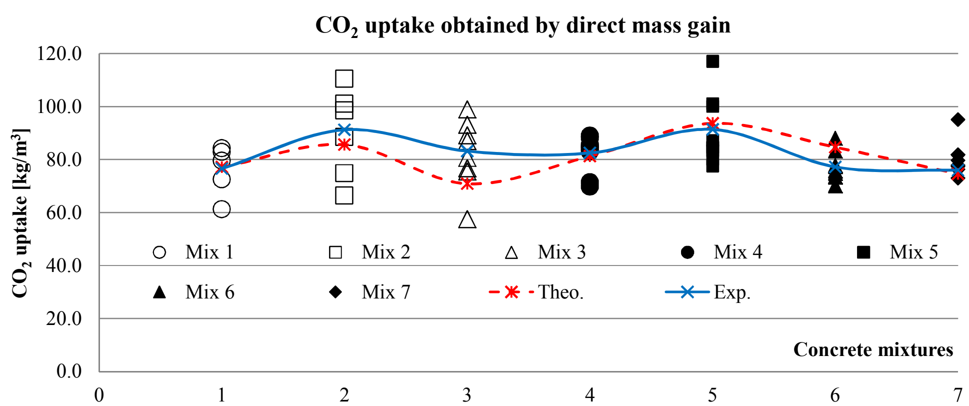
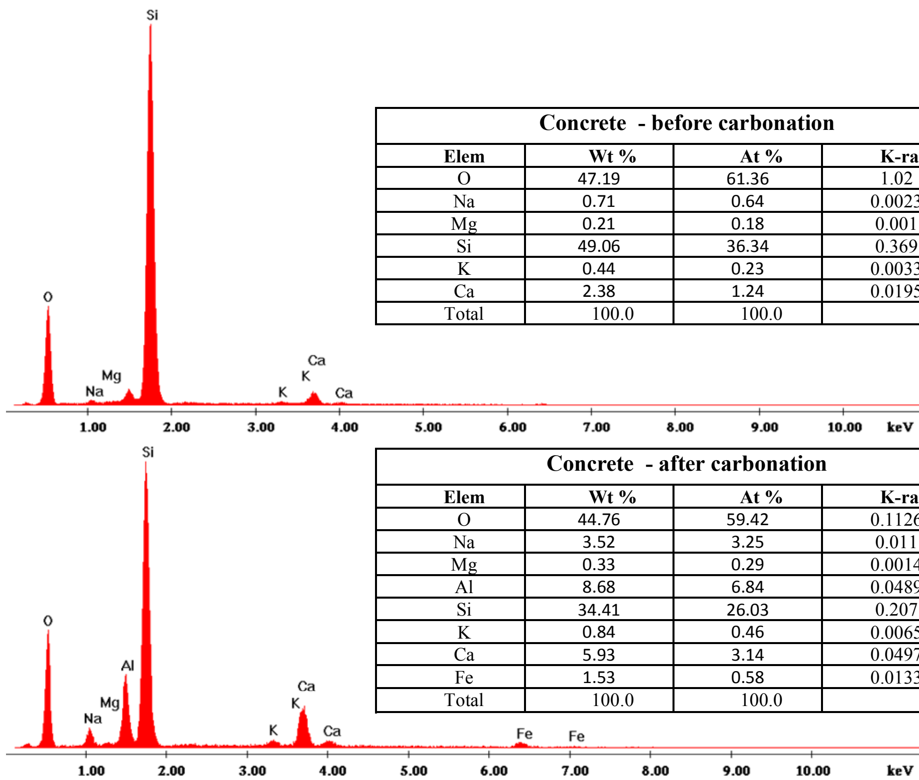


Figure 7.13. Experimental and theoretical CO_2 uptake capacity of the 7 concrete mixes

7.2. SEM/EDAX

SEM and EDAX analysis have been performed on both non-carbonated and carbonated concrete. Their purpose was to measure the carbon content in the samples before and after carbonation, in order to see how much CO_2 has been absorbed by the concrete. As it can be seen in Figure 7.14 neither in the X-ray spectrum of noncarbonated concrete sample, nor in that of the carbonated one could carbon peaks be identified. The compositional analysis showed great amount of silicium and oxigen molecules, which originates mainly from the cement, but also from powderized aggregate, but no presence of carbon. The analysis were repeated with different powdery samples, but no concludent results were obtained. For this reason the SEM/EDAX analysis have not been continued.



Concrete - before carbonation			
Elem	**Wt %**	**At %**	**K-ratio**
O	47.19	61.36	1.02
Na	0.71	0.64	0.0023
Mg	0.21	0.18	0.001
Si	49.06	36.34	0.369
K	0.44	0.23	0.0033
Ca	2.38	1.24	0.0195
Total	100.0	100.0	

Concrete - after carbonation			
Elem	**Wt %**	**At %**	**K-ratio**
O	44.76	59.42	0.1126
Na	3.52	3.25	0.011
Mg	0.33	0.29	0.0014
Al	8.68	6.84	0.0489
Si	34.41	26.03	0.207
K	0.84	0.46	0.0065
Ca	5.93	3.14	0.0497
Fe	1.53	0.58	0.0133
Total	100.0	100.0	

Figure 7.14. Energy-dispersive X-ray spectrums of concrete samples before and after carbonation

7.3. XRD

The X-Ray diffraction analysis have been performed on homogeneous powder mixtures of carbonated concrete, taken from different depths and surface points as indicated by the phenolphthalein test. As shown in Figure 7.15, the XRD test results indicated four main crystalline structures in the non-carbonated concrete sample: Quartz (SiO_2), Feldspar, $Ca(OH)_2$ and $CaCO_3$. Quartz and feldspar originate mainly from the aggregates and are present in every sample. However, the presence of $Ca(OH)_2$ indicated the samples as being noncarbonated. The small peaks of $CaCO_3$ could have resulted from the carbonation of the samples during preparation, as it was not carried out in a CO_2 free environment. From Figure 7.16 it is evident that there exists a peak for $CaCO_3$ but no peak for $Ca(OH)_2$, which indicates that the sample is fully carbonated.

XRD is a usefull qualitative method to determine the carbonation front of concrete samples. As the determination of the carbonation profile was not the main purpose of the experiment, the traditional phenolphtalein indicator has been used for such determinations, which can offer sufficient informations for the proposed experiment.

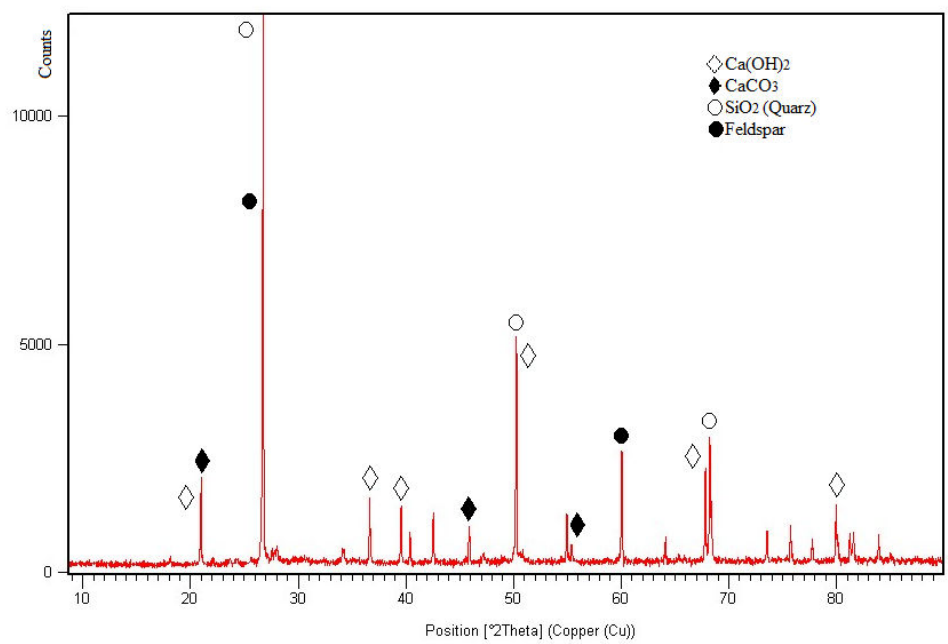


Figure 7.15. XRD result of non-carbonated concrete

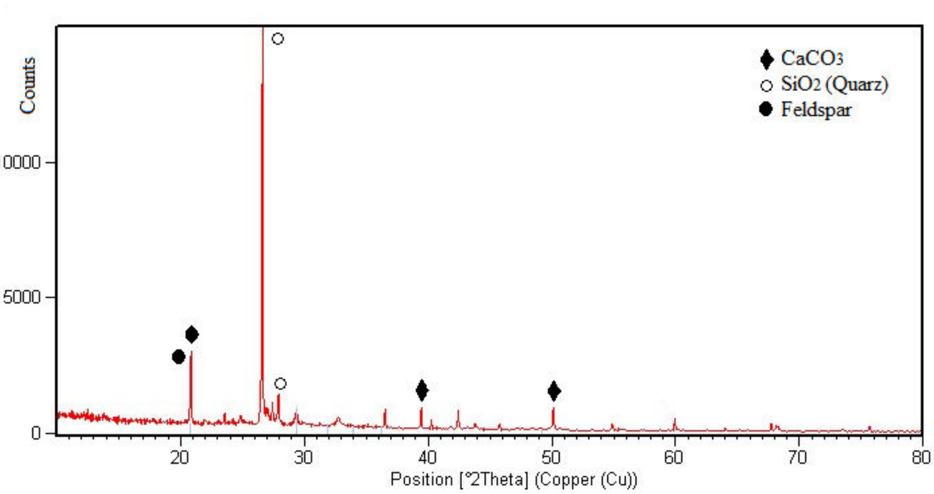


Figure 7.16. XRD result of fully carbonated concrete

7.4. TGA

Thermal gravimetric analysis (TGA) have been performed on powder samples from each concrete mixture taken before and after carbonation. The same powder samples have been used as for SEM/EDAX and XRD.

Each chemical component is characterized by its own temperature range of decomposition and a specific mass loss involving gaseous emissions. Table 7.3 shows the temperature ranges of the cement-hydrate decomposition during TGA measurements for a heating rate of 10°C /minute, as presented by [161].

Table 7.3.Temperature ranges of the cement-hydrate decomposition during TGA

Temperature range	**Decomposition of hydrates or carbonated products**
25 to 430°C	Free and adsorbed H_2O, H_2O from CSH, AFt, AFm, gypsum, and CO_2 adsorbed in CSH
430 to 520°C	H_2O from portlandite $Ca(OH)_2$
520 to 620°C	OH^- from structure of hydrates, structure H_2O or CO_2 from vaterite, and CSH carbonation
650 to 720°C	CO_2 from calcite of carbonation
720 to 900°C	CO_2 from calcite of aggregates
900 to 1150°C	Other structural H_2O

The results for noncarbonated and carbonated samples are presented in Figures 7.17 to 7.30. The figures show simultaneously the thermogravimetric curve (TG), the derived thermogravimetric curve (DTG) and the curve from differential thermal analysis (DTA), coupled with mass spectroscopy (ion currents for H_2O mass number 18 and CO_2 mass number 44).

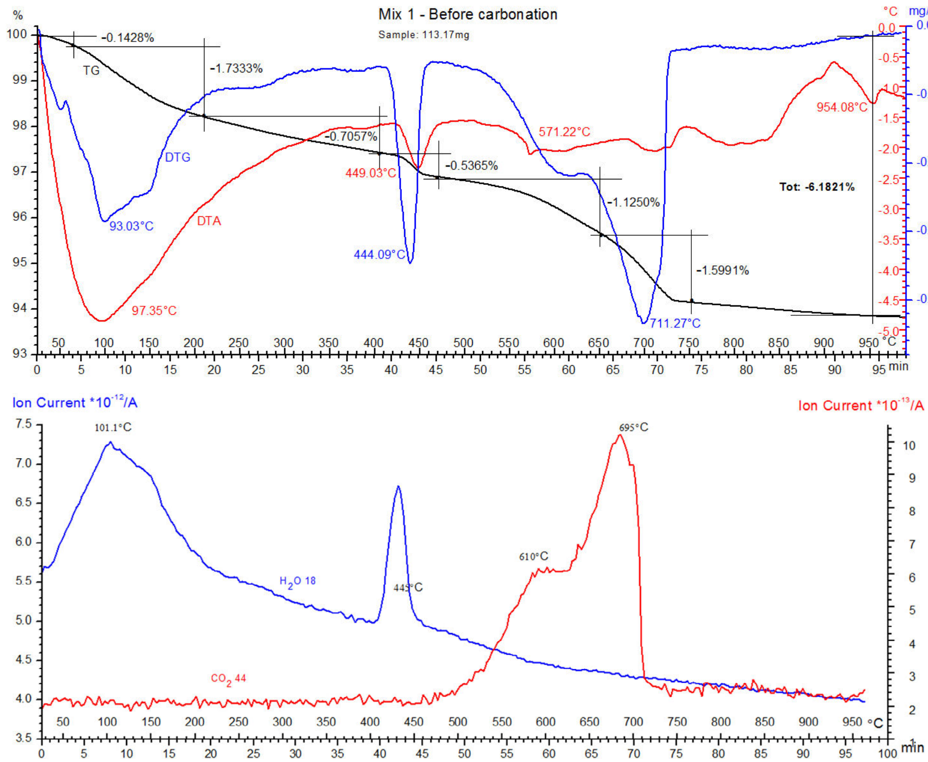
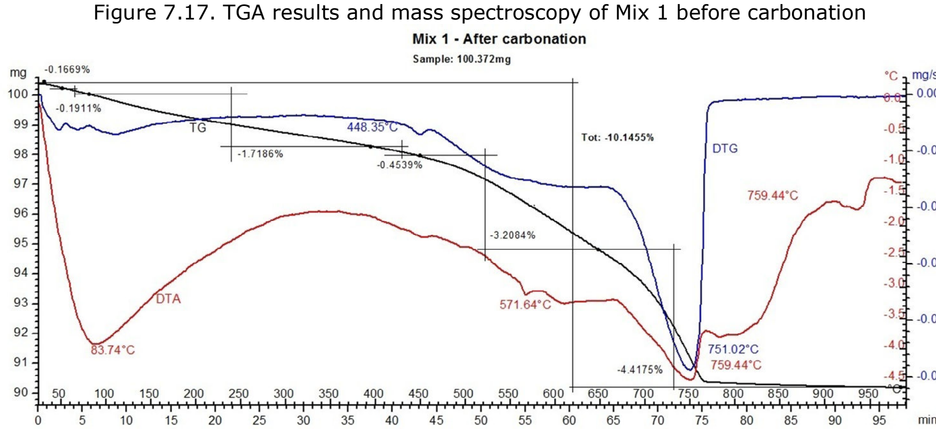


Figure 7.17. TGA results and mass spectroscopy of Mix 1 before carbonation



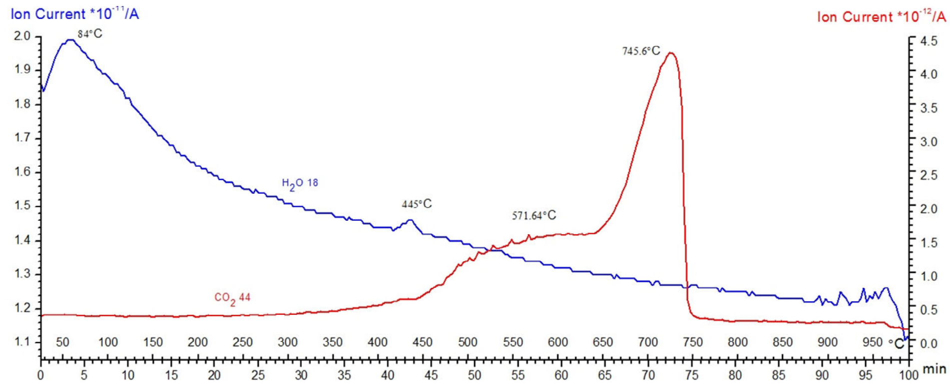


Figure 7.18. TGA results and mass spectroscopy of Mix 1 after carbonation

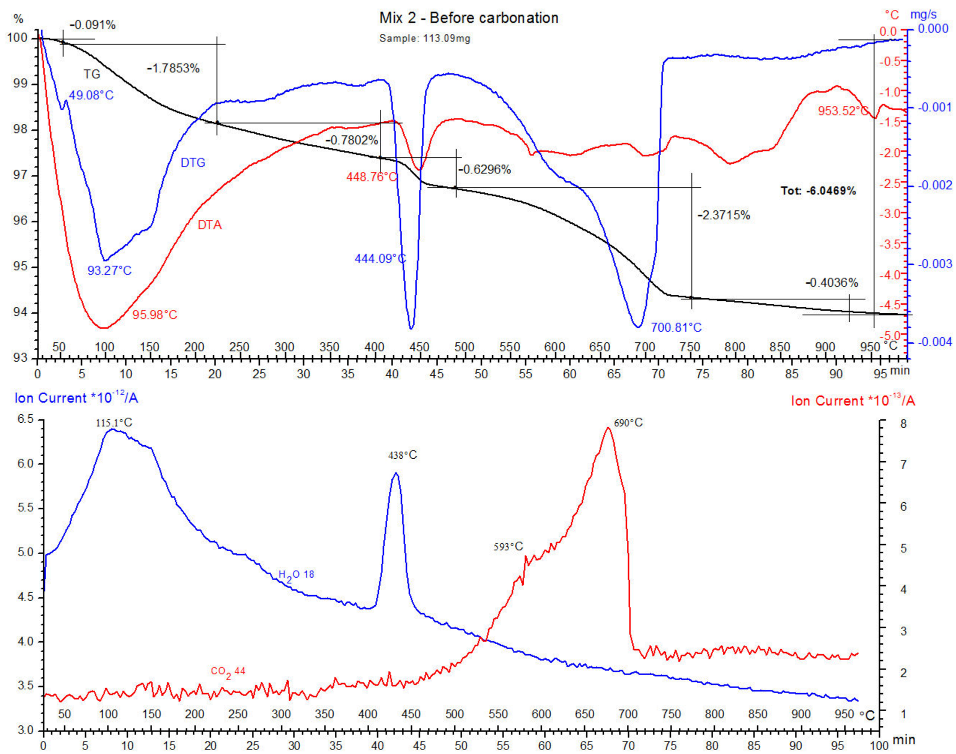


Figure 7.19. TGA results and mass spectroscopy of Mix 2 before carbonation

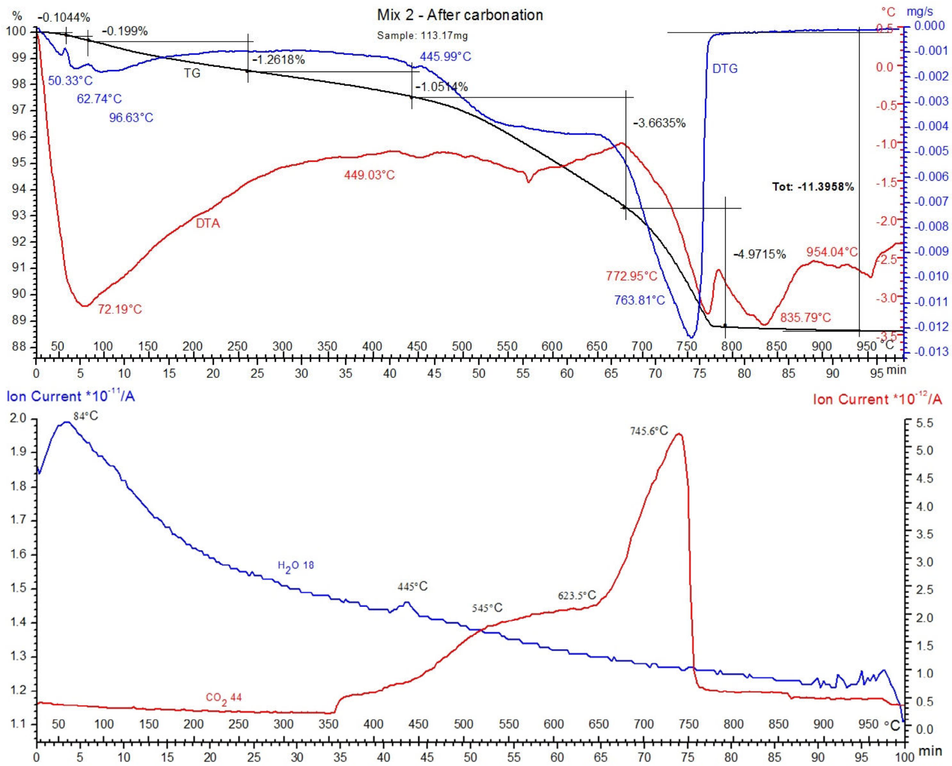
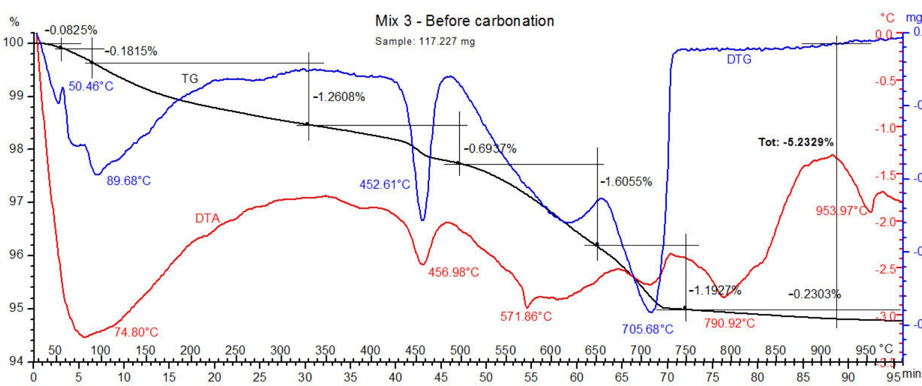


Figure 7.20. TGA results and mass spectroscopy of Mix 2 after carbonation



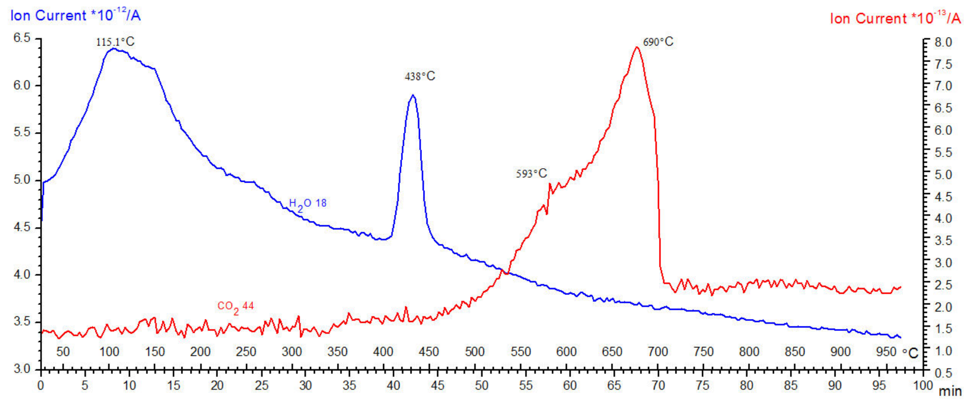


Figure 7.21. TGA results and mass spectroscopy of Mix 3 before carbonation

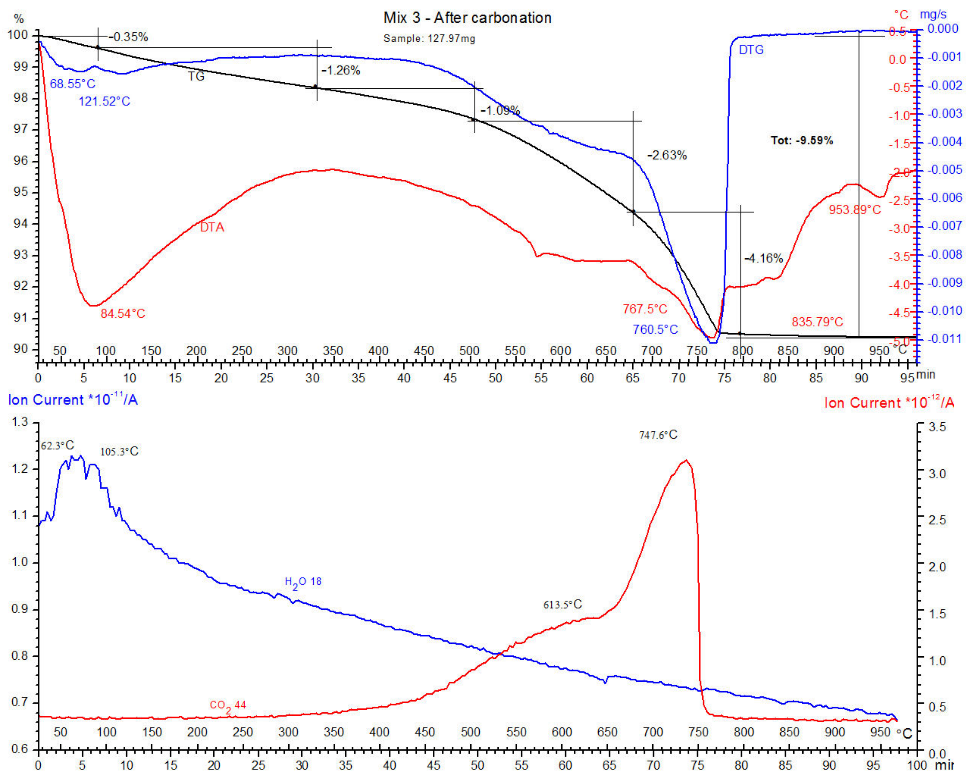


Figure 7.22. TGA results and mass spectroscopy of Mix 3 after carbonation

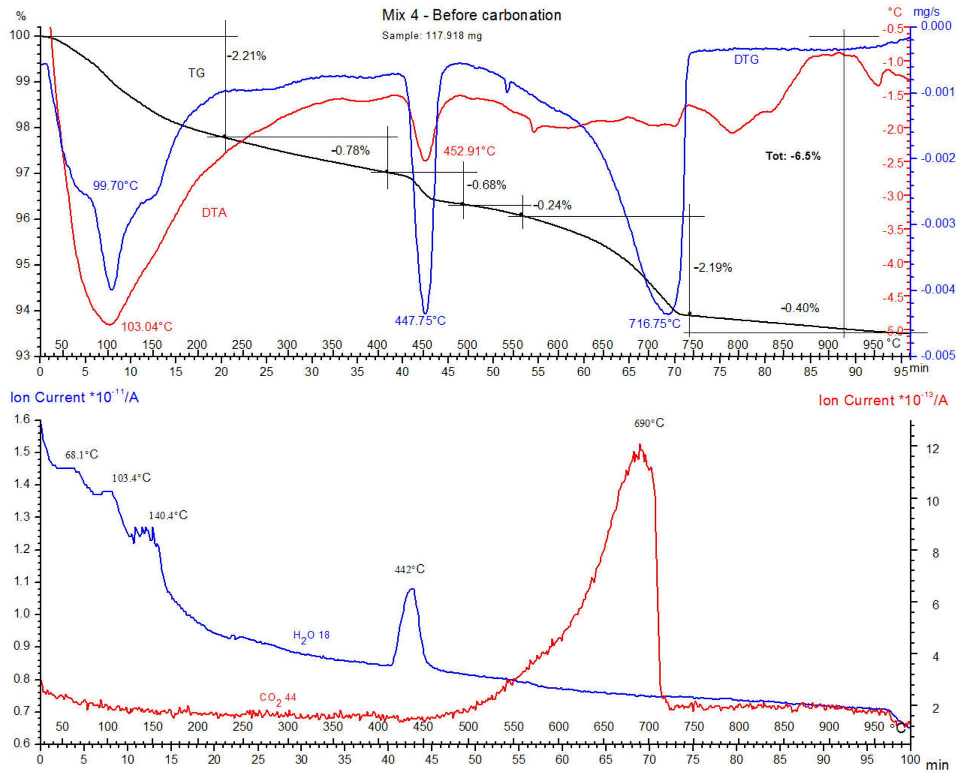
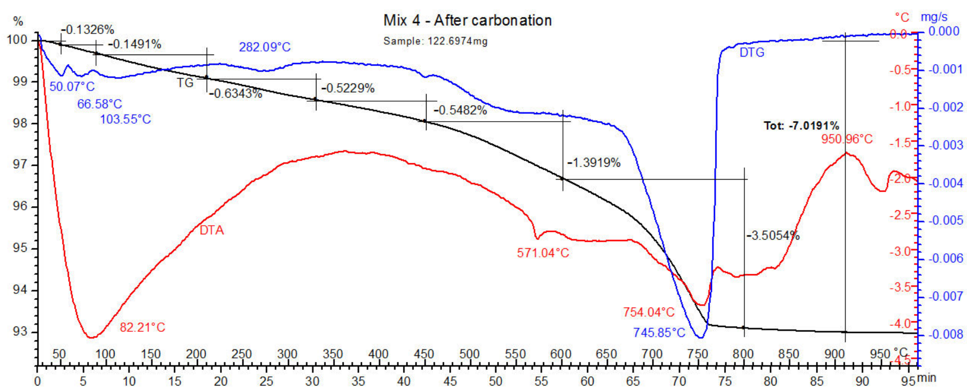


Figure 7.23. TGA results and mass spectroscopy of Mix 4 before carbonation



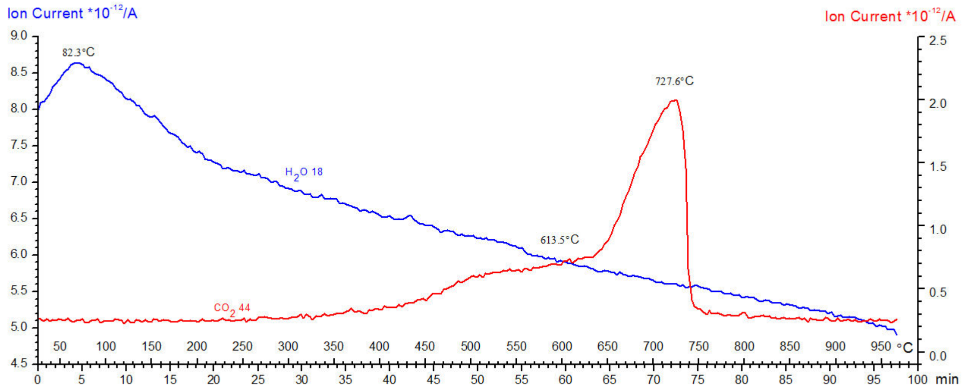


Figure 7.24. TGA results and mass spectroscopy of Mix 4 after carbonation

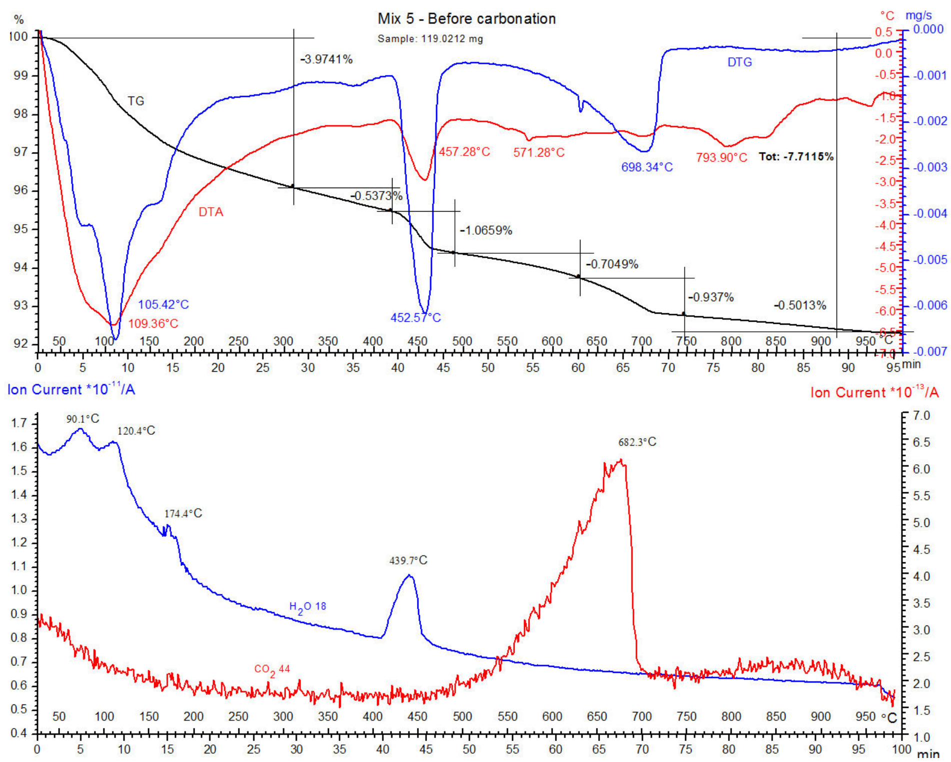


Figure 7.25. TGA results and mass spectroscopy of Mix 5 before carbonation

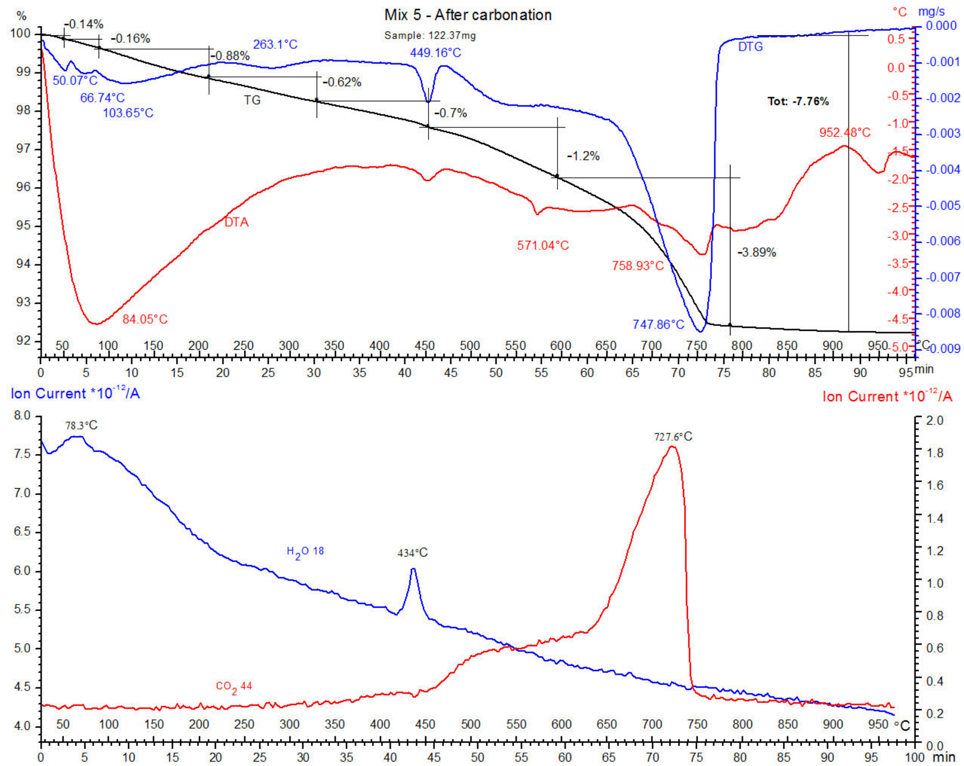
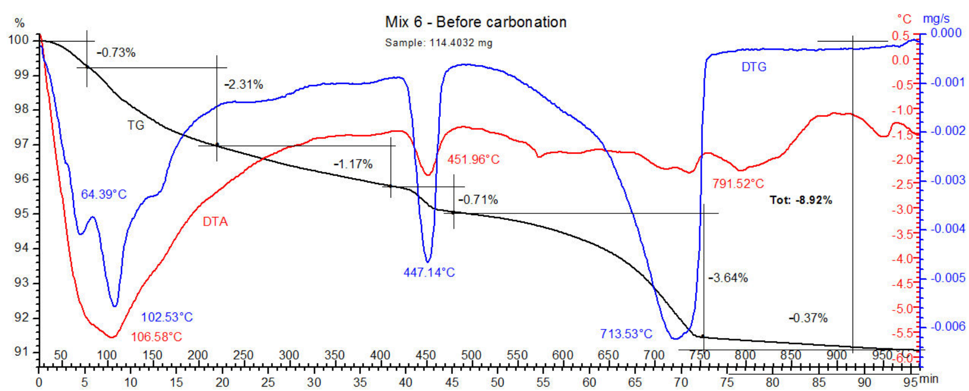


Figure 7.26. TGA results and mass spectroscopy of Mix 5 after carbonation



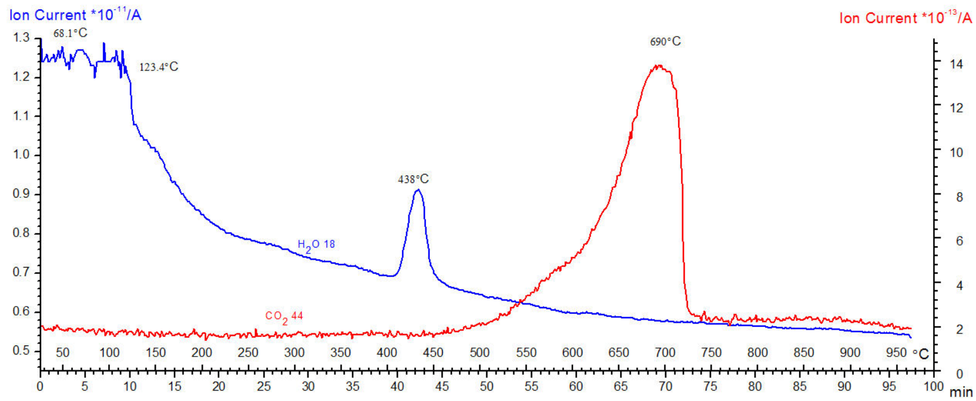


Figure 7.27. TGA results and mass spectroscopy of Mix 6 before carbonation

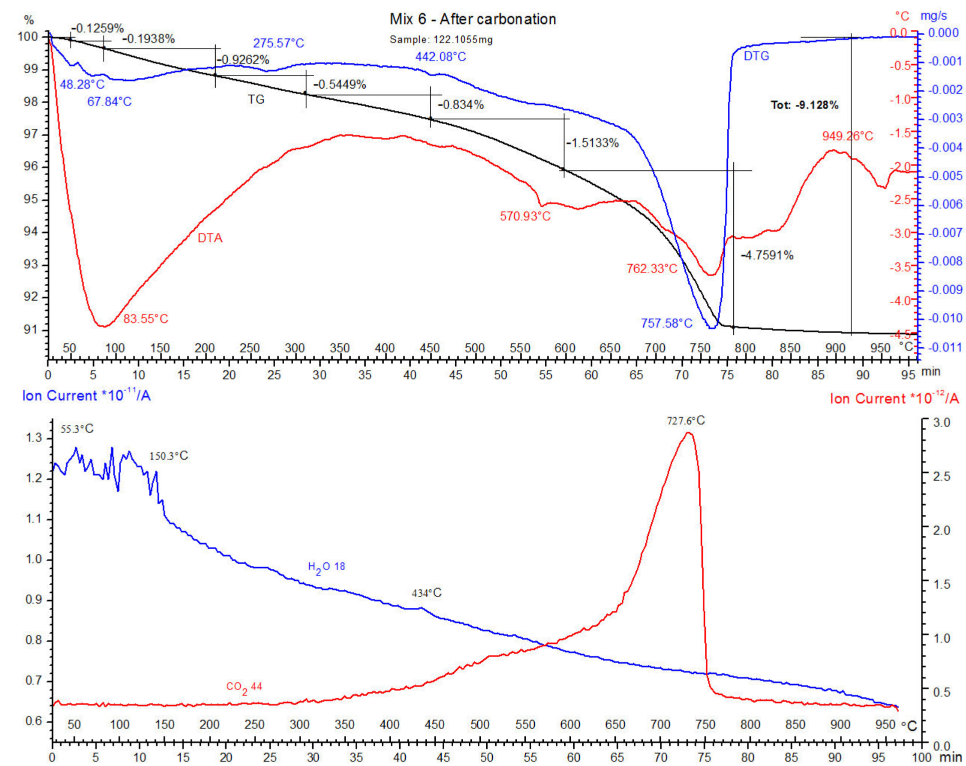


Figure 7.28. TGA results and mass spectroscopy of Mix 6 after carbonation

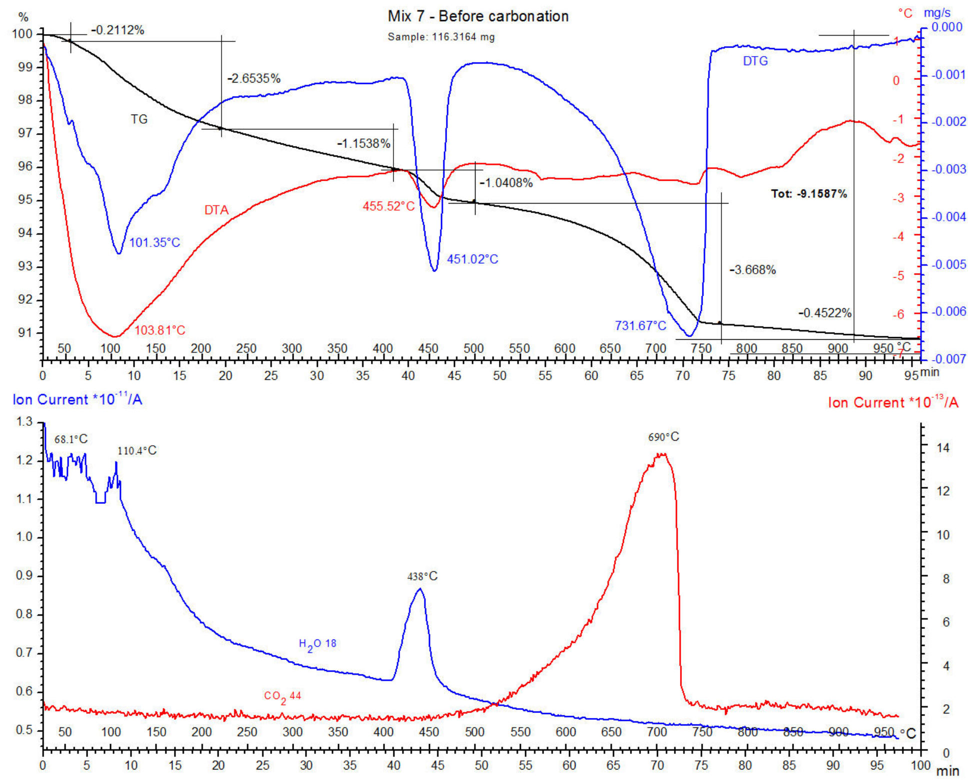
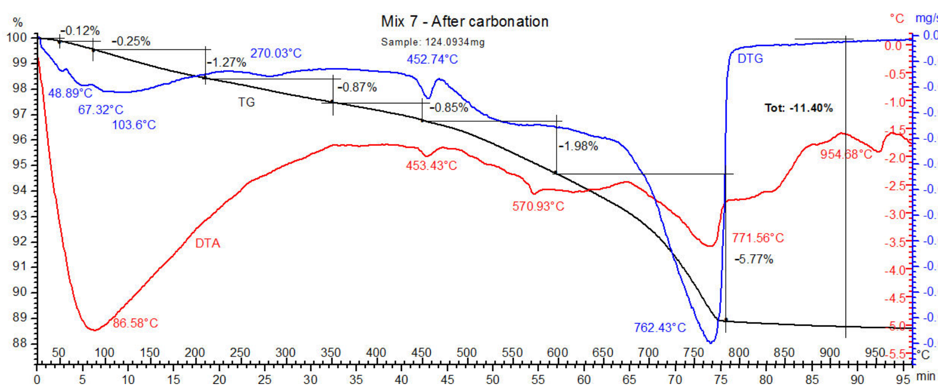


Figure 7.29. TGA results and mass spectroscopy of Mix 7 before carbonation



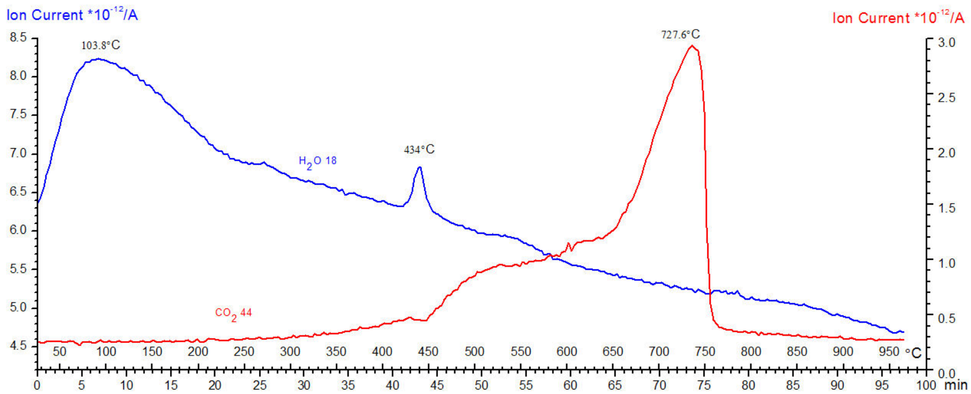


Figure 7.30. TGA results and mass spectroscopy of Mix 7 after carbonation

For all specimens in the noncarbonated phase, the characteristic sharp endotherm peak in the DTA and DTG curves at around 450°C indicated the decomposition of $Ca(OH)_2$ formed during hydration. The initial portlandite content has been calculated from the weigth loss due to dehydroxylation, measured from the TG curve between initial and final temperature of the corresponding peak, considering the following decomposition reaction:

$$\underset{[74g/mol]}{Ca(OH)_2} \rightarrow \underset{[56g/mol]}{CaO} + \underset{[18g/mol]}{H_2O} \quad (7.2)$$

$$\%CH_{H-loss} = \frac{H_{loss} \cdot 74}{18} = 4.11 \cdot H_{loss} \quad (7.3)$$

The CO_2 loss in the decarbonation region (550 - 750°C) has been deducted from the weight loss of the carbonated samples. In this manner a source of error could be eliminated, because the initial amount of carbonates can be formed both from the carbonation of CH and that of CSH. The initial carbonation of samples, before the accelerated carbonation test, could be due to atmospheric exposure during the sample preparation, as it was not carried out in a CO_2 free environment.

For all carbonated specimens the total CO_2 content and the extent of carbonation of CH and CSH was estimated. The amounts of calcium hydroxide and carbonates before carbonation has been taken as reference points. Equations 7.4 to 7.8 has been used to calculate the required parameters, as also presented in [162]:

- the amount of %CC which can be formed by the full carbonation of the initial %CH (Eq.7.5);
- neccesary $\%CO_2$ content for full carbonation of CH (Eq. 7.6);
- the amount of %CC from the loss of CO_2 during decarbonation (Eq. 7.7);
- the amount of %CH from the decarbonisation loss (Eq. 7.8)

$$\underset{[74g/mol]}{Ca(OH)_2} + \underset{[44g/mol]}{CO_2} \rightarrow \underset{[100g/mol]}{CaCO_3} + \underset{[18g/mol]}{H_2O} \quad (7.4)$$

$$\%CC = \frac{\%CH \cdot 100}{74} = 1.35 \cdot \%CH \quad (7.5)$$

$$\%CO_2 = \frac{\%CC \cdot 44}{100} = 0.44 \cdot \%CC \quad (7.6)$$

$$\%CC = \frac{\%C_{loss} \cdot 100}{44} = 2.27 \cdot C_{loss} \quad (7.7)$$

$$\%CH_{C-loss} = \frac{\%CC \cdot 74}{100} = \frac{2.27 \cdot C_{loss} \cdot 74}{100} = 1.68 \cdot C_{loss} \quad (7.8)$$

Once the %CC from calcium hydroxide has been estimated, the %CC arising from CSH may be calculated. It is the difference between the total amount of existing carbonates after carbonation and the carbonates formed from calcium hydroxid.

From the TGA of the carbonated samples it could be generally observed that the CC ensuing from the carbonation of portlandite dissociated mainly at high temperature and may correspond to calcite, which is a very stable crystalline form of CC. The other carbonates, dissociated at lower temperatures (530 - 650°C) resulted from the degradation of other hydrates, mainly CSH, as also presented in other literature results [114],[159]. The carbonation of CSH led to the formation of vaterite, which is a more unstable type of CC, imperfectly crystallized or having finer crystals [163].

The CO_2 content and carbonation degree in the carbonated samples, measured by TGA has been compared with the values obtained through the direct mass gain, as summarized in Table 7.4. To make the correlation between the mass gain and CO_2 content, formula 7.9 has been applied.

$$\begin{aligned} & mass_{initial} + CO_2 \rightarrow mass_{final} + H_2O \\ & mass_{final} - mass_{initial} = \Delta m = CO_2 - H_2O = \\ & = CO_2 - 18/44 \cdot CO_2 = 0.6 \cdot CO_2 \\ & \%CO_2 = 1.66 \cdot \%\Delta m \end{aligned} \quad (7.9)$$

Table 7.4. TGA results compared with direct mass gain method

Mix	Before carbonation		After carbonation (TGA)					Mass gain	
	%CH	**Nec. $\%CO_2$**	**%CH**	**%CC from CH**	**%CC from CSH**	**Tot $\%CO_2$**	**Carb. Deg.**	**Tot. $\%CO_2$**	**Carb. degree**
1	2.17	1.29	0	2.92	3.68	2.91	>0.5	2.17	0.45
2	2.57	1.53	0	3.47	5.97	4.16	>0.5	2.22	0.51
3	2.81	1.70	0	3.80	2.66	2.89	>0.5	2.92	0.64
4	2.80	1.66	0.24	3.78	0	1.52	0.45	1.61	0.53
5	4.38	2.60	0	5.91	0.80	2.95	0.51	1.42	0.44
6	2.90	1.73	0	3.91	0.84	2.1	0.52	2.17	0.53
7	4.27	2.54	0.19	5.51	0	2.43	0.47	1.03	0.41

The comparison might not be completlety accurate, as it is based on some assumptions. Only one TGA of each carbonated concrete mixture has been made. The TGA were made on powder samples, which were uniformly taken from the carbonated layer, as indicated by the phenolphtalein test. It means that the analyzed sample might indicate a punctual CO_2 content of a fully or partially carbonated concrete. On the other hand, the results obtained by mass gain represented an average value of the CO_2 content. This is why in case of some mixtureses the CO_2 content by TGA is much higher then by direct mass gain, as shown in Figure 7.31.

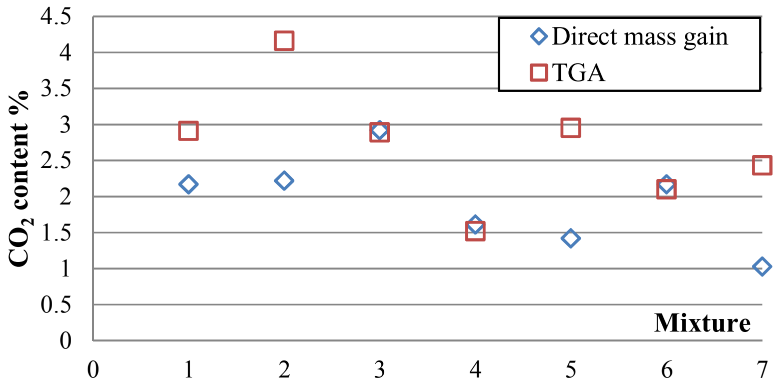


Figure 7.31. CO_2 content by TGA and direct mass gain

8. CONCLUSIONS AND PERSONAL CONTRIBUTIONS

8.1. Conclusions

Sustainability is a very complex and ambiguous expression, so in order to be approached correctly it has to be clearly defined. The construction industry plays an important role in the social and economic development, but it also has a great impact on the local and global environment. It is a major consumer of land and raw materials and generates a great amount of waste. Furthermore, constructions through their entire life cycle use significant amounts of nonrenewable energy and contribute to the emission of greenhouse gases and other gaseous wastes. A correct sustainability assessment of construction works must find the **balance between environmental impacts, economic benefits and social development**, as sustainability is defined at the confluence of all three dimensions.

The assessment, quantification and combination of a large number of parameters can be accomplished using **evaluation models and rating tools**, which can help engineers, owners and authorities to **identify the sustainability performances of the building**. Further on, different solutions can be evaluated and compared so that eventually the solution with the best overall performance can be applied.

Concrete has the property to absorb and to bind atmospheric CO_2 through the process of carbonation. A major part of the deliberated CO_2 can be reabsorbed by the exposed concrete surfaces in both primary and secondary life, reducing the environmental impact of concrete structures in a life cycle perspective. The uptake in the secondary life can be significantly higher than in primary life, because the exposed surface area to CO_2 of the crushed concrete, re-used as RCA, is much greater and carbonation can take place in better conditions.

The CO_2 uptake calculation requires two main parameters:

- **carbonation depth:**
  A theoretical formula has been presented, which takes into account the effects of binder type, environmental conditions (relative humidity and CO_2 concentration) and concrete compressive strength. This parameter is neccessary for the calculation of the carbonated concrete volume.
- **CO_2 uptake capacity of concrete (degree of carbonation):**
  Through experimental determinations, the uptake has been determined directly on seven concrete mix designs, considering as variables the concrete quality and binder type. The degree of carbonation has been obtained, which, as in the case of the carbonation rate, is also depending on the concrete compressive strength and cannot be considered a constant value. A practical formula has been proposed, which permits a quick calculation of the CO_2 uptake for different concrete elements.

The influences of admixtures, other cement types and environmental conditions on the carbonation degree and CO_2 uptake of concrete through carbonation are subjects of study for future research projects.

8.2. Personal contributions

The main contributions of the author can be considered as follows:

- brief literature study related to sustainable development and sustainability in the field of construction;
- critical review of existing international rating tools and certification programs related to the sustainability evaluation of construction works;
- development of two original sustainability evaluation models:
    - global model, which is a practical calculation tool, based on an Excel Worksheet; it includes simplified calculation procedures and database for different parameters, which eases the evaluation;
    - specific model, which is a flexible and target oriented tool, based on quantitative equations;
- theoretical study regarding concrete carbonation and re-carbonation;
- literature study related to existing researches in the field of CO_2 uptake through concrete carbonation;
- development of an experimental program for the determination of the CO_2 uptake capacity of seven different concrete mix designs, using an original procedure;
- proposal of a practical calculation formula for CO_2 uptake, which considers directly the concrete compressive strength;
- validation of the results by other experimental methods as XRD and TGA, in collaboration with specialized laboratories;

The author conducted his studies at the Deparment of Civil Engineering and Building Services, in frame of the strategic grant POSDRU/88/1.5/S/50783, Project ID50783 (2009), co-financed by the European Social Fund – Investing in People, within the Sectoral Operational Programme Human Resources Development 2007 – 2013. During his doctoral studies the author published 11 papers (10 abroad and 1 in Romania) and 1 monography on topic, which are provided below in order of publication.

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APPENDIX A. MATERIAL DATABASE

A.1. Data for embodied energy and GHG emissions

Nr. Crt	Building Material	Unit	Density [kg/m^3]	EE [MJ/unit]	EC - CO_2 [kgCO_2/unit]	EC - CO_{2e} [kgCO_{2e}/unit]
1	Aggregate	kg	2240	0.083	0.0048	0.0052
2	Sand	kg	2240	0.081	0.0048	0.0052
3	Aluminium Cast Products	kg	2700	159	8.28	9.22
4	Aluminium Extruded	kg	2700	154	8.16	9.08
5	Aluminium Rolled	kg	2700	155	8.26	9.18
6	Asphalt, 4% binder content	kg	1700	2.86	0.059	0.066
7	Asphalt, 5% binder content	kg	1700	3.39	0.064	0.071
8	Asphalt, 6% binder content	kg	1700	3.93	0.068	0.076
9	General bitumen, flooring	kg	2400	51	0.47	0.51
10	Brass general (Blech)	kg	8500	44	2.46	2.64
11	Brass primary	kg	8500	80	4.2	4.8
12	Brass secondary	kg	8500	20	0.97	1.2
13	Calcium silicate	kg	1500	1.3	0.13	0.13
14	Brick, AAC, (BCA)	kg	600	3.5	0.412	0.412
15	Brick, Clay	kg	1600	3.91	0.36	0.36
16	Brick, ceramic	kg	2000	2.5	0.18	0.21
17	Brick, concrete	kg	2300	1.72	0.209	0.23
18	Tiles, Clay	kg	1600	6.5	0.45	0.48
19	Tiles, Ceramic	kg	1900	14.2	0.75	0.782
20	Tiles, artificial stone	kg	1900	1.27	0.2	0.227
21	Tiles, rock, cut	kg	2750	11.3	0.3	0.313
22	Tiles, rock, polished	kg	2750	14.2	0.36	0.38
23	Bronze	kg	8150	69	3.73	4.00
24	Carpet general	m^2	-	187	9.8	10.8
25	Carpet, Nylon (Polyamide). Pile weight 300g/m2	m^2	-	130	6.7	6.7
26	Carpet, Nylon (Polyamide). Pile weight 500g/m2	m^2	-	180	9.7	9.7
27	Carpet, Nylon (Polyamide). Pile weight 700g/m2	m^2	-	230	12.7	12.7
28	Carpet, Nylon (Polyamide). Pile weight 900g/m2	m^2	-	277	15.6	15.6
29	Carpet, Nylon.(Polyamide) Pile weight 1100g/m2	m^2	-	327	18.4	18.4
30	Carpet, Polyurethane	kg	24	72	3.76	3.76
31	Carpet, wool	kg	-	106	5.53	5.53
32	Ceramic, Fittings	kg	1700	20	1.07	1.14
33	Ceramic, Sanitary	kg	1700	42	2.34	2.61
34	Cement Portland CEM I	kg	1800	5.5	0.93	0.95
35	Cement Stone	kg	2380	0.825	0.121	0.121
36	Fibre Cement, Planks	kg	1800	4.3	1.63	1.63
37	Fibre Cement, Roofing	kg	1800	1.02	0.73	0.73
38	Cement CEM II/A-V 6-20%Fly ash	kg	1860	5	0.8	0.8

39	Cement, CEM II/B-V 21-35% Fly ash	kg	1860	4	0.65	0.66
40	Cement, CEM II/B-S 21-35% GGBS	kg	1860	4.5	0.6	0.6
41	Cement, CEM III/A-S 35-65% GGBS	kg	1860	3.6	0.5	0.5
42	Cement, CEM II/B-S 66-80% GGBS	kg	1860	2.6	0.31	0.31
43	Mortar (Cement:sand mix 1:3)	kg	1650	1.33	0.221	0.221
44	Mortar (Cement:sand mix 1:4)	kg	1650	1.11	0.182	0.182
45	Mortar (Cement:sand mix 1:5)	kg	1650	0.97	0.156	0.156
46	Mortar (Cement:sand mix 1:6)	kg	1650	0.85	0.136	0.136
47	Mortar (Cement: Lime: sand mix, 1:1/2:4.5)	kg	1600	1.34	0.213	0.213
48	Mortar (Cement: Lime: sand mix, 1:1:6)	kg	1600	1.11	0.174	0.174
49	Mortar (Cement: Lime: sand mix, 1:2:9)	kg	1600	1.03	0.155	0.155
50	Mortar (Gypsum)	kg	1800	1.42	0.213	0.213
51	Mortar (Lime)	kg	1650	1	0.08	0.085
52	Concrete 8/10 (0%CR)	kg	2400	0.7	0.097	0.104
53	Concrete 8/10 (15-25%CR)	kg	2400	0.62	0.08	0.085
54	Concrete 8/10 (26-50%CR)	kg	2400	0.5	0.058	0.067
55	Concrete 12/15 (0%CR)	kg	2400	0.76	0.106	0.114
56	Concrete 12/15 (15-25%CR)	kg	2400	0.66	0.091	0.096
57	Concrete 12/15 (26-50%CR)	kg	2400	0.598	0.07	0.079
58	Concrete 16/20 (0%CR)	kg	2400	0.81	0.115	0.123
59	Concrete 16/20 (15-25%CR)	kg	2400	0.73	0.097	0.106
60	Concrete 16/20 (26-50%CR)	kg	2400	0.62	0.079	0.085
61	Concrete 20/25 (0%CR)	kg	2400	0.86	0.124	0.132
62	Concrete 20/25 (15-25%CR)	kg	2400	0.77	0.106	0.111
63	Concrete 20/25 (26-50%CR)	kg	2400	0.7	0.086	0.93
64	Concrete 25/30 (0%CR)	kg	2400	0.91	0.131	0.14
65	Concrete 25/30 (15-25%CR)	kg	2400	0.73	0.11	0.125
66	Concrete 25/30 (26-50%CR)	kg	2400	0.71	0.89	0.97
67	Concrete 28/35 (0%CR)	kg	2400	0.95	0.139	0.148
68	Concrete 28/35 (15-25%CR)	kg	2400	0.865	0.12	0.1285
69	Concrete 28/35 (26-50%CR)	kg	2400	0.75	0.099	0.106
70	Concrete 32/40 (0%CR)	kg	2400	1.03	0.153	0.163
71	Concrete 32/40 (15-25%CR)	kg	2400	0.94	0.134	0.1425
72	Concrete 32/40 (26-50%CR)	kg	2400	0.83	0.111	0.118
73	Concrete 40/50 (0%CR)	kg	2400	1.17	0.176	0.188
74	Concrete 40/50 (15-25%CR)	kg	2400	1.065	0.154	0.163
75	Concrete 40/50 (26-50%CR)	kg	2400	0.93	0.125	0.135
76	Copper virgin	kg	8400	57	3.65	3.81
77	Copper 37% recycled	kg	8400	16.5	0.8	0.84
78	Glass	kg	2500	15	0.91	0.91
79	Insulation, Glasswool	kg	30	49	1.54	1.6
80	Insulation, Cellular Glass	kg	110	27	1.54	1.54
81	Insulation, Mineral wool	kg	12	16.6	1.2	1.28
82	Insulation, Paper wool	kg	215	20.17	0.63	0.63
83	Insulation, Polystyrene Expanded EPS	kg	18	96.2	3.68	4.02
84	Insulation, Polystyrene Extruded	kg	18	90.21	11.1	11.1
85	Insulation, Polyurethane	kg	30	102	4.06	4.84
86	Insulation, Rockwool	kg	70	16.8	1.05	0.12
87	Insulation, Corkboard	kg	500	50.3	1.16	1.19
88	Hydraulic lime	kg	2200	5.3	0.76	0.78
89	Lime CaO	kg	2200	6.1	0.99	1.05
90	Lime hydrated Ca(OH)2	kg	2211	4.8	0.76	0.86

91	Linoleum	kg	1200	25	1.18	1.21
92	Paint, Waterborne	kg	1250	59	2.12	2.54
93	Paint, Solventborne	kg	1250	97	3.13	3.76
94	Paperboard	kg	1090	24.8	1.29	1.29
95	Plasterboard	kg	950	6.75	0.38	0.39
96	Plastic, PVC	kg	1380	77.2	2.9	3.1
97	Polyurethane	kg	30	107.2	4.32	4.54
98	Polypropylene	kg	900	101.3	4.1	4.4
99	Epoxy resin	kg	2000-11000	137	5.7	5.7
100	Steel-Bar and rod, virgin	kg	7850	29.2	2.59	2.77
101	Steel-Bar and rod, 59% recycled	kg	7850	8.8	0.42	0.45
102	Steel-Bar, 37% recycled	kg	7850	23	1.48	1.48
103	Steel engineering recycled	kg	7850	13.1	0.68	0.72
104	Steel section virgin	kg	7850	38	2.82	3.03
105	Steel section recycled	kg	7850	10	0.44	0.47
106	Steel secction average recycled	kg	7850	21.5	1.42	1.53
107	Natural stone, plates, refined	kg	2750	11.2	0.31	0.31
108	Natural stone, plates, cut	kg	2750	8.1	0.23	0.23
109	Windows, Single glazed timber framed	m^2	-	198.6	10.1	10.1
110	Windows, double glazed timber framed	m^2	-	243	11.11	11.11
111	Windows, double aluminium - Clad timber framec	m^2	-	763.8	38.2	38.2
112	Windows, double aluminium framed	m^2	-	3798.6	193.75	193.75
113	Windows, double PVC framed	m^2	-	1597.2	83.33	83.33
114	Timber, Softwood, air dried, roughsawn	kg	540	7.4	0.59	0.59
115	Timber, Softwood, kiln dried, roughsawn	kg	540	9.4	0.69	0.69
116	Timber, Softwood, air dried, dressed	kg	540	8.4	0.6	0.6
117	Timber, Softwood, kiln dried, dressed	kg	540	10.4	0.73	0.73
118	Timber, Softwood, mouldings	kg	540	13.1	0.92	0.92
119	Timber, Softwood, hardboard	kg	540	16	1.03	1.09
120	Timber, Softwood, MDF	kg	350-800	14.3	0.642	0.642
121	Timber, Softwood, plywood	kg	514	15	1.07	1.1
122	Timber, Softwood, OSB	kg	594	15	0.96	0.99
123	Timber, Softwood, Glulam	kg	550	12	0.84	0.87
124	Timber, hardwood, air dried, roughsawn	kg	770	10.4	0.87	0.87
125	Timber, hardwood, kiln dried, roughsawn	kg	770	12.2	0.93	0.93
126	Barrier against steam, Bitumen film	kg	1160	54.3	0.14	0.14
127	Barrier against steam, polyethylenfilm	kg	940	93	2.7	2.8
128	Barrier against steam, PVC	kg	1380	69.4	2.57	3.16
129	Door, ext., timber+aluminium	m^2	-	1893.5	87.7	87.7
130	Door, ext., timber+glass	m^2	-	1746	90.3	90.3
131	Door, int., timber	m^2	-	1808	36.9	36.9
132	Door, int., timber+glass	m^2	-	1758	48.7	48.7
133	Rubber	kg	860	91.18	2.66	2.75
134	Nylon (Polyamide) 6 Polymer	kg	1240	120.5	5.47	9.14
135	Nylon (Polyamide) 6.6 Polymer	kg	1240	138.6	6.54	7.92
136	Acrylglass	kg	1180	145.2	8.4	9.02
137	Carbon Fibre reinforced plastic	kg		315		10.1
138	Glass Fibre reinforced plastic	kg		100	8.1	8.1
139	Carbon Fibre reinforced polymer	kg	1800	187.2		12.3
140	Glass Fibre reinforced polymer	kg	2500	123.4		7.8

A.2. Data for embodied energy and GHG emissions - Disposal

Nr crt	Building Material -Disposal	Unit	EE [MJ/kg]	EC - CO_{2e} [$kgCO_{2e}$/unit]
1	Timber, uncoated	kg	0.195	0.0137
2	Timber, coated	kg	0.21	0.0142
3	Door, ext., aluminium	m^2	32.6	3.2
4	Door, ext., glass	m^2	31.5	4.76
5	Door, int. timber in WIP	m^2	14.6	7.28
6	Door, int.timber+glass, in WIP	m^2	75.3	10.5
7	Brick in landfill	kg	0.296	0.0134
8	Brick sorted	kg	0.15	0.00771
9	Brick, disposalmix	kg	0.184	0.0097
10	Bulks (combustible) in WIP	kg	0.425	0.435
11	Reinforced concrete, in landfill	kg	0.34	0.0157
12	Reinforced concrete, sorted	kg	0.181	0.00993
13	Reinforced concrete, disposal	kg	0.198	0.0105
14	Concrete in landfill	kg	0.31	0.0142
15	Concrete sorted	kg	0.159	0.00833
16	Concrete disposal	kg	0.59	2.34
17	Concrete gravel disposal	kg	0.173	0.00893
18	Plasterboard disposal	kg	0.29	0.0133
19	Plasterboard landfill	kg	0.296	0.0134
20	Plasterboard sorted	kg	0.216	0.0124
21	Bitumen film disposal	kg	0.328	0.114
22	Mineral plaster, sorted	kg	0.1	0.00447
23	Mineral Plaster, landfill	kg	0.25	0.0101
24	Mineral Plaster, disposal	kg	0.112	0.0049
25	Cement and mortar, disposal	kg	0.195	0.00963
26	Cement and mortar, landfill	kg	0.31	0.0141
27	Cement and mortar, sorted	kg	0.16	0.00823
28	Polystyrene Expanded EPS, removel	kg	0.263	3.15
29	Glass, removel	kg	0.245	0.01
30	Rubber in WIP	kg	0.245	0.0101
31	Windows, timber framed in WIP	m2	28.1	19.2
32	Windows, steel framed in WIP	m2	27.6	25.3
33	Windows PVC frame in WIP	m2	710.7	132
34	Timber-cement board, removel	kg	0.34	0.0199
35	Cardboard (carton), in WIP	kg	0.363	0.0252
36	Cork, disposal	kg	0.125	0.00783
37	Mineral wool, removel	kg	0.25	0.0101
38	Barrier against steam, polyethylenfilm, removel	kg	0.386	2.82
39	Polyetylen/Polypropylen products, removel	kg	0.26	3
40	Polyvinylchlorid (PVC), removel	kg	13.5	2.26
41	Timber, Hardwood, dried, WIP	kg	0.099	0.00683
42	Timber, Hardwood, moist, WIP	kg	0.069	0.00484
43	Timber, Softwood, dried, WIP	kg	0.099	0.00683
44	Timber, Softwood, moist, WIP	kg	0.069	0.00484
45	Reinforcement bars, secondary production	kg	0.87	0.0576

A.3. Data for embodied energy and GHG emissions – Transport and combustion

Nr crt	Transport	Unit		EE [MJ/unit]		EC - CO_{2e} [$kgCO_{2e}$/unit]
1	Truck, < 3.5t	tkm		27		1.54
2	Truck 3.5-20t	tkm		4.6		0.28
3	Truck 20-28t	tkm		3.25		0.195
4	Truck >28t	tkm		2.36		0.137
5	Train freight	tkm		0.82		0.0142
6	Ship cargo	tkm		0.66		0.0464
7	Ship tank	tkm		0.95		0.043
8	Airplane	tkm		24.8		1.67
9	Car, diesel	km		4.86		0.285
10	Car, petrol	km		5.41		0.322

Nr crt	Combustion	Unit	Density kg/m3	EE [MJ/kg]		EC - CO_{2e} [$kgCO_{2e}$/unit]
1	Petrol, unleaded	kg	737	58		0.768
2	Diesel	kg	850	55		0.601
3	Propan/ Butan	kg	600	55		0.697
4	Petrol, premium	kg	737	58.2		0.774

A.4. Data for heat island effect

Nr. Crt	Roofing material	Solar reflectance	Infrared emittance	Temperature rise	Solar reflectance index
1	Red clay tile	0.33	0.9	14	36
2	Red concrete tile	0.18	0.91	22	17
3	unpainted cement tile	0.25	0.9	18	25
4	white concrete tile	0.73	0.9	-6	90
5	concrete tile, light beige coating	0.63	0.9	-1	76
6	concrete tile,pale bluish purple (mauve)	0.41	0.9	10	46
7	Concrete tile, pink and grey coating	0.53	0.9	4.43	63
8	Concrete tile, off-white coating	0.74	0.9	-7	92
9	fiber cement, earth brown	0.26	0.9	18	27
10	fiber cement, pewter gray color	0.25	0.9	17	25
11	New, bare galvanized steel	0.61	0.04	13	46
12	Aluminium	0.61	0.25	9	56
13	Aluminium field-applied coating				62
14	bare zincalme steel				68
15	MBCI Siliconized Polyester White	0.59	0.85	3	71
16	Snow white metal products	0.67	0.85	-2	82
17	Gray EPDM (ethylene propylene diene Monomer)	0.23	0.87	20	21
18	White EPDM	0.69	0.87	-4	84
19	Black EPDM	0.06	0.86	28	-1
20	Hypalon	0.76	0.91	-8	95
21	T-EPDM	0.81	0.92	-10	102
22	Firestone SBS Bitumen on white	0.26	0.92	17	28
23	Smooth Bitumen	0.06	0.86	28	-1
24	White Granular Surface Bitumen	0.26	0.92	17	28
25	Carlisle Syntec System Brite-ply	0.77	0.9	-8	96
26	Ecology roof	0.8	0.9	-10	100
27	Hypsam roofing system, hyload	0.75	0.9	-7	93
28	Sarnafil beige	0.43	0.92	9	49
29	Sarnafil blue	0.61	0.92	0	73
30	Sarnafil white	0.83	0.92	-12	104
31	Trocal roofing system, white	0.77	0.9	-8.3	96
32	Dark gravel on Built-up roof	0.12	0.9	24	9
33	Light gravel on Built-up roof	0.34	0.9	14	37
34	White coated gravel on Built-up roof	0.65	0.9	-2	79
35	White	0.21	0.91	20	21
36	ISP K-711 White	0.36	0.91	13	40
37	Generic white	0.25	0.91	18	26
38	Generic gray	0.22	0.91	20	22
39	Antique silver	0.2	0.91	20	19
40	Beachwood sand	0.2	0.91	22	19
41	Light brown	0.19	0.91	20	18
42	Medium brown	0.12	0.91	22	7
43	Dark brown	0.08	0.91	23	4
44	Green	0.19	0.91	20	18
45	Black	0.03	0.91	25	-2
46	Coral	0.16	0.91	21	14
47	Tan	0.16	0.91	22	9

A.5. Data for sound level of construction equipments

Nr. Crt	Equipment	Sound level at Average [dB]	
1	Front End Loader	88	
2	Backhoe	86.5	
3	Bulldozer	96	
4	Roller	90	
5	Scraper	96	
6	Grader	85	
7	Truck	96	
8	Paver	101	
9	Concrete mixer	85	
10	Concrete pump	85	
11	Crane	100	
12	Derrick	85	
13	Generators	85	
14	Compressors	85	
15	Pile driver (diesel and pneum.)	98	
16	Pile driver (gravity, board)	82.5	
17	Pneumatic breaker	106	
18	Hydraulic Breaker	95.5	
19	Pneumatic chipper	109	
20	Poker vibrator	94.5	
21	Compressed air Blower	104	
22	Power Saw	88.5	
23	Electric Drill	102	
24	Air Track Drill	113	
	Standards:		
	OSHA (at workers ear)	90	
	Day time Community (at property line)	65	

A.6. Data for calculation of noise comfort

Absorption coefficients of common building materials and finishes						
Floor Materials	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
conrete (unpainted, rough finish)	0.01	0.02	0.04	0.06	0.08	0.1
concrete (sealed or painted)	0.01	0.01	0.015	0.02	0.02	0.02
linoleum/vinyl tile on concrete	0.02	0.03	0.03	0.03	0.03	0.02
wood on joists	0.15	0.11	0.1	0.07	0.06	0.07
parquet on concrete	0.04	0.04	0.07	0.06	0.06	0.07
carpet on concrete	0.02	0.06	0.14	0.37	0.6	0.65
carpet on foam	0.08	0.24	0.57	0.69	0.71	0.73
carpet	0.01	0.02	0.06	0.15	0.25	0.45
Marble or glazed tile	0.01	0.01	0.01	0.01	0.02	0.02
Seating Materials	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Seats fully occupied - fabric upholstered	0.6	0.74	0.88	0.96	0.93	0.85
Occupied wooden pews	0.57	0.61	0.75	0.86	0.91	0.86
Seats empty - fabric upholstered	0.49	0.66	0.8	0.88	0.82	0.7
Empty metal/wood seats	0.15	0.19	0.22	0.39	0.38	0.3
Wall Materials	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Brick: unglazed	0.03	0.03	0.03	0.04	0.05	0.07
Brick: painted	0.01	0.01	0.02	0.02	0.02	0.03
Concrete block - coarse	0.36	0.44	0.31	0.29	0.39	0.25
Concrete block - painted	0.1	0.05	0.06	0.07	0.09	0.08
Curtain: 340 g/m2, flat against wall	0.03	0.04	0.11	0.17	0.24	0.35
Curtain: 476 g/m2, flat against wall	0.07	0.31	0.49	0.75	0.7	0.6
Curtain: 612 g/m2, flat against wall	0.14	0.35	0.55	0.72	0.7	0.65
Curtain: 476 g/m2, pleated 50%	0.07	0.31	0.49	0.75	0.7	0.6
Curtain: 612 g/m2, pleated 50%	0.14	0.35	0.53	0.75	0.7	0.6
Doors (solid wood panels)						
Fiberglass: 2" 703 no airspace	0.22	0.82	0.99	0.99	0.99	0.99
Fiberglass: spray 5"	0.05	0.15	0.45	0.7	0.8	0.8
Fiberglass: spray 1"	0.16	0.45	0.7	0.9	0.9	0.85
Fiberglass: 2" rolls	0.17	0.55	0.8	0.9	0.85	0.8
Foam: Sonex 2"	0.06	0.25	0.56	0.81	0.9	0.91
Foam: SDG 3"	0.24	0.58	0.67	0.91	0.96	0.99
Foam: SDG 4"	0.33	0.9	0.84	0.99	0.98	0.99
Foam: polyur. 1"	0.13	0.22	0.68	1	0.92	0.97
Foam: polyur. 1/2"	0.09	0.11	0.22	0.6	0.88	0.94
Glass: 6mm plate, large pane	0.18	0.06	0.04	0.03	0.02	0.02
Window: glass	0.35	0.25	0.18	0.12	0.07	0.04
Plaster: smooth on tile/brick	0.013	0.015	0.02	0.03	0.04	0.05
Plaster: rough on wood lath	0.02	0.03	0.04	0.05	0.04	0.03
Marble/Tile	0.01	0.01	0.01	0.01	0.02	0.02
Sheetrock 1/2" 16" on center	0.29	0.1	0.05	0.04	0.07	0.09
Wood: 3/8" plywood panel	0.28	0.22	0.17	0.09	0.1	0.11
Plasterboard (12mm paneling on studs)	0.29	0.1	0.06	0.05	0.04	0.04
Plywood (3mm paneling over 31.7mm airspace)	0.15	0.25	0.12	0.08	0.08	0.08

Plywood (5mm paneling over 50mm airspace)	0.38	0.24	0.17	0.1	0.08	0.05
Plywood (6mm paneling, airspace, light bracing)	0.3	0.25	0.15	0.1	0.1	0.1
Plywood (10mm paneling, airspace, light bracing)	0.28	0.22	0.17	0.09	0.1	0.11
Fiberglass board (25mm thick)	0.06	0.2	0.65	0.9	0.95	0.98
Fiberglass board (50mm thick)	0.18	0.76	0.99	0.99	0.99	0.99
Fiberglass board (75mm thick)	0.53	0.99	0.99	0.99	0.99	0.99
Ceiling Materials	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Acoustic Tiles	0.05	0.22	0.52	0.56	0.45	0.32
Acoustic Ceiling Tiles	0.7	0.66	0.72	0.92	0.88	0.75
Fiberglass: 2" 703 no airspace	0.22	0.82	0.99	0.99	0.99	0.99
Fiberglass: spray 5"	0.05	0.15	0.45	0.7	0.8	0.8
Fiberglass: spray 1"	0.16	0.45	0.7	0.9	0.9	0.85
Fiberglass: 2" rolls	0.17	0.55	0.8	0.9	0.85	0.8
wood	0.15	0.11	0.1	0.07	0.06	0.07
Foam: Sonex 2"	0.06	0.25	0.56	0.81	0.9	0.91
Foam: SDG 3"	0.24	0.58	0.67	0.91	0.96	0.99
Foam: SDG 4"	0.33	0.9	0.84	0.99	0.98	0.99
Foam: polyur. 1"	0.13	0.22	0.68	1	0.92	0.97
Foam: polyur. 1/2"	0.09	0.11	0.22	0.6	0.88	0.94
Plaster: smooth on tile/brick	0.013	0.015	0.02	0.03	0.04	0.05
Plaster: rough on lath	0.02	0.03	0.04	0.05	0.04	0.03
Sheetrock 1/2" 16" on center	0.29	0.1	0.05	0.04	0.07	0.09
Wood: 3/8" plywood panel	0.28	0.22	0.17	0.09	0.1	0.11
Plasterboard (12mm in suspended ceiling grid)	0.29	0.1	0.06	0.05	0.04	0.04
Underlay in perforated metal panels (25mm batts)	0.51	0.78	0.57	0.77	0.9	0.79
Metal deck (perforated channels, 25mm batts)	0.19	0.69	0.99	0.88	0.52	0.27
Metal deck (perforated channels, 75mm batts)	0.73	0.99	0.99	0.89	0.52	0.31
Sprayed cellulose fiber (16mm on solid backing)	0.05	0.16	0.44	0.79	0.9	0.91
Sprayed cellulose fiber (25mm on solid backing)	0.08	0.29	0.75	0.98	0.93	0.76
Sprayed cellulose fiber (25mm on timber lath)	0.47	0.9	1.1	1.03	1.05	1.03
Sprayed cellulose fiber (32mm on solid backing)	0.1	0.3	0.73	0.92	0.98	0.98
Wood tongue-and-groove roof decking	0.24	0.19	0.14	0.08	0.13	0.1
Miscellaneous Material	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Water	0.008	0.008	0.013	0.015	0.02	0.025
People (adults)	0.25	0.35	0.42	0.46	0.5	0.5

Nr. Crt	Impact noise transmission reduction index	
1	Carpet PVC, 1.5mm	5
2	Carpet PVC, 2.5mm	8
3	PVC	16
4	Corkboard	20
5	Synthetic rubber	14
6	Recycled rubber with a PVC layer on top	22
7	Corkboard with a PVC layer on the top	25
8	Cork-wood	15
9	Undercarpet with carpet	35
10	Parquet, Hardwood, 10mm, direct on floor	5
11	Laminated parquet glued on 12mm poros PFL	7
12	Laminated parquet glued on 16mm poros PFL	9
13	Laminated parquet glued on 25mm poros PFL	11

A.7. Data for fuel prices

	1Euro=	4.55	Lei
Nr. Crt	**Fuel type**	**Price**	**Unit**
1	Electricity	0.1207	Euro/ kWh
2	Coal (weighted average)	48.35165	Euro/ tonne
3	Industrial wood	42.85714	Euro/m3
4	Fuel oil	1.176	Euro/litre
5	LPG	0.743	Euro/litre
6	Gas/ diesel oil	1.35	Euro/litre
7	Burning oil	1.176	Euro/litre
8	Petrol	1.35	Euro/litre
9	Natural gas	0.2769	Euro/m3
10	Water	0.76923	Euro/m3

APPENDIX B. MEASUREMENTS DURING THE DRYING PROCESS

B.1. Initial drying of Mix 1, Mix 2 and Mix 3

Mix 1										
Mass g Nr.	**Initial Mass**	**Mass at re-wet.**	**Mass at 1. drying**	**Mass at 2. drying**	**Mass at 3. drying**	**Mass at 4. drying**	**Mass at 5. drying**	**Mass at 6. drying**	**Mass at 7. drying**	**Constant Mass**
1	7739.5	7687.6	7716.6	7695.2	7414.4	7378.2	7342	7345.6	7314.9	7314.5
2	7735.9	7791.5	7729.9	7700	7470.8	7452	7433.9	7408.4	7396	7395.4
3	7735.4	7763.5	7733.7	7626.8	7586.8	7430	7364.2	7364.4	7337.8	7337.2
4	7751.2	7718.4	7750.2	7737.1	7521.4	7425	7388.8	7385.2	7378.2	7377.7
5	7785.4	7796.1	7758.6	7755	7734.7	7707.6	7588.1	7427.6	7394.1	7393.8
6	7787.1	7795.7	7781.5	7707.2	7611.9	7552	7438.4	7438.2	7413.5	7412.9
7	7798.9	7861.4	7795.3	7794.5	7554.8	7535	7527.5	7517.1	7489.6	7489.5
8	7747.4	7783.6	7745.4	7748.9	7664.1	7531	7487.6	7471.7	7413	7403
9	7728.8	7766.8	7695.7	7597.4	7580	7572	7561.7	7479.9	7344.2	7343.3
10	7807.7	7800.7	7786.2	7801.2	7749.5	7642.3	7506.1	7486	7404.8	7404.3
11	7749.5	7798.8	7731.6	7748.1	7688.8	7671.2	7627.7	7432.2	7362.9	7362.6
12	7791.5	7834.5	7771.9	7688.3	7595.6	7546.8	7519.1	7404.7	7406.3	7406.1
Time of drying	Hours	**5**	**14**	**12**	**10**	**10**	**14**	**12**	**12**	
		5	**19**	**31**	**41**	**51**	**65**	**77**	**89**	
Temperature	°C	130°C			165°C					

Mix 2										
Mass g Nr.	**Initial Mass**	**Mass at re-wet.**	**Mass at 1. drying**	**Mass at 2. drying**	**Mass at 3. drying**	**Mass at 4. drying**	**Mass at 5. drying**	**Mass at 6. drying**	**Mass at 7. drying**	**Constant Mass**
1	7730.8	7694.1	7709	7666.4	7470.3	7428	7392.4	7382.9	7352.2	7352.1
2	7730	7763.5	7733.4	7650	7618.7	7596	7579.9	7439	7351	7325.2
3	7845.3	7795.8	7854.8	7812.4	7720.6	7656	7501.1	7486.4	7458.2	7455.7
4	7803.1	7738.3	7812.3	7698	7478.2	7479.9	7475.8	7430.5	7396.2	7396.6
5	7838.5	7766	7811.5	7785.5	7705.3	7699	7670.7	7637.4	7427.1	7426.8
6	7806	7833.7	7810	7785.7	7714.3	7631.3	7585.2	7569.3	7535.2	7535.5
7	7868.2	7866.5	7876	7851.6	7797.9	7628	7534	7522.8	7506	7485
8	7790	7703.3	7795.2	7674.3	7487.5	7485	7484.4	7463.5	7372.8	7372.3
9	7785.8	7683.5	7756.4	7615.2	7442.8	7410.2	7394.5	7396.4	7371.3	7370.5
10	7793.5	7799.9	7777.5	7775.5	7700	7552	7493.6	7484.2	7431.6	7431.2
11	7740.8	7781.9	7724.8	7722.8	7583.8	7562.3	7451.3	7415.5	7388.9	7388.3
12	7754.9	7789.7	7740.3	7687.3	7627.4	7600.2	7586	7567.7	7419.2	7419.5
Time of drying	Hours	**5**	**14**	**12**	**10**	**10**	**14**	**12**	**12**	
		5	**19**	**31**	**41**	**51**	**65**	**77**	**89**	
Temperature	°C	130°C			165°C					

Mix 3										
Mass g Nr.	**Initial Mass**	**Mass at re-wet.**	**Mass at 1. drying**	**Mass at 2. drying**	**Mass at 3. drying**	**Mass at 4. drying**	**Mass at 5. drying**	**Mass at 6. drying**	**Mass at 7. drying**	**Constant Mass**
1	7653.3	7615.6	7622.8	7607.3	7416.1	7409.2	7403.8	7293.6	7257.1	7257.4
2	7701.8	7690.9	7692	7642.2	7421.7	7398.6	7386.1	7329.7	7302.3	7302.1
3	7716.5	7706.7	7711.5	7600	7480	7467.5	7463.3	7361.7	7351.5	7351.3
4	7744.1	7745.2	7739.5	7706.4	7629.2	7581.4	7553.9	7392.9	7370.2	7370.6
5	7780	7728.9	7752.8	7738.5	7493.7	7491.9	7480	7423.4	7425.1	7424.3
6	7661.3	7673.6	7650.7	7557.3	7307.3	7312	7309.6	7280.1	7277.5	7277.5
7	7733	7729.3	7727.5	7700.1	7587	7578	7558.9	7496.9	7370.5	7370.3
8	7634.5	7677.2	7630.4	7604.1	7567.1	7521	7481.3	7354.8	7311.8	7311.5
9	7607.7	7642.3	7575	7462.5	7439.2	7401.2	7387.1	7326.7	7223.1	7223.5
10	7812	7827	7790.4	7781.9	7535.4	7533.5	7528.3	7452.3	7444.3	7444.9
11	7643.9	7667.6	7623.3	7609.8	7539.9	7515	7506.2	7447.4	7256.2	7256.4
12	7716.6	7721	7696.5	7605.2	7516	7500.2	7491.8	7387.4	7340.3	7340
Time of drying	Hours	**5**	**14**	**12**	**10**	**10**	**14**	**12**	**12**	
		5	**19**	**31**	**41**	**51**	**65**	**77**	**89**	
Temperature	°C	130°C			165°C					

B.2. Drying after 30 days of carbonation of Mix 1, Mix 2 and Mix 3

After 30 days of carbonation										
Mix 1										
Mass g Nr.	**Initial Mass**	**Mass at 30 days**	**Mass at 1. drying**	**Mass at 2. drying**	**Mass at 3. drying**	**Mass at 4. drying**	**Mass at 5. drying**	**Mass at 6. drying**	**Final const. mass**	**Initial const. mass**
1	7687.6									7314.5
2	7791.5									7395.4
3	7763.5									7337.2
4	7718.4									7377.7
5	7796.1	**7845.8**	**7575.3**	**7480.5**	**7469.1**	**7456.1**	**7448.8**	**7444.1**	7441.1	7393.8
6	7795.7									7412.9
7	7861.4									7489.5
8	7783.6	**7816.7**	**7544.7**	**7438.1**	**7427.1**	**7415.4**	**7408.3**	**7404.7**	7408.7	7403
9	7766.8	**7808.3**	**7494.8**	**7429.4**	**7421.6**	**7411.8**	**7407.7**	**7402.1**	7400.1	7343.3
10	7800.7									7404.3
11	7798.8		↑	↑	↑	↑	↑	↑	↑	7362.6
12	7834.5									7406.1
Time of drying	Hours	**25**	**14**	**11**	**15**	**10**	**13**	**8**		
		25	**39**	**50**	**65**	**75**	**88**	**96**		
Temperature	°C	140°C								

Mix 2										
Mass g Nr.	**Initial Mass**	**Mass at 30 days**	**Mass at 1. drying**	**Mass at 2. drying**	**Mass at 3. drying**	**Mass at 4. drying**	**Mass at 5. drying**	**Mass at 6. drying**	Final const. mass	Initial const. mass
1	7694.1									7352.1
2	7763.5									7325.2
3	7795.8	**7875.9**	**7661.6**	**7573.4**	**7559.2**	**7550**	**7539.9**	**7534.5**	7530.5	7455.7
4	7738.3									7396.6
5	7766									7426.8
6	7833.7									7535.5
7	7866.5	**7909.3**	**7644**	**7571.7**	**7564.1**	**7550.2**	**7543.1**	**7539.1**	7536.1	7485
8	7703.3									7372.3
9	7683.5	**7791.2**	**7579.1**	**7534.7**	**7526.8**	**7500.2**	**7493.1**	**7490.4**	7487.4	7370.5
10	7799.9									7431.2
11	7781.9		↑	↑	↑	↑	↑	↑	↑	7388.3
12	7789.7									7419.5
Time of drying	Hours		**25**	**14**	**11**	**15**	**10**	**13**	**8**	
			25	**39**	**50**	**65**	**75**	**88**	**96**	
Temperature	°C	140°C								

Mix 3										
Mass g Nr.	**Initial Mass**	**Mass at 30 days**	**Mass at 1. drying**	**Mass at 2. drying**	**Mass at 3. drying**	**Mass at 4. drying**	**Mass at 5. drying**	**Mass at 6. drying**	Final const. mass	Initial const. mass
1	7615.6									7257.4
2	7690.9									7302.1
3	7706.7									7351.3
4	7745.2	**7819.4**	**7577.3**	**7468**	**7461.7**	**7455.2**	**7447.3**	**7444**	7441	7370.6
5	7728.9									7424.3
6	7673.6	**7746.4**	**7505.1**	**7419.2**	**7404.8**	**7373.3**	**7370**	**7365.4**	7361.4	7277.5
7	7729.3									7370.3
8	7677.2									7311.5
9	7642.3	**7704.6**	**7439.9**	**7359.4**	**7342.2**	**7313.3**	**7309.3**	**7307.2**	7305.2	7223.5
10	7827									7444.9
11	7667.6		↑	↑	↑	↑	↑	↑	↑	7256.4
12	7721									7340
Time of drying	Hours		**25**	**14**	**11**	**15**	**10**	**13**	**8**	
			25	**39**	**50**	**65**	**75**	**88**	**96**	
Temperature	°C	140°C								

B.3. Drying after 60 days of carbonation of Mix 1, Mix 2 and Mix 3

After 60 days of carbonation													
Mix 1													
Mass g Nr.	Initial Mass	Mass at 60 days	Mass at 1. drying	Mass at 2. drying	Mass at 3. drying	Mass at 4. drying	Mass at 5. drying	Mass at 6. drying	Mass at 7. drying	Mass at 8. drying	Mass at 9. drying	Final const. mass	Initial const. mass
1	7687.6	7757.9	7555.5	7506.9	7479.7	7465.1	7460.8	7462.2	7461.6	7460.7	7456.3	7455.1	7314.5
2	7791.5												7395.4
3	7763.5												7337.2
4	7718.4												7377.7
5	7796.1											*7441.1*	7393.8
6	7795.7												7412.9
7	7861.4												7489.5
8	7783.6											*7408.7*	7403
9	7766.8											*7400.1*	7343.3
10	7800.7	7819.1	7607.4	7527.5	7509.7	7504.2	7499.4	7497.7	7498.4	7498.4	7497.6	7497.4	7404.3
11	7798.8	7760.3	7548	7480.7	7437.7	7429.5	7425.8	7423.7	7421.4	7419.8	7419.8	7418.9	7362.6
12	7834.5		↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	7406.1
Time of drying	Hours	24	12	12	12	13	13	13	12	12	12		
		24	36	48	60	73	86	99	111	123	135		
Temperature	°C	140°C											
Mix 2													
Mass g Nr.	Initial Mass	Mass at 60 days	Mass at 1. drying	Mass at 2. drying	Mass at 3. drying	Mass at 4. drying	Mass at 5. drying	Mass at 6. drying	Mass at 7. drying	Mass at 8. drying	Mass at 9. drying	Final const. mass	Initial const. mass
1	7694.1	7730.1	7596.2	7488	7453.5	7446.2	7443.5	7442	7440.5	7439.2	7437.7	7435.2	7352.1
2	7763.5	7729.3	7560.5	7526.2	7505.2	7483.8	7472	7464	7455.3	7415.3	7405.8	7386.1	7325.2
3	7795.8											7530.5	7455.7
4	7738.3												7396.6
5	7766												7426.8
6	7833.7												7535.5
7	7866.5											7536.1	7485
8	7703.3												7372.3
9	7683.5											7487.4	7370.5
10	7799.9												7431.2
11	7781.9	7758.8	7662.2	7499.4	7456.3	7439.1	7433	7431.8	7429.2	7426.7	7425.1	7424.1	7388.3
12	7789.7		↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	7419.5
Time of drying	Hours	24	12	12	12	13	13	13	12	12	12		
		24	36	48	60	73	86	99	111	123	135		
Temperature	°C	140°C											

Mix 3													
Mass g Nr.	Initial Mass	Mass at 60 days	Mass at 1. drying	Mass at 2. drying	Mass at 3. drying	Mass at 4. drying	Mass at 5. drying	Mass at 6. drying	Mass at 7. drying	Mass at 8. drying	Mass at 9. drying	const. mass	Initial const. mass
1	7615.6	7729.5	7622	7549.3	7504.1	7475.4	7465.2	7423.2	7411.7	7410.4	7408.8	7405.5	7257.4
2	7690.9												7302.1
3	7706.7												7351.3
4	7745.2											7441	7370.6
5	7728.9												7424.3
6	7673.6											7361.4	7277.5
7	7729.3												7370.3
8	7677.2	7693.6	7487.8	7401.5	7348.6	7341.4	7337.3	7336	7334.4	7332.9	7331.1	7330.3	7311.5
9	7642.3											7305.2	7223.5
10	7827												7444.9
11	7667.6												7256.4
12	7721	7764.9	7656.1	7600.7	7554.4	7523	7510.9	7498.6	7458.4	7447.4	7443.4	7439.2	7340
Time of drying		Hours	24	12	12	12	13	13	13	12	12	12	
			24	36	48	60	73	86	99	111	123	135	
Temperature		°C	140°C										

B.4. Drying after 120 days of carbonation of Mix 1, Mix 2 and Mix 3

After 120 days of carbonation															
Mix 1															
Mass g Nr.	Initial Mass	Mass at 60 days	Mass at 1. drying	Mass at 2. drying	Mass at 3. drying	Mass at 4. drying	Mass at 5. drying	Mass at 6. drying	Mass at 7. drying	Mass at 8. drying	Mass at 9. drying	Mass at 10. drying	Mass at 11. drying	Final const. mass	Initial const. mass
1	7687.6													7455.1	7314.5
2	7791.5	7794.8	7683.5	7617	7571.6	7548.7	7525.5	7508.1	7496	7449.1	7437.3	7436.7	7435.1	7425.4	7395.4
3	7763.5	7808.8	7698.1	7623.9	7602.5	7558.6	7518	7512.5	7501.3	7463	7462.9	7464.8	7459	7456.1	7337.2
4	7718.4	7797.1	7639.2	7619	7553	7528.3	7513.8	7508.4	7503.4	7490.1	7477.7	7472.1	7461.5	7450.2	7377.7
5	7796.1													*7441.1*	7393.8
6	7795.7	7801.7	7632.5	7565.1	7519.1	7514.2	7497.1	7494.5	7488.3	7477.1	7473.3	7469.8	7466.9	7468.2	7412.9
7	7861.4	7864.1	7694.5	7671.2	7596.1	7567	7544.4	7530.2	7510.6	7503.9	7499.6	7495.2	7490.9	7482.1	7489.5
8	7783.6													*7408.7*	7403
9	7766.8													*7400.1*	7343.3
10	7800.7													7497.4	7404.3
11	7798.8													7418.9	7362.6
12	7834.5	7836.6	7691.1	7598.4	7587.7	7557	7530.6	7525.3	7521.7	7501.1	7502.1	7501.7	7501.9	7501.5	7406.1
Time of drying	Hours	24	14	14	13	17	12	12	20	11	12	12	12		
		24	38	52	65	82	94	106	126	137	149	161	173		
Temperature	°C	140°C													
Mix 2															
Mass g Nr.	Initial Mass	Mass at 60 days	Mass at 1. drying	Mass at 2. drying	Mass at 3. drying	Mass at 4. drying	Mass at 5. drying	Mass at 6. drying	Mass at 7. drying	Mass at 8. drying	Mass at 9. drying	Mass at 10. drying	Mass at 11. drying	Final const. mass	Initial const. mass
1	7694.1													7435.2	7352.1
2	7763.5													7386.1	7325.2
3	7795.8													7530.5	7455.7
4	7738.3	7813.2	7759.8	7687.2	7645.7	7588.7	7555.4	7542.7	7539.1	7533.5	7530.9	7531.5	7531.2	7528.4	7396.6
5	7766	7853.4	7793.5	7705.3	7691.1	7670.8	7658.7	7653.4	7645.3	7624	7613.4	7603	7599.7	7594.6	7426.8
6	7833.7	7823.7	7735	7688	7650	7637.4	7619.2	7573.8	7571.3	7549	7534.7	7523.9	7520.5	7516	7535.5
7	7866.5													7536.1	7485
8	7703.3	7806.3	7730.5	7684.5	7651	7622.7	7600.9	7589.9	7567.7	7542.3	7540.5	7539.6	7538.5	7534.7	7372.3
9	7683.5													7487.4	7370.5
10	7799.9	7816.7	7666.3	7653.8	7639	7624.8	7597.7	75767.7	7573.3	7548.9	7546.5	7534.4	7521.3	7512.5	7431.2
11	7781.9													7424.1	7388.3
12	7789.7	7806.2	7730.8	7679.7	7640.2	7568.3	7521.7	7516.3	7512.3	7501.6	7497.2	7482	7480.9	7475.5	7419.5
Time of drying	Hours	24	14	14	13	17	12	12	20	11	12	12	12		
		24	38	52	65	82	94	106	126	137	149	161	173		
Temperature	°C	140°C													

Mass g Nr.	Initial Mass	Mass at 60 days	Mass at 1. drying	Mass at 2. drying	Mass at 3. drying	Mass at 4. drying	Mass at 5. drying	Mass at 6. drying	Mass at 7. drying	Mass at 8. drying	Mass at 9. drying	Mass at 10. drying	Mass at 11. drying	Final const. mass	Initial const. mass
1	7615.6													7405.5	7257.4
2	7690.9	7765	76665.6	7607.3	7546.9	7521.3	7502.3	7480.1	7467.1	7447.6	7440	7438.7	7437.1	7435.5	7302.1
3	7706.7	7798.1	7702.5	7611.4	7577.7	756.7	7542.9	7519.2	7513.3	7506.3	7487.1	7487.5	7482	7480.2	7351.3
4	7745.2													7441	7370.6
5	7728.9	7847.7	7717.2	7678.2	7614.2	7607.3	7583	7563.9	7562.7	7559.5	7556.1	7554.2	7547.2	7545.5	7424.3
6	7673.6													7361.4	7277.5
7	7729.3	7833.6	7751.1	7631.5	7581	7571.3	7533.5	7532.5	7527.8	7518.7	7514.9	7512.6	7509.9	7509.6	7370.3
8	7677.2													7330.3	7311.5
9	7642.3													7305.2	7223.5
10	7827	7901.6	7828.1	7767.9	7733.5	7645.8	7634.9	7627	7608.2	7602.5	7582.4	7582.6	7578.2	7577	7444.9
11	7667.6	7738.5	7605.3	7543.3	7456.9	7421.8	7402.5	7403.8	7393.9	7386.4	7384.1	7382.5	7380.5	7379.1	7256.4
12	7721													7439.2	7340
Time of drying	Hours	24	14	14	13	17	12	12	20	11	12	12	12		
		24	38	52	65	82	94	106	126	137	149	161	173		
Temperature	°C	140°C													

B.5. Initial drying of Mix 4, Mix 5, Mix 6 and Mix 7

Mix 4									
Mass g Nr.	**Initial Mass**	**Mass at re-wet.**	**Mass at 1. drying**	**Mass at 2. drying**	**Mass at 3. drying**	**Mass at 4. drying**	**Mass at 5. drying**	**Mass at 6. drying**	**Constant Mass**
1	7617.8	7745	7451.3	7380.8	7356.7	7350.7	7328.7	7308.7	7290
2	7549.8	7676.2	7372.6	7286.1	7252.4	7221.3	7221.7	7220.3	7220.1
3	7621.1	7703.6	7500.8	7334.8	7299	7301	7286	7280	7278.9
4	7648.8	7740.5	7497	7344.6	7339.4	7327.5	7320	7314.8	7312.3
5	7617.1	7699.6	7469.6	7271.8	7274.2	7272.4	7271.2	7270.6	7270.2
6	7709.3	7822.8	7638.3	7500.8	7486.3	7451.5	7444.2	7434.1	7432.2
7	7635.8	7723.8	7408	7382.8	7328.5	7316	7314.1	7311.3	7310.6
8	7702.1	7822.9	7567.5	7388.1	7385.2	7386.7	7386	7385.8	7385.6
9	7639.7	7742.7	7566.3	7313	7312.1	7310.8	7310.6	7310	7309.6
10			↑	↑	↑	↑	↑	↑	↑
11	**Date**								
12	**13.10.2011**		**25**	**26**	**48**	**24**	**36**	**10**	**20**
Time of drying		Hours	**25**	**51**	**99**	**123**	**159**	**169**	**189**
Temperature		°C	**130-150°C**						

Mix 5									
Mass g Nr.	**Initial Mass**	**Mass at re-wet.**	**Mass at 1. drying**	**Mass at 2. drying**	**Mass at 3. drying**	**Mass at 4. drying**	**Mass at 5. drying**	**Mass at 6. drying**	**Constant Mass**
1	7612.4	7703.8	7469.3	7322.8	7292	7275.9	7272.9	7269	7258
2	7675.4	7775.5	7448.3	7376.6	7368.6	7371	7350	7332	7328
3	7574.9	7688.7	7301.1	7270.3	7258.7	7253.3	7250	7251	7251
4	7765.3	7805.5	7653.9	7595.2	7581.2	7502.2	7444.8	7435.3	7410
5	7689.5	7748.4	7499.9	7395.2	7351.9	7330.9	7322.8	7307.2	7298
6	7699.3	7773.6	7593.2	7392.5	7406	7361.8	7355.7	7341.7	7339
7	7637.7	7691.9	7509.1	7517.6	7300.1	7295.6	7282.1	7274.2	7271.3
8	7563.4	7691.3	7491.7	7298.9	7262.7	7262.5	7262.5	7262.5	7262.5
9	7690.8	7759	7510.1	7265.2	7347	7335.1	7324.3	7312	7308
10			↑	↑	↑	↑	↑	↑	↑
11	**Date**								
12	**13.10.2011**		**25**	**26**	**48**	**24**	**36**	**10**	**20**
Time of drying		Hours	**25**	**51**	**99**	**123**	**159**	**169**	**189**
Temperature		°C	**130-150°C**						

Mix 6									
Mass g Nr.	**Initial Mass**	**Mass at re-wet.**	**Mass at 1. drying**	**Mass at 2. drying**	**Mass at 3. drying**	**Mass at 4. drying**	**Mass at 5. drying**	**Mass at 6. drying**	**Constant Mass**
1	7658.4	7730.3	7392.8	7314.1	7294.6	7284.4	7283	7282	7281.3
2	7690.2	7784.8	7353.4	7345.7	7348.1	7341.3	7341	7341	7341
3	7626.7	7715.1	7269	7238.6	7242.9	7240	7239.2	7239	7239
4	7542.1	7671.3	7248.1	7188.6	7180.5	7182.3	7181.2	7180	7180
5	7573.3	7667.3	7225	7187.7	7188.6	7185	7185	7185	7185
6	7623.7	7713.4	7285.7	7283.1	7278.2	7266.5	7253	7254.9	7254
7	7531.6	7665.3	7423.8	7168.3	7165.7	7167.7	7166.3	7166	7166
8	7596.6	7733.1	7402.4	7359.4	7322.8	7248.4	7247.8	7247	7247
9	7672.3	7777.4	7345.7	7306.9	7310.2	7311	7310	7310	7310
10			↑	↑	↑	↑	↑	↑	↑
11	**Date**								
12	**13.10.2011**		**25**	**26**	**48**	**24**	**36**	**10**	**20**
Time of drying		Hours	**25**	**51**	**99**	**123**	**159**	**169**	**189**
Temperature		°C	**130-150°C**						

Seria 7									
Mass g Nr.	**Initial Mass**	**Mass at re-wet.**	**Mass at 1. drying**	**Mass at 2. drying**	**Mass at 3. drying**	**Mass at 4. drying**	**Mass at 5. drying**	**Mass at 6. drying**	**Constant Mass**
1	7737	7818.9	7540.3	7449.3	7362.7	7364	7363	7363	7363
2	7763.3	7865	7527.9	7482.1	7467	7415.2	7415	7415	7415
3	7587.9	7696.9	7352.6	7323	7309.3	7258.1	7252.2	7251	7251
4	7718.9	7796	7434.5	7389.1	7360	7330.9	7331.4	7330	7330
5	7682.2	7738.3	7444.8	7292	7288.4	7291.5	7290	7290	7290
6	7725	7799.6	7357.4	7341.6	7340.1	7338.7	7338	7338	7338
7	7724.8	7802.1	7378.4	7343.7	7341.8	7343.4	7343	7343	7343
8	7703.1	7784	7382.6	7366.5	7350.1	7332.5	7321.3	7321.3	7321
9	7791.9	7873.6	7598.5	7421.4	7423.9	7426.2	7424	7424	7424
10			↑	↑	↑	↑	↑	↑	↑
11	**Date**								
12	**13.10.2011**		**25**	**26**	**48**	**24**	**36**	**10**	**20**
Time of drying		Hours	**25**	**51**	**99**	**123**	**159**	**169**	**189**
Temperature		°C	**130-150°C**						

B.6. Drying after 30 days of carbonation of Mix 4, Mix 5, Mix 6 and Mix 7

After 30 days of carbonation										
Mix 4										
Mass g Nr.	Initial Mass	Mass at 30 days	Mass at 1. drying	Mass at 2. drying	Mass at 3. drying	Mass at 4. drying	Mass at 5. drying	Mass at 6. drying	Final const. mass	Initial const. mass
1	7745	7750	7332	7326	7324	7324			7324	7290
2	7676.2	7666	7373.7	7307	7299	7292			7289	7220.1
3	7703.6	7729	7442.7	7386	7362.4	7350			7345	7278.9
4	7740.5									7312.3
5	7699.6									7270.2
6	7822.8									7432.2
7	7723.8									7310.6
8	7822.9									7385.6
9	7742.7									7309.6
10			↑	↑	↑	↑	↑			
11	**Date**									
12	**16.12.2011**		**70**	**28**	**21**	**20**	**20**			
Time of drying		Hours	**70**	**98**	**119**	**139**	**159**			
Temperature		°C	**130-150°C**							
Seria 5										
Mass g Nr.	Initial Mass	Mass at 30 days	Mass at 1. drying	Mass at 2. drying	Mass at 3. drying	Mass at 4. drying	Mass at 5. drying	Mass at 6. drying	Final const. mass	Initial const. mass
1	7703.8	7706.6	7318	7316	7313.8	7313			7313	7258
2	7775.5	7787	7464.6	7449.7	7435	7414			7390	7328
3	7688.7	7710	7430	7367	7326.6	7320			7322	7251
4	7805.5									7410
5	7748.4									7298
6	7773.6									7339
7	7691.9									7271.3
8	7691.3									7262.5
9	7759		↑	↑	↑	↑	↑			7308
10	**Date**									
11	**16.12.2011**		**70**	**28**	**21**	**20**	**20**			
Time of drying		Hours	**70**	**98**	**119**	**139**	**159**			
Temperature		°C	**130-150°C**							

			Seria 6							
Mass g Nr.	**Initial Mass**	**Mass at 30 days**	**Mass at 1. drying**	**Mass at 2. drying**	**Mass at 3. drying**	**Mass at 4. drying**	**Mass at 5. drying**	**Mass at 6. drying**	Final const. mass	Initial const. mass
1	7730.3	7767.7	7426.2	7411.8	7402	7392			7375	7281.3
2	7784.8	7824.8	7434.7	7429	7430	7428.4			7426	7341
3	7715.1	7760.5	7363.5	7358.4	7357	7358			7358	7239
4	7671.3									7180
5	7667.3									7185
6	7713.4									7254
7	7665.3									7166
8	7733.1									7247
9	7777.4		↑	↑	↑	↑	↑			7310
10	**Date**									
11	**16.12.2011**		**70**	**28**	**21**	**20**	**20**			
Time of drying		Hours	**70**	**98**	**119**	**139**	**159**			
Temperature		°C	**130-150°C**							

			Seria 7							
Mass g Nr.	**Initial Mass**	**Mass at 30 days**	**Mass at 1. drying**	**Mass at 2. drying**	**Mass at 3. drying**	**Mass at 4. drying**	**Mass at 5. drying**	**Mass at 6. drying**	Final const. mass	Initial const. mass
1	7818.9	7812.3	7524.8	7460	7433	7412			7386	7363
2	7865	7868	7500.5	7493.5	7480	7478			7477	7415
3	7696.9	7707.6	7449.8	7319	7315.1	7314			7314	7251
4	7796									7330
5	7738.3									7290
6	7799.6									7338
7	7802.1									7343
8	7784									7321
9	7873.6		↑	↑	↑	↑	↑			7424
10	**Date**									
11	**16.12.2011**		**70**	**28**	**21**	**20**	**20**			
Time of drying		Hours	**70**	**98**	**119**	**139**	**159**			
Temperature		°C	**130-150°C**							

B.7. Drying after 60/120 days of carbonation of Mix 4, Mix 5, Mix 6 and Mix 7

After 60/ 120 days of carbonation

Mix 4

Mass g Nr.	Initial Mass	Mass at 60/120 d	Mass at 1. drying	Mass at 2. drying	Mass at 3. drying	Mass at 4. drying	Mass at 5. drying	Mass at 6. drying	Mass at 7. drying	Mass at 8. drying	Mass at 9. drying	Mass at 10. drying	Final const. mass	Initial const. mass
1													7324	7290
2													7289	7220.1
3													7345	7278.9
4	7740.5	7756.1	7437.4	7415	7390.7	7378	7375	7372				60 days	7370	7312.3
5	7699.6	7750	7535	7399	7376.4	7368.3	7365	7361					7360	7270.2
6	7822.8	7850	7596	7549	7534.6	7521	7505.2	7485	7478				7475	7432.2
7	7723.8	7771.2	7407.1	7400	7403.4	7395	7393.7	7392.4	7385			120 days	7382	7310.6
8	7822.9	7864.6	7696	7572	7515.2	7514.1	7501.9	7496	7486.3				7485	7385.6
9	7742.7	7770	7514.6	7433	7417.6	7383	7382.3	7383.1					7383	7309.6
10			↑	↑	↑	↑	↑	↑	↑	↑				
11	Date													
12	29.03.2012		64	19	24	25	16	9	11	12				
Time of drying		Hours	64	83	107	132	148	157	168	180				
Temperature		°C	130-150°C											

Mix 5

Mass g Nr.	Initial Mass	Mass at 60/120 d	Mass at 1. drying	Mass at 2. drying	Mass at 3. drying	Mass at 4. drying	Mass at 5. drying	Mass at 6. drying	Mass at 7. drying	Mass at 8. drying	Mass at 9. drying	Mass at 10. drying	Final const. mass	Initial const. mass
1													7313	7258
2													7390	7328
3													7322	7251
4	7805.5	7826.7	7670	7617	7489.1	7460	7454	7452				60 days	7450	7410
5	7748.4	7779	7423	7403	7391.7	7379.4	7377.1	7362	7354				7352	7298
6	7773.6	7790	7493.8	7450	7447.6	7441	7435.4	7403.5	7389.1				7385	7339
7	7691.9	7726.2	7426.5	7402	7386	7371.5	7358.9	7349.2	7337.6	7329.2	7323.2	120 days	7321	7271.3
8	7691.3	7705	7372.2	7355	7341	7337.8	7331.9	7323.2	7315.1	7312.8			7312	7262.5
9	7759	7784.5	7526.3	7505.2	7457.3	7416.9	7393	7375.1	7369.2	7358.5	7355.7		7354	7308
10			↑	↑	↑	↑	↑	↑	↑	↑	↑	↑		
11	Date													
12	29.03.2012		64	19	24	25	16	9	11	12	12	12		
Time of drying		Hours	64	83	107	132	148	157	168	180	192	204		
Temperature		°C	130-150°C											