DIPLOMA THESIS

The unused potential of green road pavements

Technical and economic-political obstacles of the competitiveness and spread of alternate, environmentally friendly pavement materials, and their potential solution for the future

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DIPLOMARBEIT

Ungenutztes Potential von Nachhaltigem Straßenbau

Die technischen und wirtschaftspolitischen Hindernisse der Wettbewerbsfähigkeit und Ausbreitung von alternativen, umweltfreundlichen Straßenbaumaterialen, und Lösungsansätze für den zukünftigen Einsatz

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Kurzfassung

Die derzeitige Situation der Umwelt zeigt die Notwendigkeit eines sofortigen Umdenkens und einer Neuplanung unseres Wirtschaftssystems. Obwohl der Bausektor nicht der weltweit größte Emittent ist, müssen die Treibhausgasemissionen und der Energieverbrauch in naher Zukunft reduziert werden, um ein positives Beispiel für andere Wirtschaftssektoren zu zeigen und einem grünen Wandel der Wirtschaft zu ermöglichen. Vor diesem Hintergrund zählt die Diplomarbeit die wichtigsten Umweltaspekte aktueller Straßenbaustoffe und fasst Konzepte neuer Innovationen auf. Ihre Möglichkeiten und Schwierigkeiten werden präsentiert und die Probleme der aktuellen Situation und die möglichen Lösungen für die Entwicklung in naher Zukunft nähergebracht.

Offene Interviews mit Fachleuten sowie eine Überprüfung verschiedener schriftlicher Materialien bilden die Hauptquellen der Studie.

Die These zeigt, dass viel ungenutztes Potenzial bei Konventionellen Straßenbaumaterialen – wie Asphalt und Beton – und bei Innovationen für alternative Straßenbaumaterialien vorhanden ist, aber die Verbreitung umweltfreundlicherer Methoden steht vor vielen Hindernissen. Asphaltprodukte müssen entwickelt werden, um die technischen Anforderungen bei einer niedrigeren Produktionstemperatur zu erfüllen, die die Warm-, Kalt- und Halbwarmasphaltprodukte wie LEA bieten, um die Treibhausgasemissionen zu reduzieren und einen Schritt zu einer nachhaltigeren Produktion sicherzustellen. Die Menge an Asphaltprodukten - sowie anderen Abfallstoffen -, die in der Produktionskette recycelt werden, muss erhöht werden, um einen Teil des Rohstoffs zu ersetzen - die Auswirkungen der Gewinnung zu verringern - und um zu vermeiden, dass mehr Abfallmaterial erzeugt wird. Es gibt Konzepte, um Kunststoff für vorgefertigte Straßenbauplatten zu recyceln, aber Kunststoff und Polymere können auch als Additiv bei der Asphaltproduktion verwendet werden. Sowohl für die Asphalt- und Betonproduktion ist es förderlich, die Energieproduktion der Mischanlagen und Fabriken von fossilen Brennstoffen auf grüne, erneuerbare Energiequellen umzustellen. Neue Konzepte experimentieren mit der Möglichkeit, Straßenoberflächen als Solarenergiequelle zu nutzen, zusätzlich können Straßentechnologie-Geräte Solarpanels ergänzen. Um die Auswirkungen verschiedener Technologien zu vergleichen, sind Managementinstrumente, wie die Lebenszyklusanalyse für den Entscheidungsprozess hilfreich. Neben den grundlegenden technischen Anforderungen müssen neue Innovationen auch nach dem erfolgreichen Nachweis ihrer Geeignetheit aus wirtschaftspolitischen, rechtlichen und sozialen Aspekten mit vielen Hindernissen konfrontiert werden.

Stichworte: Grüne Straßenpflaster, Warmasphalte, LEA, Nachhaltige Entwicklung, Lebenszyklusanalyse, Treibhausgas-Emission, Energieverbrauch, Recycling

Abstract

The current situation of the environment highlights the necessity of immediate rethinking and re-planning our economic system. Although the building sector is not the highest emitter of greenhouse gases (GHG) worldwide, the amount of GHG emissions and energy consumption must be reduced in the near future, in order to lead by example for other sectors and to contribute to a green change of the economy.

In light of this background, the thesis aims to summarize the most important environmental aspects of current road building materials and the concepts of new innovation, presenting their opportunities and difficulties to spread, as well as made an attempt to highlight the most recent difficulties, pointing out possible solutions that can contribute to emission reductions and technological advancement in the near future. In-depth, opened interviews with professionals of the field, as well as a review of various written materials, constitute the primary sources of the study.

The thesis reveals that there is significant unused potential in the conventional road materials – asphalt and concrete – and in innovations for alternative materials as road pavements, but the spread of environmentally friendly methods is facing many obstacles. Asphalt production should be developed further in order to achieve the existing technical requirements of the road surface, but on a lower temperature. Applying warm-, cold- and half warm mix asphalt products - like LEA – in the production might be a possible way to reduce GHG-emission and ensure more sustainable production. The amount of asphalt products – as well as other waste materials – recycled in the production chain must be increased to replace some of the raw material – by reducing the impacts of extraction – and to avoid generating more waste material. There are concepts to recycle plastic for prefabricated road pavement panels, but plastic and polymers can be used as additive in asphalt production too. For both asphalt and concrete production, it is promotable to change the energy production of the mixing plants and factories from fossil fuels to green, renewable energy sources. New concepts are experimenting the opportunity of using road surfaces as solar energy sources, but the road technology devices also have the potential to complement with solar panels. To compare the impacts of different technologies, management tools like Life-Cycle Analysis are useful in the process of decision making. Next to the basic technical requirements for a new innovation must face many obstacles even after the successful demonstration of their technical viability from economic-political, legal, and social aspects.

Keywords: Green Road Pavements, Warm Mix Asphalts, LEA, Sustainable Development, Life-Cycle Analysis, GHG-Emission, Energy Consumption, Recycling

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1. Introduction

Until the year 2020 the scientific consensus about the climate crisis caused by human activity is finally started to be accepted in wide public opinion. Not only the existence of the problem proved without any doubt, but also the presence of its fatal consequences. These are not threatening in the distant future but already changed the way of life on earth, which has required us to immediately adapt.

The issue of environmental protection has a long history – even the ancient civilizations placed strong emphasis on the protection of their immediate environment – and the end of the 20th century already featured some success in local and global[1] areas. However, seeing climate change as an actual, global threat – only preventable with united effort – emerged only in the last couple of years. Scientists, climate specialists, researchers and green organisations have been warning us for decades about the fast escalating effects of environment destruction on a global scale, but real, effective steps to prevent the worst possible scenario have not been taken. Global difficulties like preventing wars, ensuring continuing evolution of economic and livelihood of human civilians have been the understandable priorities as well as the difficulties that come with prompt threats, but we are now close to the point, when the effects of climate crisis overwrite any other difficulties, and become the obligate problem humankind must face. The Brundtland Report [1] – also known as Our Common Future – was released in 1987 defining the term of "sustainable development" more than thirty years before, meaning that the future generations – for whom the direct environmentally protective steps should have been taken – are already facing the threats of the absence of stricter rules and laws of this issue. It is hard to say how long will it be possible to hold this conservative policy towards the inevitable effects of climate change, but when the time of a desperate need of immediate action comes, our efforts will not be enough for our survival. In the last few years – sensing the seriousness of the issue – more and more people put out their voice for immediate climate saving actions, starting to put pressure on governments and economic operators. Environmentally friendly innovations started to get increased attention as the ecological attitude of companies become more important for the consumers, climate laws, green deals and renewed standards started to base as the attention of the public focused on the environmental act of politicians and leaders. These steps are promising for the survival, but are still only the beginning of a long and hard

[1] Positive examples are the extraction of toxic lead from fuels to decrease air pollution, or the total ban of CFC-s (Chlorofluorocarbons) for the protection of the ozone-layer.

development, which should have been done decades before, to sense its effects. Even with some positive, hopeful steps to a greener future, our society still heading to the wrong direction, which could only be changed with much stricter rules, even if they cause economic and social difficulties. Facing the biggest challenge of mankind there is no time to waste, and the probable – but still not sure – success only could be achieved by united effort, independent from nations, industrial sectors, or former environmental impacts.

By analysing the impacts of some parts of human activity, the different sectors of economy or simply the impacts of countries or geographical areas, we can set up rankings to define the main sources of pollution. There are many different processes to help the consummation of this comparison; Green House Gas (GHG) emission and the energy consumption[2] of a sector, company or just a process are great indicators for an environmental analysis. If we compared the sectors of human activity, we would find that the building sector is still lagging behind sectors like energy production or transport both in emission and energy consumption. Reducing the focus of the issue only to road building, the data are drastically lower, which brings up the question whether the road building sector is the ideal area to implement sustainable action to begin with. Since we can no longer wait for the largest emitter countries to start the process first, the sectors have the great responsibility to reduce their own impacts on the globe. Next to other sectors, road building might be seen as less relevant emitter, but the emission data is still too high to ignore. The near twenty-thousand asphalt mixing plants working everyday with tenth or hundreds of tonnes of carbon-dioxide emission, and using hundreds of millions megajoule energy – mostly from fossil energy sources – polluting the air everyday making it irrelevant, that there are even greater emitters. On the other hand, there is the hope that most part of this energy consumption could be reduced or replaced with more sustainable alternatives, making the transition to green economy possible not only with the drastic decrease of road building demand – which is necessary but economically speaking less possible solution – but also with the same amount of road structure built. Building sector always had a leading role in human history supporting development of civilisations, leading to great turning points in the past, also indicating the degree of actual development. Still affected by political and economic decisions, road building has the potential to fulfil the role of green innovator with many concepts for a more sustainable future, which also could set positive examples for other sectors too. Even eliminating every negative effect from road building, and turning it fully sustainable would not be enough to resolve the climate problems – might be even tight to slow

[2] The two indicators are heavily connected by the nature of the energy sources used.

down the climate change – but still an inevitable step to at least have the opportunity for reaching these goals. That shows the importance of road building alternatives which luckily developing in great numbers.

This master thesis attempts to summarize the actual situation of road building sector from the environmental view. Presenting the two most important road pavement materials – asphalt and concrete – from their potent of saving energy and decreasing emissions, I had the chance to analyse the weaknesses and strengths of these conventional materials, highlighting the changes must be done in the near future to reach their potential as green alternatives, while keeping all the requirements being appropriate as road pavement structures. The environmental aspects of the whole lifespan will be presented from raw material extraction and transport, through production until the construction and maintenance. This concept also encouraged the necessity of management tools like Life-Cycle Analysis (LCA) and Life-Cycle Cost Analysis (LCCA) for environmental and economic comparison of conventional and new alternatives, which are introduced in the thesis. Not only the direct alternatives of the conventional materials – implemented with subtle changes in production process or material composition like in case of the Low Energy Asphalt (LEA) – but new, innovative ideas are presented – heavily concentrated on the theory of solar pavements and plastic material road structures. Seeing the practical difficulties of these innovations I approached these ideas with sceptical view trying to highlight not only the opportunities but also analysing their suitability for road structures. After introducing some of the major alternatives for the last decades I focused on the basic requirements of a road pavement structure based on the Construction Products Regulation (CPR) harmonized with the European Standardization. Not only the difficulties to correspond to these requirements, but also potential solutions will be presented in topics like safety, local environmental protection, or the case of recycling. At the end of the thesis I also felt the necessity to touch issues with less direct contact to engineering knowledge, but still important to see through for successful economic widespread of the alternative products. The economic-political and social boundaries are equally important to technical boundaries, their impacts on a technically proved alternative can be represented through the situation of Low Energy Asphalt in Hungary. Understanding all these aspects holds the secret to develop a new alternative which might have the potential to revolutionize the whole sector in the direction of a green change.

2. Conventional Road Paving Materials and Methods

To understand the environmental emphasis of the road engineering, the present state of the road construction industry as well as the specific parameter of extant road networks must be known. By recognising the brief history of road building through the human civilisation, understanding the main focuses and turning points of its development – technical and social difficulties, already solved with the development, or maintaining problems waiting for the future solution – the present state and the importance of forthcoming progresses will be apprehensible. As the title shows, this chapter of the thesis presents those materials and methods, which are - due to their general widespread – seen as conventional in road construction sector. To present these aspects in a nutshell, the paragraph focuses on the environmental impacts of the methods – as the technical attributes are certified through theoretical and practical tests and long-term services. The knowledge of basic environmental burdens of conventional materials and methods conduce the innovation of improved generations of roads by eliminate the harmful aspects of the present methods – without reducing their advantages from economic and technical view – and help to evaluate the solutions of necessary innovations in the near future.

2.1 History of road construction in a nutshell

The brief history of roads could be easily conferred with the metaphor of the IFSTTAR university in France (in collaboration with the European Union Forever Open Road programme by FEHRL) [2] which describes the phases of development as different generation of road construction. With this interpretation, the alternative road paving systems can be described as the fifth generation, and every previous step until nowadays are belonging to the first four generations.

The first-generation of roads involves any manmade objects, different from the natural grounds, that were used for transportation. In this group we can label the first bridges or tunnels of human history, as well any incipient geographical interventions – like tracks through forests and mountains - with the goal of supporting local mobility of humans. This generation of roads present the prehistoric phase of humans – from the first settled communities – until the first paved roads for wheel-carriage (firstly in ancient Mesopotamia) which preludes the second generation. The paved roads were developed during the ancient Roman era (called Via Appia as a merged system) [2], as connections to maritime transport, with planned subgrade and subbase for the block stones[3]. As durable structures with long life cycle and even proper water drainage, the Roman roads based the planning and construction works that are used nowadays.[4] After the collapse of the Roman Empire in 476, the development of roads stopped, as the mostly local demand of transport was supported by the first-generation transport routes and the residuals of the roman road system throughout the middle ages. The demand increased rapidly with the arrival of the industrial revolution. The Scottish engineer John Loudon McAdam invented the Macadam pavement which was composed of a compacted subgrade of crushed granite, covered by a light stone layer to absorb water. [3] This pavement structure was capable to support the load of first vehicles[5], but still did not begin the next phase of roads, as the third generation means road constructions with "smooth" surfaces. The first "smooth" surfaced pavements were the asphalt roads built by John Metcalf in England[6] in the 17th century. The first asphalt roads were built from natural asphalt which was quite extraordinary in Europe and North America. In Europe there were only two major nature-asphalt habitats found in the 19th century, the Val der Traves mountains in Switzerland, and the Derna-Tatarosi mountains in Austro-Hungarian Monarchy (now Romania). [4] As the scarce resources were quickly drained, the real era of asphalt roads was beginning with the industrial process of crude oil and the expansion of fossil fuel-powered vehicles, as the artificial asphalt could be manufactured from the by-products of crude oil refining. The first concrete roads – likewise defined as "smooth" surfaces – were also constructed in the end of the 19th century.

The fourth generation of roads defines more an infrastructural system, than a technical parameter of road structures. This generation means the international, continental infrastructure systems which needs the massive production of different – but mostly asphalt and concrete – road materials all around the globe. It has begun with the spread of motorways in the last century, which identify national and international road networks. The road network must secure the global mobility for goods and people and an easy access to the other three (air, water and railway) infrastructure system.

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[3] The base of the pavement was mostly sand and gravel mix or crushed aggregate, but even concrete was used in the Roman Empire as subbase.

[4] Not only European examples can be found for durable block stone structures: in the Inca Empire most of the buildings, as well as stone footpaths were made without binder agent, and still can be used – mostly by tourists.

[5] But its biggest disservice was the continuous demand of crushed stone supplement, as the structure were constructed without binding agent. As a solution for that problem, the first use of asphalt as a binder was added to the surface layer of McAdam roads to prevent or at least reduce the loss of crushed stones and gravels from road structure.

[6] These were the first asphalt roads, but the asphalt as a waterproof, durable material was already used in the ancient times mostly for sealing aqueducts and other water suppling elements.

These are the four steps of the road construction history by chronological sorting, which is followed by the fifth generation of roads with environmental aspects in the innovation. We can classify roads by their role in the infrastructure system (motorways, main roads), by their location (periphery or urban) and from the point of production and construction view by the pavement layers and by the type of material. The standard pavement structures are defined [5] as flexible pavement roads, rigid pavements, semi-rigid pavements, and block pavements. Flexible pavements are mostly built from bituminous surface and binder course with unbound (or bituminous bound) upper and lower bases, (which could maintain reclaimed asphalt pavements (RAP) up to 95% by low load classes). The number, thickness and variation of layers are depending on local conditions, foreseen traffic volumes and the construction methods. The two upper courses must have the ability to withstand high traffic- and environment-induced stresses without cracking and rutting, and the same time offer skid resistance, noise reduction and durability. The base courses support the top layers and protect the underlying layers. Sub-bases must have the mechanical resistance and the ability to transmit the reduced loads to the ground.

Rigid pavements have similar unbound or stabilized sub-base layers as the flexible structures, but the bituminous bound layer only can be found in some cases beneath the surface layer. The surface course has Portland Cement Concrete material which provides the necessary durability against high traffic loading. The lower layer of concrete could be reinforced with additional materials to prevent cracking and thermal deformations. In some cases, reinforced concrete pavement can be poured direct on the compacted ground – or only on a thin stabilisation layer – which makes this form of rigid pavement economical to construct.

If the Portland cement layer is overcoated with bituminous surface and base layers – and becoming a base course instead of surface layer – it is called semi-rigid pavement, as a combination of the two main structure. It termed originally as Resin Modified Pavement (RMP) which is mostly porous asphalt concrete (PAC) with air voids between 25-30% [6]. These types of pavements have lower flexural strength than rigid pavements but derives support by the lateral distribution of loads as in flexible pavement. Semi-rigid pavements can be constructed with lean cement concrete, soil cement and lime-puzzolanic concrete.

2.2 Basic characteristic of asphalt pavements

2.2.1. Types of asphalt mixtures

As the most important pavement material, which constitutes 95% of the pavements worldwide, asphalt mixtures are causing global impact of the environment, and playing a meaningful role in the global economy too. Asphalt pavement[7] [7] consist of bitumen as the binder material, stone aggregate as the load-bearing frame and additives (like polymers) if its performance requires it. There is a wide scale of different asphalt products depends on their position in the structure, the rate of its ingredients or the production temperature. In a flexible structure asphalt mixture can be used as a base, binder or surface layer or as a combination of these layers. In semi-rigid pavement structure, it plays the role of a covering surface layer on the PCC concrete layer. It also can be used as bituminous bound layer for rigid pavements and block stones. As a surface layer, asphalt mixture must fulfil the requirement of bearing the traffic loading with direct contact, providing ideal friction for traffic, protecting the bellowed layers from traffic and weather conditions, and providing resistance (to polishing from vehicle tyres, chemicals or extreme temperature conditions). Binder layer has the purpose to connect surface and base layers and transfer traffic loadings, while base layer distributes and transfers them to the unbound layers. By the location in the structure the asphalt mixtures have different parameters: from surface to the base layer the thickness of the layer increases, as well as the maximal aggregate size, but the binder content decreases.

Asphalt mixtures can be classified by the temperature during the manufacturing and paving, which plays a major issue in the environmental sustainability of the products. The first – and till today most standard – production technique requires temperature over 130 ºC, that is why it is called Hot Mix Asphalt (HMA). Temperature reduction can be reached by using bitumen or asphalt mixture additives on HMA for energy saving, called as Half-Warm Mix Asphalts (HWMA) There are mixtures with specific binder contents, like emulsified or fluxed bitumen

[7] At this point a subtle interpretation is necessary to the etymology of the word asphalt. The word is derived from Ancient Greek *asphaltos* (Herbert, 1939), and used in much of the world as the product of the material manufacturing which consists of crushed stone aggregate, binder material and a combination of additives. In American English asphalt means the dark coloured binder known as bitumen (or called asphalt-binder), and the term „asphalt road" is used for the product. It also called confusingly asphalt cement, as it plays similar role in asphalt, as the cement in concrete, but the two component has nothing else common. In my thesis – to avoid definitional misunderstandings – I will refer the binder material as bitumen and the mixed product of bitumen, aggregate and additives as asphalt.

which can be produced on lower temperature mostly as surface treatment, slurries[8] or in recycling methods[9]. If these products can be produced between 40 – 120 °C, they are belonging to the Warm Mix Asphalts (WMA). Under that temperature we are talking about Cold Mixtures. With the reduced production temperature, the construction temperature proportionally decreases, reaching better transportation and logistics opportunities and more favourable build-in condition from point of view of health and emissions. Some of the most important asphalt products are presented in Table 2.1.

Table 2.1 - Most common hot mix asphalt products and their properties

Name	Void content [V%]	Binder content [M%]	Properties and advantages
Asphalt Concrete (AC)	2,5 - 6	3,5 - 4	Most common Dense aggregate structure (curve represents fuller parable) Optimal for all three asphalt layers
Stone Mastic Asphalt (SMA)	6 - 12	5,5 - 6,5	Gap graded mixture Surface layer for high stability Noise reduction Macro texture Skid and rut resistant surface
Porous Asphalt (PA)	17-25	5 - 5,5	Distinctive gap grading Water drainage Noise reduction Bearing Capacity Lower Service life Cost-efficient

[8] Slurries are mostly sprayed layers of bitumen emulsified with fatty acid, amid, or imid. They are used for surface treatment like coating, for cold in-place recycling, or as cold-mix asphalts.
[9] With the constant technological development more and more HWMA and WMA products can be used, not only as an additional product for maintenance or recycling of HMA asphalts roads, but also as a main material for new road structures, such as LEA (Low Energy Asphalt).

Hot Rolled Asphalt (HRA)	2 – 7,5	>5,5	Dense aggregate structure (with gap grading) Weather resistant, durable surface Skid resistant Coated chippings for resistance to polishing
Mastic Asphalt (MA)	~ 0	7,5 - 10	No compaction needed (pouring) Chipped or Rolled Flexible construction Reduced emission External fire resistance

2.2.2 Aggregate

The mineral aggregate constitutes 75-85 % of the mixture by volume, and 90-95 % by weight – depends on the type of asphalt structure and layer - and is responsible for the stability, bearing capacity and long-lasting of the pavement as well as for the proper friction for the surface layer. It is mostly containing igneous rocks, like basalt or granite as the stone skeleton of the asphalt structure. As unbound layers below the asphalt layers a range variety of types are available from sedimentary to metamorphic rocks, as well as synthetic rocks or recycled materials or waste from maintenance. By size we can differ the grains of the aggregate as crushed stone (coarse fraction with D≤45mm/d≥2 mm), gravel, sand (fine fraction D≤2mm) and dust (filler fraction D≤0,063 mm).[10] The most important property of a high-quality aggregate is the optimal grading curve to the type of the asphalt mixture. By asphalt concrete it represents the fuller parable which means no lack of the fractions. On the other hand, stone mastic asphalt is poor in sand and fine stone, while porous asphalt has no sand fraction. It shows that the defined type of the asphalt material not only requires punctually defined aggregate, binder and void content, but also an adequately defined content of each aggregate fractions with small limit values. Not only the grading curve but also the properties of the grains must be defined through lithology test methods. The most important properties of the aggregate are the abrasion resistance (defined with Los Angeles Test), polish resistance (with Polished Stone Value (PSV)- or Wehner Schulze (PWS) test) and long-term resistance (mostly measured through chemical resistance). Furthermore, the particle shape (to filter out the adverse laminar grains) and the rate of rounded and crushed surfaced grains must be defined (mostly evaluated through empirical test).

[10] Where D is maximum size and d is the smallest grain size, defined through the sieve size.

2.2.3 Bitumen

The typical properties of the asphalt mixture mostly depend on the quality of its binder agent, the bitumen. Bitumen is a dark coloured mixture of organic substances like high-molecular hydrocarbons, sulphur, oxygen and nitrogen. It shows viscoelastic properties, which means more viscos behaviour at higher temperature, causing deformations and rutting in summer. In winter the more rigid, elastic properties are becoming dominant (less significant but still with a present viscosity).

As the formerly mentioned natural asphalt resources are mostly ran out in Europe and America[11], the industrially used bitumen is manufactured from the by-product from purchasing crude oil. Thanks to its great sealing performance to water, bitumen has secondary uses as insulation material – as it was already used in by the time of ancient Greece – could also produce roof shingles – offering an effective outcome for the recycling methods too – but more than 80% of the produced bitumen will be used as asphalt binder.

Artificial bitumen will be manufactured during refining of crude oil. The heated and vaporized oil get through atmospheric distillation, which separates the products to fractions by weight. With increasing weight, boiling point, and length of hydro-carbon molecules the fractions are gasoline, naphtha, kerosene, diesel, heavy oil and residues (Figure 2.1 And Table 2.2).

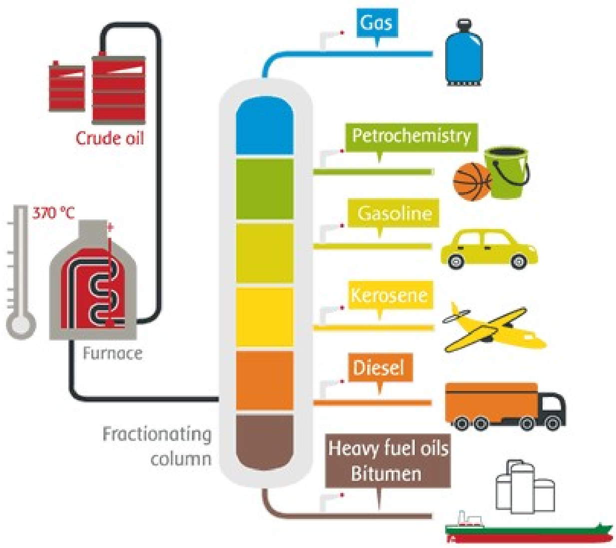

Figure 2.1 - Products obtained from crude oil refinery [8]

[11] One exceptional example of natural bitumen is the so-called Pitch Lake in Trinidad and Tobago, which contains natural asphalt, as the bitumen of the lake naturally mixed with the aggregates of the surface. It is the only natural asphalt source which supplies high amount of asphalt, but its numbers are far from the rates of artificial asphalt manufacturing.

Table 2.2 - Products from crude oil and their properties

Fraction	Boiling Point [°C]	Carbon in molecules	Common Use
Refinery Gas	<40	C_1 to C_4	Heating
Petrol	20-70	C_5 to C_9	Fuel
Naphtha	70-160	C_5 to C_{10}	Source for plastics and chemicals
Kerosene	160-250	C_{10} to C_{16}	Jet fuel, Rockets, Lighting, Parrafin
Diesel	250-350	C_{14} to C_{20}	Truck fuel
Residue group Fuel Oil Lubricating Oil Waxes	300-370	C_{20} to C_{70} C_{20} to C_{50}	Power stations, Ships Fraction reduction Polishing
Bitumen	>370	>C_{70}	Road Construction Roof Shingles Roof and basement sealing

To produce soft to medium hard straight-run bitumen a second heating cycle and a vacuum distillation is needed. The production of different bitumen classes needs further steps of refinery. For harder – so called hard grade – bitumen high vacuum distillation is necessary. To improve performance, the distillations bitumen can be mixed with polymers (polymer modified bitumen)[12], flux oils (cutback bitumen), or emulsified with water and stabilizer (emulsified bitumen). As a second step of vacuum distillation, oxidation can be reached at 260 °C to produce harder oxidized bitumen. With these further steps the chemical composition of the bitumen can be changed to reach advanced rheological properties. These are based on the double-phase system of the bitumen consisting maltenes and within dispersed asphaltenes. The additives like polymers, emulsifiers or oils increases the general advantages of this colloidal system, like good adhesion, sealing, or chemically resistance to acids, baes and salts. The most important properties which must be tested for both conventional and innovative bitumen products are the ductility, empirical performance span, consistency, elastic recovery (for modified bitumen), workability, stability, deformability, fatigue and low temperature behaviour. (5th chapter)

[12] For polymer-modification polyethylene or polypropylene are mostly used, but natural or recycled rubbers can also be modifiers to improve the rheological properties of the bitumen.

2.2.4 Manufacturing of asphalt at a stationary mixing plant

The production of asphalt is mostly separated from the bitumen manufacture, as its production demand does not depend on the crude oil refining. The production mostly going on in stationary asphalt mix plants. By capacity we can classify small (60-80 t/hour), medium (80-160 t/hour) and large mix plants (160-300 t/hour). There are two basic types of asphalt plants, the batch plant, and the drum plant. Batch plants are known as discontinuous tower plants with periodic production cycles, while drum plants (also known as parallel drum mix plants) offer continuous asphalt manufacture. The plants must have landfill areas for the components like crushed stones and aggregates, and for the composed asphalt as material of RAP. The aggregate is transferred to the drying drum and will be separated according to the size after the efficient drying at round 170-200 ºC. After extract, the avoidable rock dust and fillers, the aggregate mix will be dosed according to the pre-defined grading curve to the binder agent. The liquid bitumen is pre-weighed from heated storage tank before mixing, which means spraying the bitumen at 20 atm pressure to the dry mixture of the aggregates and dosing the necessary additives. After the mixing the ready mixture can be stored in a hot storage silo or can be moved direct to the transport truck. In drum mix plants drying and mixing with bitumen happens parallel, after the weighing which takes place on a charging conveyor belt. The avoidable fractions of the aggregate will be eliminated with dry and wet dust collectors to assure the optimal adhesion of bitumen on the aggregate surfaces. The other version of drum plants is called counter drum plant with the difference from parallel plants, that the aggregate moves opposite direction to the flame, and the bitumen mixing zone has no direct contact with the flames.

2.3 Environmental issues of asphalt production

Manufacturing of asphalt is highly energy consuming industrial process with huge demand of electricity and heat (from diesel or biogas), which results high emission of green-house gases (GHG) as an aftermath. The punctual definition of energy data and emission through road construction industry is nearly impossible knowing the always changing circumstances, and the uncertainty of the measurement. The input and output of energy mostly depends of the size, type and state of the mixing plant, the type of its heating unit (electric or oil-fired) and the composition and type of the asphalt. The Table 2.3. shows an evaluated energy demand of the product components only focuses on the manufacturing at the mix plants.

Table 2.3 - Energy demand for production components of asphalt [1313]

Energy source	Energy demand of production components of asphalt in MJ/kg					
	Bitumen	Granite, crushed sand	Lime filler	Fibre	WMA additive	Heating of recycled asphalt
Mix content [%]	6,55	88,59	4,66	0,2	3% [13]	-
Diesel			0,04	1,2		8,78
Natural gas	3,25		0,55	0,06	3,25	
Electrical Power	1,09	21,2	0,06	0,04	1,09	
Oil		17				
Source:	Euro bitumen	Swedish rock pit	Fakse Chalc	theoretical	theoretical	EAPA

From these data we can have a rough picture about the energy rates within the mixing plant. As seen from the table, the crushed stones and sand requires the highest energy demand per kg for the drying and mixing, which means the highest summarized demand with the extremely high[14] weight-ratio in the mixtures compared to the other component. Fibre and limestone require slighter demand on diesel, gas, and electrical power[15], while bitumen and the WMA additives shows similar data. The heating of the recycled asphalt has peak values at diesel usage, but these standout values will be compensated by the energy saving as seen on the next tables.
The Table 2.4 shows the energy demand of some asphalt products from component production and preparation until laying, while the Table 2.5 the GHG emissions of the same products.

[13] In percent of the bitumen mass
[14] For most of the products 80-85% weight is given as aggregate content. This example shows slightly higher values
[15] The demand of electrical power – shown in Table 2.3 - can be converted to energy demand on other natural resources. The writer of the thesis defines the electrical power equivalence to oil, coal, natural gas as well as sustainable energy forms, like wind power, established based on Danish data. As most of the countries are still lagging the Scandinavian countries respect to renewable energy sources, the most common source of energy are coal and gas, which are showing 1,113 MJ and 0,674 MJ energy demand for 1 MJ electrical power.

Table 2.4 - Total Energy Use for pavement Construction Materials [9]

Energy consumption [MJ/t] for different products						
Product	Binders	Aggregates	Manufacture	Transport	Laying	Total [MJ/t]
Asphalt Concrete (HMA)	279	38	275	79	9	**680**
Road Base Asphalt Concrete	196	36	275	75	9	591
Warm Mix Asphalt Concrete	294	38	234	80	9	654
Emulsion Bound Aggregate	227	37	14	81	6	365
Cold Mix Asphalt	314	36	14	86	6	457
Road Base Asphalt Concrete with 20% RAP	157	33	275	64	9	538
Road Base Asphalt Concrete with 30% RAP	137	39	275	58	9	510
Road Base Asphalt Concrete with 50% RAP	98	25	275	47	9	454
Emulsion In-Situ Recycling	105	4	-	15	15	139

Table 2.5 - Total GHG Emissions for pavement Construction Materials [9] [16]

Greenhouse Gas Emissions [kg/t] for different products						
Product	Binders	Aggregates	Manufacture	Transport	Laying	Total [kg/t]
Asphalt Concrete (HMA)	16	9,4	22	5,3	0,6	**54**
Road Base Asphalt Concrete	11	7,6	22	5,3	0,6	47
Warm Mix Asphalt Concrete	17	9,4	20,5	5,3	0,6	53
Emulsion Bound Aggregate	14	9,4	1	5,4	0,4	30
Cold Mix Asphalt	20	9,1	1	5,7	0,4	36
Road Base Asphalt Concrete with 20% RAP	9	7,8	22	4,3	0,6	44
Road Base Asphalt Concrete with 30% RAP	8	7	22	3,9	0,6	41
Road Base Asphalt Concrete with 50% RAP	6	5,2	22	3,1	0,6	37
Emulsion In-Situ Recycling	7	1	1,1	1,0	0,4	10

[16] As seen from the source, these data based on 2003 measurements, but still can be used as a comparison of different asphalt products. The age of these parameters also shows that the energy sparing alternatives as well as recycling methods are not new innovations of the industry, but still need further development and economic support to fulfil their potential.

The data from Chappat and Bilal estimate the full energy demand and emission of the asphalt products. Through the total amount of energy and emission the hot mixed asphalt concretes display the highest values, while recycling methods (specifically in-situ recycling) have by far the lowest. It would be premature to draw any final conclusions as regard of these values, since it needs deeper investigation, to understand the correlation of energy data and the different processes. According to these tables, the manufacturing assumes the highest energy demand, closely followed by the binder preparation processes. The aggregates show even lower values as the binders, which might sound like a contradiction with the Table 2.3, but the Table 2.4 and 2.5 tables are referring to the heating and mixing demand of the components – summarized in the column of the manufacture – and not containing the transport and preparation. By manufacture, CMA, Emulsion Bound demand negligible small amount of energy – compared to the other methods – while In-Situ Recycling implicitly needs no manufacture at the mixing plant. The laying requires quite similar energy demand by each product while transport shows small differences by most of the asphalt products. It is clearly visual how much sparing the use of RAP in asphalt concrete mean, but the technical requirements make a strict boundary at 50% RAP given the current state of our knowledge, which maximized at 20% by most of the products (like Low Energy Asphalt for example). The values might not be representative according to the conditions of life cycle analysis - as it is ignoring some essential part of the product life cycle like dissociation of pavement for RAP or transport of machines for in-situ recycling – but helps to explain the procedure of asphalt manufacturing and construction from an energy considerate aspect.

The global emission of road construction – and its environmental impacts - can be investigated from two opposite viewpoint. If the road construction is seen as crucial part of the transportation sector, which became the most polluting sector with 28,9%[17] of the global emission [10] than its direct emission scale is dwarfed by the transportation (which contains road, rail, water and air traffic). In 2010 less than 0,5% of the global emission was caused by road construction and maintenance. This data includes both asphalt, and concrete roads, but as more than 90% of the

[17] The globally expanding transport sector taken the lead from electricity sector, and – according to the data – reaches 29% of the U.S. emission (epa.gov 2017) being a sample not only for developed countries. This expansion of the last decades can be explained through the continuously increasing demand of global transport of goods and global travel from both business part and tourism, which was overheated during the recovery phase after the global economic crisis in 2008. During the writing of this thesis the further development of these trends are hard to predict as a potential economic crisis would severely affect this sector.

world roads made of asphalt, the impacts must be considered mostly at this chapter. After a decade, the emissions increased significantly, but on a smaller scale, than the transportation itself. As a result, the emission rates are still round 0,5% or even less, thanks to the global expand of transport and its emissions. This reasoning leads us to the conclusion, that the road construction – specifically the asphalt road construction – has only indirect effects which are significant globally, and its actual emissions are infinitesimal.

On the other hand, the 0,5% of the global emission covers still an unbelievably high amount of GHG emission and energy demand. As the road construction sector shows endeavour to sustainability, every opportunity must be taken to reduce these numbers for a self-sufficient, sustainable system with lower carbon footprint.

Carbon footprint is a relative new definition to describe the climate changing impact of a product or service, mostly from its GHG emission. It helps the comparison of different processes, systems or even regional economies by transform the units of different green-house gases to CO_2 equivalence. With this 'simplification' there is no need to weigh the importance of energy demand against GHG emissions, or the impact of different green-house gas emissions, which could be quite divergent by products or production processes. The ton CO_2 equivalence (t CO_2e) is the official unit of the carbon footprint, also can be used to define the sustainability of an innovation through Life Cycle Analysis. *The official statement of the carbon footprint based on the ISO 14046 standard, or the GHG Protocol of the World Resource Institute (WRI) and World Business Council on Sustainable Development (WBCSD)* [11]. The HMA asphalt product has approximately 60 g CO_2e pro kilogram [12], which is appreciably lower than many other everyday life used products (like foods or electronics), but the amount of produced asphalt product every year underlines the importance of further cutback of this value. As the evaluated data from the Table 2.3-2.5 and the process description shows, the most important steps an alternative asphalt product, or asphalt production process must take in the direction of environmentally friendly development are the following:

2.3.1 Alternative processing of bitumen for reduced manufacturing and construction heat

As presented, bitumen is one of the by-products of the crude oil-refinery, which means there is hardly any process with the main goal to produce bitumen. Crude oil-refinery is one of the most polluting process in the energy sector, with high amount of GHG emission. It increases the negative effects of the asphalt production, if we are following the "cradle to grave" aspect of the life cycle analysis, on the other hand, this topic belongs to one of the unclear parts of life cycle assessment. The production of bitumen has a high energy demand, but most part of the energy was used mainly for the oil refining. Without asphalt roads, the by-product of bitumen could still be used as roof shingles or as waterproofing material, however these processes are not commonly used in first place – but mostly as an option of recycling bitumen-based materials. The bitumen production not only depends on the oil refining industry, but until the shutdown of this branch it also secures enough binder material to supply the demand for asphalt roads. Even with the environmental concerns and the - without any doubt proved - connection between the usage of fossil fuels - like crude oil - and local and global climate change, it does not appear to stop the oil industry to refine crude oil in the near future. Unless drastic changes of the economics or a long-term global crisis of the energy sector, the oil industry will produce in the near future at least on the same, but possibly on higher level than nowadays. Even with exponential growth of oil refinery most of the professionals are agree, that the known oil sources guarantee enough resource for at least 50-60 years, not even talking about the potential of new, unknown oilfields. As much as its far from perfect sustainability, it is still highly recommended to hold on with bitumen production for most of the road construction and trying to reach energy and material effectiveness throughout its elaboration to asphalt.

The most promising step to reduce the energy demand are the presented half-warm mix, warm mix and cold mix processes. In these cases, the investigated additives conduce the necessary processes between the binder and the aggregate (affinity on the aggregate surface, adhesion, full coating etc.) on a much lower production temperature to spare the energy from heating. These additives are also generating lower transport-[18] and construction temperature. HWMA and WMA products also have better compaction opportunities which expands the life span of the pavement and minimize the number of the maintaining interventions, even though maintenance has the smallest part from the carbon-footprint of asphalt life cycles[19] These positive side-effects can be observed by polymer-modified and rubber-modified asphalts, and high RAP contained asphalts as well. The Warm Mix Asphalt products can be produced with foaming technology, with organic, wax or chemical additives. The production condition of the

[18] At this point the additives have some economical advantage opposite to ecological benefits, as the shorter transport routes are a stated purpose of the energy efficiency, while the lower temperature asphalt even expand the chance of the transport routes. WMA and other low temperature products can transport further which provoke more fuel consumption, but this side-effect can be balanced with the lower construction energy, as well as the fact, that the longer transport route reduce the risk of failed transportation and their waste.

[19] According to Van der Zwan 2012 published measurements, the material extraction and transport causes the largest part of the carbon footprint with 44%, the manufacturing responsible for 31% while the transport and construction causes 18% together [12].

additives – especially the chemical agents – must be well examined not only for the possible improvement of the asphalt properties, but also for their environmental impact. If the emissions of the chemical production is higher than the expected reduction from the asphalt production, or it has some severe effect on either environment (water poisoning) or human health (mutagenicity or carcinogenicity) it must be avoided.

Water based foaming technology does not use any additives[20], but take advantage of the water evaporation, which was injected on a low temperature to the hot binder. The evaporated water is encapsulated in the binder, building foam in the mix. The so increased volume of binder lowers its viscosity, which improves the coating and workability and through that offers reduced mixing and paving temperature [13]. Water containing foaming technologies are using synthetic zeolite additives, which are releasing their contained water (about 21%) over 85 °C, to foaming the binders.

Organic or wax additives are also reducing the viscosity of the binder above the melting point – that is why they are in the WMA temperature interval. The wax tends to increase the stiffness and deformation resistance of the asphalt. Chemical additives are usually a combination of emulsification agents, polymers, and surfactants. Some examples for each technique are presented in the Table 2.6.

Table 2.6 - WMA technologies [13]

WMA Technology	Product	Company	Additive	Production temperature	Country[21]
Water based foaming technology	**Low Energy Asphalt**	LEACO	Coating and adhesion additive	≤100 °C	France, USA
	Low Emission Asphalt	McConnau-ghay Technologies	Coating and adhesion additive	90 °C	USA

[20] In some cases, antistripping additives can be used to prevent stripping problems caused by too much added water, but it mostly can be replaced with proper definition and control of water addition.

[21] As seen from this column, the research and development of the WMA products mostly located in the USA, France or Germany. These are the countries, where most of the energy reduced technologies are used, but many products are worldwide offered, even when the economical spread shows significant fallbacks.

Water containing foaming technology	Advera	PQ Corporation	Zeolite	20-30 °C reduction from HMA	USA
	Aspha - Min	Eurovia	Zeolite	20-30 °C reduction from HMA	USA, France, Germany
Organic or wax additive	Sasobit	Sasol	Fischer-Tropsch wax	~10-50 °C reduction from HMA	USA, EU
	Asphaltan A-B	Romonta GmbH	Montan wax	20-30 °C reduction from HMA	Germany
Chemical Additive	Evotherm ET	Mead-Westvaco	Chemical bitumen emulsion	50-75 °C reduction from HMA	USA, France
	REVIX	Malty Ergon	Surface-active agents, polymers etc.	15-26 °C reduction from HMA	USA

Some of the developed additives or foaming technics enable affinity of modified bitumen even on wet surfaces ensure effective coating, which makes possible to drastically reduce the amount of heat for drying aggregates. But the impacts of the asphalt aggregate can already be decreased before the heating at the mixing plant.

2.3.2 Minimize the impact of aggregate extraction

The crushed stone extracted in most of the countries from stone-mines through guided explosions. Gravel and sand mostly originate from alluvial areas, like lake and river bends. As both extraction procedure heavily impacts the geographical landscape, the hydrologic system (groundwater in case of stone-mines, both ground and surface water in case of gravel and sand) and the biosphere the revitalization of the area must be planned already during the extraction phase. Recycling used asphalt pavements or other wastes as the aggregate of the new road structure, not only spare the amount of construction waste, but also can replace part of the newly extracted aggregate from the nature, reducing the impact of the extraction. Even with the long-term availability the natural stones must be considered as non-renewable material sources. Many countries facing the problem of the exhaustion of stone-mines, and the limited opportunities of opencast mining and quarrying. We would not run out of usable stones in a human-scale defined near future, but the opening of new mines would mean more and more economical and technical difficulties, not even mentioning the environmental impacts. This level of raw material consumption can be replaced or at least delayed with the increasing use of recycled materials, which would assist a material effective composition of asphalt. Not only the aggregate of used asphalt can be recycled, but by-products from other industrial processes too. *Artificial aggregates obtained from the rejected slags in the production of steel, being previously processed for its reuse, can be incorporated into asphalt mixtures* [14]. This so called Electric Arc Furnace Steel Slag (EAFS) mostly contains calcium, magnesium and aluminium obtained from blast furnace, electric arc furnace or mixed slag, and provenly can replace some fractions of natural aggregates even in SMA and WMA mixtures. Other artificial aggregates like fly ash, metal ore, foundry sand, ceramic aggregates or even construction debris like waste wood or bricks are still under investigation as potential replacement. A new material only can replace natural aggregate if every key requirement will be satisfied like *cleanliness, size and grading; strength; durability; particle shape; texture and angularity; water absorption and affinity aggregate/bitumen*[22] *[14].* These are only the minimum criterions, next to further technical properties the whole process of artificial aggregate transport and potential elaboration must be compared to the impact of extraction, transport and elaboration (like crushing to the expected surface) of natural aggregates. These artificial aggregates can be combined with other Recycled, Co-Product or Waste Materials (RCWM) to reach the ideal grading curve with as few natural materials as possible. As a combination of the two most common road pavement materials, even the recycled and crushed concrete can be the artificial aggregate. Its cement component can be added with different quality and porosity, to reach ideal density, porosity, water adsorption and bitumen affinity in the asphalt mixture.

2.3.3 Increasing the rate of recycled material

As seen from the last two paragraph, material recycling is an effective way to preserve material and avoid unnecessary energy consumption and to reduce material waste. The last one is a

[22] The density of the artificial aggregate is also a considered factor by planning the road pavement structure as too light aggregates are not recommended in most of the situation. They must be separated, but still not useless from road construction view, on the contrary beneficial in bridge construction, where most of the commonly used stone aggregates would increase self-weight of the construction on a dangerous scale.

crucial point for sustainability as the fossil originated bitumen in the asphalt pavement waste made up 82% of carbon. The carbon stored in the waste material, but in case of deposing it on landfills, the amount of carbon will sooner or later get back into the carbon-circle, so the burden of the emission will pass on to future generations, which is clearly against the aspect of sustainable development[23]. The demolished asphalt material had been reused mainly for temporary access as the lower layer sub-base material in road construction, or even in concrete manufacturing. In these cases, the re-used material plays only the aggregate role, and the potential of the binder agent stays unexploited, which makes these methods avoidable. It is better to reuse the properties of both aggregates and bitumen in the demolished asphalt, by recycling it at the mixing plant. In this case we are talking about RAP (Reclaimed Asphalt Pavement), which can be used even in 70%[24] rate in hot mix asphalt used for asphalt base layers, as the aggregate content of RAP would not match the prescribed grading curve of surface or bound layers. As an additive to unbound layer RAP can reach even 90% rate. Using of RAP needs slight modifications in the system of asphalt mix plant; ensure the deposition of RAP separately from aggregate, configure a crusher system to separate the coarse and fine fraction, and build in a so-called recycling-ring in the middle of the drum mixer, further from the drying section. This step is essential, as the addition of wet aggregate happening by the dryer flame would damage the bitumen layer of RAP. At some recycling asphalt compatible mixing plants, this step could execute in a disjoint recycling drum, from where through a buffer silo, the preheated RAP will be conveyed into a mixer to blend with the heated natural materials, according to the mixture properties. This product called Recycled Asphalt Concrete. *1 ton of RAP contains approximately 2300 MJ energy, which correspond 50 litre of gasoline use. Studies in the USA shows that the recycled asphalt concrete has 16% less energy consumption, 11% less water demand and 21% less costs* [15]. Sadly, this recycling technology has its own disadvantages and boundaries, as the used bitumen makes the recycled asphalt concrete more brittle and rigid, and compromised to oxidation. These effects can cause top-down cracking in pavement and make the maintenance cycle shorter. The re-recycling ability of the asphalt is also tested, as the shown effect would multiple with new recycling cycles. As seen, hundred percent recycling and so total sustainability is impossible to reach, but with proper mixing

[23] The sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs [1] – as defined more than 30 years ago by Brundtland Commission – named after the WCED Chairman, Gro Harlem Brundtland.
[24] The addition rate is defined for every single product and much lower by lower temperature asphalts (WMA and HWMA). 70% rate defined in the European Standards; many countries permit more strictly only 20-30% for HMA too.

technologies and necessary additives, these effects can be reduced, and the life span of recycled asphalt concrete can be extended.

The other opportunity for recycling is the in-situ recycling, when the material will be re-used through a maintenance process. In case of Cold In-Place Recycling (CIPR) the upper layers of the road pavement will be crushed and mixed with the aggregate base, and some stabilisation additive – like zeolite or cement – to become a new, compacted base-layer, covered mostly with slurries or other sealing technology. The advantage of this process – as seen in the Table 2.4 and 2.5 – the low amount of energy consumption which is spared through the lack of transportation – to mixing plant and back to construction site – and the lack of heating. On the other hand, the reuse of asphalt mixtures as a base layer has the same counterargument as the reuse in concrete or groundwork, that the binder material will be wasted.

2.3.4 Changing the energy/electricity source of the mixing plant

As one of the greatest impacts from road constructions still caused by the asphalt mixing plant the environmental aspects can be manipulated not only from the side of the materials and products by energy saving methods, but also from the plant side through alternative energy sources. The ideal version of an asphalt mixing plant would operate sustainably, fuelled with only renewable energy sources, but as a first step a more energy efficient replacement of the energy sources is necessary. Here split the Tables 2.4 and 2.5 as the energy demands and GHG emissions are might connected but do not depend on each other linear. There are great differences between fossil fuels and as a first step the changing of the asphalt plants heating system from diesel or gasoline to natural gas is promising. As the heating demand of most asphalt products are high – as CMA products constitute only minor part of all products – the energy efficient heating would probably depend on fossils fuels in the next decades. Renewable energy sources might not effective enough for that kind of energy usage – at least on the present level of development – part of the electricity need can be satisfied from green energy. Hydroelectricity plants and wind turbines are mostly dependent on the local environment and geographical properties, which makes the solar plants the most promising solution. It also has its own boundaries, but the most part of the human-dominated landscapes are capable for effective solar energy production. An average solar plant can work on 110 W/m^2 power – using quite 30% of the solar power at present technical development – which means circa 62 m^2 solar plant for a smaller, and 310 m^2 for a bigger mixing plant. Next to the demand of the area, the other problem is the weather and time of day dependence of the electricity production, which suggest the combined operation of solar and fossil electricity source at an asphalt mixing plant.

Not only the energy source of the plant must be reformed, but also the design of the whole plant. In most of the East-European countries older asphalt mixing plants are responsible for the asphalt production. These stations need to be rebuilt to satisfy the modern requirements. Apart from periodical maintenances, the asphalt mixing plants must be examined for energy and material losses, to reduce waste from inappropriate operation. If its technically and financially possible, plant should expand to be able to store and build in recycled pavement material and produce alternative asphalt products parallel to the HMA which still plays monopole role in Eastern-Europe. This investment might unreachable for smaller asphalt companies or looks inefficient[25], but it could return soon with the production and sale of energy-saving products.

2.3.5 Reducing the emission through transport

The stone-mine and the crude oil refinery are probably located in a great distance from the mixing plant; that is why the emission from transportation could not be reduced radically. As many countries are purchasing their aggregate from foreign land, the long-distance transportation should include railway or water transport if the circumstances are given to minimize the role of fossil fuelled trucks – only from terminals to the destination. The transportation of the final product to the construction site could only be enforceable via road transport, as most of the destinations can be find inland, or in the road network system, which are hardly accessible for other transport systems[26]. As presented, some WMA and HWMA products causes lower construction temperature that indicates longer transport time, but the contraction of transport time is a goal to achieve even in case of WMA products. With proper logistic and dense coverage of the country most of the companies can serve countrywide any construction side – which is their interest from the point of economic competitiveness – but there is another solution for constant availability. To present the manufacturing of asphalt the conventional, stationary asphalt mixing plant was the example, but there is a spread of the alternative so called mobile plants, which can be easily established at the construction site, making it possible to paving the produced asphalt product immediately without any transport. These constructions could not replace existent stationary plants, but in case of planning a new mixing plant, mobile and half-mobile plants should be considered. The half-mobile mix plant – mostly in form of a continuous drum mix – involves the same parts, as the stationary versions,

[25] With this regard the government or international organisations must play supporting role with financial aid to encourage the companies to invest in these new technologies, just like supporting green energy sources. The lack of support is a severe difficulty to spread alternative asphalt technics as it will be presented in later chapters.
[26] Not to mention the loss of time during transhipment.

like a bitumen supplying system, mixing tower, drying drum, cold aggregate feeding system, dust collector, heating system and a control room. It designed for an easy installation near to the construction site and easy disposal after construction work. It could reach even 140 t/h capacity which would easily cover the asphalt demand of a road construction site until the displacement. Mobile mix plants are more like a chain of vehicles, which are easily transportable on road, need minimal foundations for the setup, but still containing every important parts of a stationary plant (Figure 2.2) on a smaller scale. After one day (or only a few hours) on-site setup, these systems are offering round 80-90 t/h capacity [16].

Figure 2.2 - Structure of a mobile asphalt mixing plant, RoadStar 500/1000 Mobile Asphalt Plants [1616]

Some asphalt companies are already offering all three options, not only supplying from stationary plants but also offer the settlement at the construction. As the environmental aspect could not be part of the application procedure and the contract, the preference of a company with further plants counts as a violation of competition law, but there are precedents for such competition disadvantages of smaller asphalt companies. With the offer of mobile plants there is not even environmental aspect to discriminate those companies.

It is clear that for supporting mobile plants, the energy demand of the settlement and not only the longer transport route for components, and fuels but also the plant parts must be considered opposite to stationary plants, but with proper logistic, mobile plants could offer a satisfying alternative.

Next to these challenges the environmental effectiveness of the asphalt road highly depends on the planning of the road and the supplementary traffic system, which must be considered accompanied with the asphalt road construction, as a coherent system.

2.4 Basic characteristic of concrete pavements

The leading role of the asphalt material in road building industry is undeniable with more than 90% - likely 95% - of the road network, but the second most common material must be considered as a potential alternative with numerous benefits from technical and even environmental view. Concrete is an ancient material already used in the Ancient Egypt and the Roman Era because of its hardening even under-water, which made the use for bridge structure, buildings and road pavement bases achievable. Its worldwide usage begins in the mid-18th century, in the industrial era. As road paving material it was developed parallel with the asphalt roads at the dawn of the 20th century and became a major material for highway construction in Germany and the U.S. Concrete pavements has many advantages opposite to asphalt roads, which made the two materials to develop in the 20th parallel next to each other. The more reflective, lighter surface offers lower temperature, reducing the effect of heat islands in urban areas. The rigid surface ensures fuel efficient driving as the rolling resistance between concrete surface and tyres – especially trucks – is smaller, which induces less energy consumption from side of the vehicles, and the lifespan is significantly longer – even double of asphalt pavements - with less need of maintenance - not even mention its bearing capacity and durability as a rigid pavement. Thanks to its high bending stiffness, the pavement is less disposed to permanent deformations (rutting, shoving or pothole building). It makes concrete pavement useful for different applications like high traffic motorways, industrial yards or even as airfield runways and aprons. On the other hand, its long in-situ production and construction, the need of joint design and the necessity of surface treatment – primarily at winter maintenance – caused much smaller market share for concrete, which made the asphalt the winner as a primer pavement material. The environmental comparison of the two materials is currently in process and there is no professional agreement, about clear preference of one or other pavement material.

2.4.1. Concrete ingredients

Concrete is a mixture of cement, water, aggregate – mostly crashed stones and gravels – sand and additives like de-icing agents or air-entrainment. "Modern" concretes are a highly sophisticated family of materials. The mostly used Portland[27] cement in concretes is a complex material itself, manufactured by first burning an intimate mixture of crashed limestone and clay or shale in a kiln at temperatures in the range of 1400 °C – 1500 °C, and then intergrading the resulting clinker with a small amount of gypsum [17]. It consists of mostly calcium, silicon, iron and aluminium. Portland cement will be combined with supplementary materials such as fly ash, slag or limestone powder as form of dry powder, made only 8% of the complete concrete. During the hydration process the silicate and aluminate content of the cement will be hydrated forming different types of hydrate, hydroxide parallel with heat release as the hydration is a highly exotherm reaction. The most common compounds can be seen in the Table 2.7.

Table 2.7 - Cement compounds [18]

Cement Compound	Weight Percentage	Chemical Form	Shorthand
Tricalcium silicate (Alite)	50%	Ca_3SiO_5 or $3CaO.SiO_2$	C_3S
Dicalcium silicate (Belite)	25%	Ca_2SiO_4 or $2CaO.SiO_2$	C_2S
Tricalcium aluminate	10%	$Ca_3Al_2O_6$ or $3CaO.Al_2O_3$	C_3A
Tertacalcium aluminoferrite	10%	$Ca_4Al_2Fe_2O_{10}$ or $4CaO.Al_2O_3.Fe_2O_3$	C_4AF
Gypsum	5%	$CaSO_4.2H_2O$	CSH_2
Water		H_2O	H

The strength of the concrete defined by the Abrams water-cement ratio law (w/c). By circa 0,42 value will both water and binder agent (cement and additives together) be utilized totally. At lower value binder agent will be left making the concrete strength increasing, at higher value water will be left which means better workability. [19] Alite contributes early strength for the concrete, while Belite defines the long-term strength. They react with water during the hydration by the equations of:

[27] Portland cement is a general name for every limestone-based binder agent which chemically react with added water by hardening. It was discovered in 1824 and get its name from the limestone quarried from the English Isle of Portland.

$$2\ Ca_3SiO_5 + 7\ H_2O \text{ ---> } 3\ CaO \cdot 2SiO_2 \cdot 4H_2O + 3\ Ca(OH)_2 + 173.6kJ$$

Equation 2.1 – Alite (Tricalcium Silicate) reaction with water during hydration [19]

$$2\ Ca_2SiO_4 + 5\ H_2O \text{---> } 3\ CaO \cdot 2SiO_2 \cdot 4H_2O + Ca(OH)_2 + 58.6\ kJ$$

Equation 2.2 – Belite (Dicalcium Silicate) reaction with water during hydration [19]

forming calcium silicate hydrate (CSH) and calcium hydroxide (lime). [28] At the end of the hydration, the cement will be hardened containing CSH (50-60%), lime (20-25%), Ettringite (15-20%) with capillary void content of (5-6%) [20] . Half of concrete's CO_2 emissions are created during the manufacture of clinker, the most energy intensive part of the cement-making process. [24]

Aggregates are 60-80% of the concrete mostly consists of crushed limestone, gravel and sand, but it is also offering a great way to recycle other materials, like steel, crushed concrete or even demolition and excavation waste. The aggregate must be clean and impervious to moisture. Water makes up 14-20 percent of concrete, and only added before pouring to activate the presented hydration of cement. This process can be speed up with accelerators, like calcium chloride, which additive is useful in cold weather constructions. More additives, like air entraining agents and plasticizers can increase the durability of the hardened concrete. These additives mostly make up only one or two percent of the final concrete mix.

2.4.2 Concrete Pavement Construction

Concrete pavement can be constructed only with machine mixing at construction site between wood, metal, or plastic forms. After mixing the concrete should be poured within 1,5 hours, or within 300 revolution of the mixing drum. Pouring can be fulfilled directly from ready-mix trucks. The pavement can be constructed unreinforced or reinforced, jointed, or continuously. Jointed form is necessary because of the small relaxation ability of the hardened concrete. Jointed unreinforced pavement is composed of batch work of concrete slab layers, in small square units. The pieces are connecting with tie bars or steel dowels, leaving joints between them. (Figure 2.3) These joints are only few centimetres deep, formed with cutting after the hardening of the concrete but within one day after pouring.

[28] Aluminate and aluminoferrite react with gypsum immediately in the presence of water to produce ettringite.

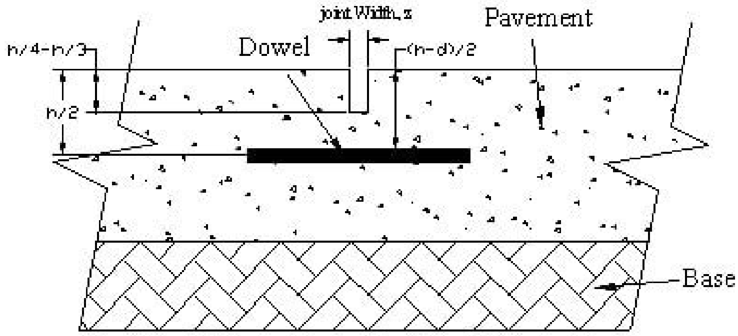

Figure 2.3 - Details of joints in jointed unreinforced concrete pavement [21]

The size of the concrete panels is dependent on the shrinkage strain created due to hardening, which causes tensile stress. The shrinkage strength of the concrete must be greater than the tensile stresses to avoid cracks. Pavement thickness highly affects the recommended length and width of concrete panels, which effects the recommended spacing of transverse and longitudinal joints. As a rule of thumb, the spacing between transverse joints must be less than 25 times of the panel thickness. If the panel length must be longer, jointed reinforced pavement must be used. With greater spacing of joints – generally ten meters but can reach up to twenty meters - comes smaller thickness of the pavement (circa 150 mm), in case of steel reinforcing. Steel bars are installed in the middle of the panel to control cracking and improve thickness. To improve the travel comfort for the car drivers and decrease the maintenance work on joints, reinforced concrete pavements can be built continuously like long slabs. The free building of cracks in continuous pavement is initiated with 0,4-2,0 meters distance.

2.5 Environmental issues of the concrete production compared to asphalt

The dominance of the concrete in building industry is clear, as more than 4,1 billion tonnes of cement was produced in 2019 world-wide[29] [22] [23]. Concrete is the second most widely used substance of the world, after water, which indicates an unbelievable high emission – 4-8 % of the worlds CO_2 emission – higher than the summarized emission of most of the countries except China and the U.S. – as Jonathan Watts claims in an article from 2019. [24] It also presumed

[29] The main producers were in Asia in 2017 with more than three-quarters of the global production. China alone responsible for 56,5% of the production, which dwarf the amount of 2,1% from U.S. and 6,3% of the CEMBUREAU – The European Cement Association for the European Union [23]

that the carbon mass stored in concrete structures already outnumbered the carbon in all of the world trees. Even with more than 30% reduction on energy demand since 1972 the concrete industry has one of the highest energy- and water consumption because of its incredible scales world-wide. The road construction plays a negligible small part of global concrete, but the environmental innovation must be fulfilled, for that part too. The greatest energy and emission problems are being indicated from the production of cement. Cement production increased to 4,1 gigatons globally in 2018 (from 3,1 Gt only in eight years). The largest producer of cement is China with 60% of global production, followed by India at 7% 25 The production of one tonne of Portland cement leads on average to about 0,5-0,6 t of CO_2 being released into the atmosphere, accounting for between 7% and 8% of the worldwide production of greenhouse gases. That means an extreme amount of 2,46 Gt of yearly without any sign of slowing tendency in production.[30] The emission came from the high temperature need of the lime-burning, at round 1450 ºC in cement kilns. At this temperature, the chemical bonds of raw limestone and clay are broken down to recombined into clinker in form of round chippings between 1-25 mm. After the clinker cooled down, the gypsum will be added, and the mixture will be grinded – with further energy demand - to produce cement. As seen the energy consumption of the cement is by magnitude higher than the bitumen (which was round 400 ºC) and only used for the concrete production purpose not as a by-product. To compare the two materials and their production and construction methods, there are many reports and published examination, many are leading to contradictory results, which came from the different perspectives. Many cases leave out the raw material production out of consideration by not taking bitumen and cement production into account – as seen them like other industrial sectors. Without the energy demand of cement, the concrete is mor beneficial than asphalt, as its mixing can be conducted without further temperature demand. Not only the production, but also the transport and construction (pouring) are fuel-saving compared to asphalt pavements. But taking cement production into account the total carbon-footprint of the asphalt is preferable even with the consumption of bitumen producing at crude oil refinery.

As a project showed in 2019 [26] the comparison of concrete and asphalt clearly highlights the energy consumption of the cement production with no opportunity to lower the values. On the other end of the spectrum the concrete mixing plant requires negligible energy compared to the production of the two binder agents. The asphalt mixing energy consumption as well as the

[30] According to the International Energy Agency, cement production slowed down from 4,19 to 4,1 between 2014 and 2018, but it has followed the sharp rise from 3,2 with near 33% expand.

extraction of aggregate for both pavements are by magnitude smaller than bitumen production. The study – which had compared five concrete and four asphalt pavements – has the conclusion by comparing the result of the lowest energy value from concrete and asphalt[31], that the construction of 1 kilometre long highway structure (with one lane od width 3,75m) requires approximately 60% more energy in case of concrete, than in case of asphalt [26].

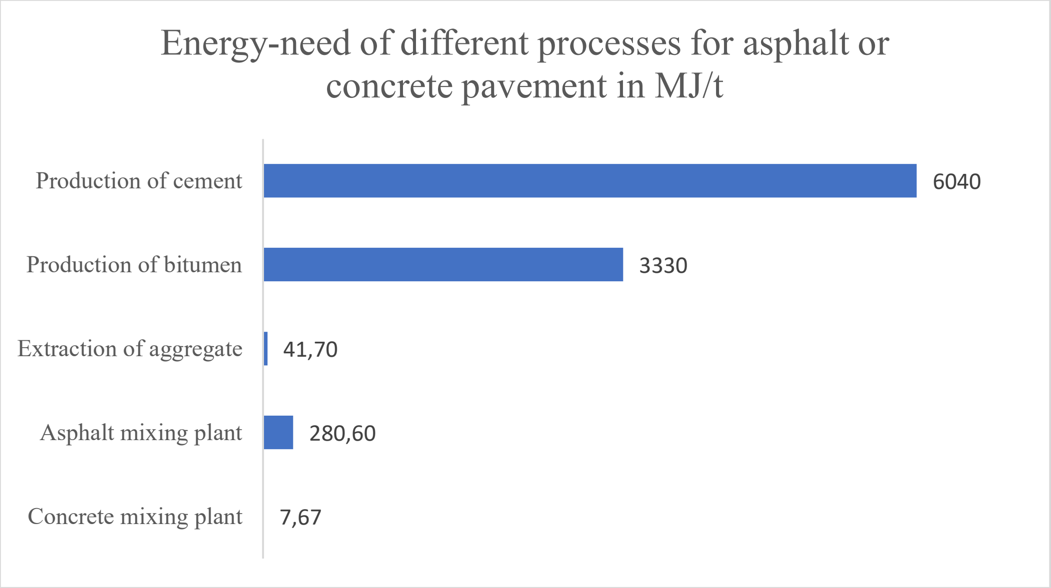

Figure 2.4 - Energy-need comparison for asphalt or concrete pavement [26]

From these statements it would be easy to prefer asphalt against concrete, but the latter has some other advantages as well as potential, which must be considered.

The smaller subbase thickness and thinner pavement means less material and energy consumption, optimal aggregate usage, and usually less preparation works at construction site. As mentioned, the sometimes 50 years long life span and the less maintenance is a huge accomplishment from emission view. The repair works – called Concrete Pavement Restoration (CPR) – are mostly involve surface treatment and grinding. This method uses mostly a diamond-drill to repair the surface texture and the friction coefficient of the used pavement as well. This method can be repeated at least three times during the life span of the concrete and replaces the need of full restoration of the pavement in case of surface problems. Next to CPR

[31] According to the calculations of the author, the concrete pavement with lowest energy demand (from the five compared one) has CP4/2,7 concrete surface with 260 mm thickness, 150 mm thick asphalt base, and a protection layer with min. 100 mm. The asphalt pavement has total of 290 mm asphalt concrete (with different polymer modified bitumen to each layer) and a 200 mm thick dense graded crushed aggregate base.

only the winter maintenance and the joint reparation count to maintaining costs after the construction. The lighter colour of concrete not only reduces the heat island effect in urban area, but also reflect more at night which indicates small number of streetlights, or energy saving lightbulbs. The paler colour concrete is more resistant to temperature indicated deformations. Finally, at the end of life cycle, the concrete pavement is 100% recyclable as subbase aggregate, base layer, or as addition to new mixture of concrete or asphalt. Recycling could be happened in-situ, if not only the breaking but the sieving (mostly with mobile washing-sieving plant) and classification of the crushed concrete is feasible at construction site, to use it as subbase, or aggregate to fresh concrete mixture. To reach ideal properties of the aggregate, the crushing method will be finished with so-called impact crushing to avoid the effect of cracking, durability loss and freeze-thaw resistance. If the concrete pavement is reinforced with steel, the deportation of steel can be done with industrial magnets. The water absorption of crushed concrete could be 10 times higher than the raw materials, which means higher water demand. Crushed concrete from other demolished building materials is not allowed to use in pavement recycling, because of the high content of "pollution" like gypsum, plastic or wood, as well as the crushed sand could not be used neither from concrete pavement for it is causing reduced workability of the pavement mixture. On the other hand, crushed asphalt is allowed till round 20%. Higher part would cause a change in compression and tensile strength and E-Modul.

To environmentally friendly procedures to make asphalt more sustainable, are mostly useful in case of concrete. Minimizing the impact of aggregate extraction, reducing – fundamentally lower – emissions from transport, or increasing the rate of recycled materials and other RCWM-s can help the green efforts further. Only the temperature of cement production could not be lower under 1450 °C, but it also makes an open door for alternative binder agents which might replace cement in the near future.

3. Alternatives

As seen in the last chapter, the development of road building methods and materials can be summarized into four generations throughout the history of human civilisation until the recent years. The next step of the evolution of roads shows a major improvement for the fourth generation's material, which simultaneously guarantees the properties and specifications of the materials and design, which are defined in the former phases. The improvement – that alternatives must offer – mostly have an environmental aspect closely linked to economic considerations. It means for example an energy saving manufacture and/or construction method, an economically efficient production system, or a brand-new product or design as an assistant for the environmental and economic aspects. For the successful spread of the invention these improvements must be confirmed, while proving the infrastructural and technical requirements. But which innovations can be defined as alternatives for road building materials? The short answer is all innovations that partly or fully replace the listed materials – asphalt, concrete and stone pavements – maintaining their parameter and advantages as a proper part of the infrastructure, while minimizing their disadvantages. If we observe this definition, we can find a more complex answer with many subcategories within.

3.1 Variations of conventional materials

In the last chapter the asphalt and concrete properties were presented, in particular to their environmental impacts through energy demand and emissions. It is hard to find an objective boundary between conventional materials and their alternatives, as some of the inventions – like WMA and CMA asphalts, or the method of recycling – are already identified as part of the conventional materials, even if their potential separates them for the most common use of these materials worldwide. Strictly holding onto the four generations concept all materials offering a "flat" pavement are part of the third generation which involves all kind of asphalt- or cement-based products.[32] On the other hand, if the product has a wild range of objectives besides providing a flat surface for infrastructure, it should be classified into the fifth group. The thesis features significant alternatives from environmental aspects, therefore asphalt and concrete pavement with energy saving manufacturing and construction (like LEA or ECO) and pavement products with high amount of recycled materials belong in this group.

[32] With this regard all the so-called 5th generation roads would satisfy this requirement and can be grouped in the third or fourth generation.

3.1.1 Energy saving

To define energy saving methods for asphalt, manufacture has multiple benefits from the construction side. All producers have the economic interest to raise their own productivity, and energy saving methods suggest an option to produce much more product per unit time for the same energy input.[33] It makes the alternate procedure cost-efficient and provides better health situation for workers at asphalt mix plants and at construction site, because of modulated heat, and less emission locally.

The idea of asphalt mix plant working totally on renewable resources – which means, in most of the cases, solar energy as the only available source – is currently impossible because of the still high thermal energy need of the alternate procedures, which would be inefficiently solved only from solar energy. Additionally, the re-building of the plant for renewable resource compatible means too high cost, which most of the producing companies would not afford without external investors. A quite successful achievement of the producing company is to reform its mixing plants to be able to produce low energy products. This one-shot investment can quickly be recovered from energy savings, and as a short-term investment, it might be more attractive for both the company and its investors.[34] Warm Mix Asphalt (WMA) is one of the most commonly used energy saving alternative, offering a producing temperature slightly above 100 ºC, which means 20-50 ºC heat sparing against Hot Mix Asphalts. Because of the common use, WMA is mostly referred as subgroup of the asphalts and not as an alternative. To reach efficient products with lower producing energy organic and chemical additives will be employed, for WMA it is mostly added with foaming technology. Half Warm Asphalts are produced slightly under 100 ºC, and Cold Asphalt refers to unheated aggregate and bitumen mixes. The classification of asphalt alternatives after thermal demands are known for a long time but encouraging innovations can be found every now and then in all the groups.

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[33] From the point of sustainability, it still means the same amount of energy consumption – and carbon footprint – to response the increasing demand. To solve the problem of overuse of energy, the side of demand must also be modulated.

[34] Not to mention the fact that after the transformation of the plant, it would still be able to produce the former products for purchasers with this demand.

LEA

Low Energy Asphalt was developed in 2005 by the fusion of two French companies.[35] It reaches a production heat around 100-130ºC and a construction heat of only 60-80ºC, therefore parameters classify it as a Warm Mix Asphalt, but it also can be understood as a boundary product between WMA and HMA. It allows one of the greatest reductions of fuel consumption from all the practically tested and proved alternative products, and so at least 35% reduction of green-house gas emissions, which could rise even above 50%. The energy demand is around 50% of the demand of HMA (46,8 % from empirical measurements and 47,71% from calculation), which mostly covers the heating of coarse aggregate and water evaporation [27]. The promising data of GHG emission and energy efficiency classify LMA as one of the most effective – already tested and proved - road pavement innovation.

The scientific principle of LEA depends on the foaming capability of the hot asphalt. It means that the bitumen is capable of emulsion with the moisture of the aggregate over steam point, round 150-170 ºC. That indicates a lower temperature coating of the aggregates as well as thinner film on the coarse aggregate surface. Fine aggregate – or high amount of cold RAP – will be added to the mixture and expand around the coarse aggregate to coat it at round 100 ºC. The temperature equilibrates around 95ºC, with around 0,3% of water content.[36] In some cases the addition of wet fine aggregate or RAP – and plus water if it needed – can prelude the mixing with asphalt, and the components will be foamed together. The production needs some minor investment for asphalt mix plant modifications and an automatic system.

The moisture susceptibility properties of LEA mixtures are equal to or improved when compared to conventional HMA [28], which applies to all other service performances like durability, fatigue resistance, tensile strength or resistance to moisture damages.[37] Only for the defined air void content LEA needs more for-compaction with the finisher and more gyration towards WMA to reach full compacted state.

At 80 ºC the mixture could be placed and compacted after 4-5 hours of transport, without further surface damages. At the current stage, the lowest compacting temperature is 60 ºC – even in rainy weather – but there is research for additives, which can decrease this limit even lower, to

[35] The EIFFAGE Travaux Publics and the FAIRCO based together the LEA-CO (Low Energy Asphalt Company)

[36] The ideal amount of water can be defined with the macroscopic experiment of the product. The 2-50 micrometre diameter circles on the coat surface proving the water content.

[37] It had been practically proven by LEA-CO, that the higher water content does not occur higher moisture damage – towards HMA - within the life cycle of the asphalt, if the RAP content does not go beyond 30%. With 20% RAP the moisture resilience can be maximized.

reach the parameters of cold mix asphalts. The workability is compatible with current equipment and machines.[38] The lower construction temperature and the ability to compact also in bad weather conditions offers more chance for planning the timetable of construction and make the logistic of transport more flexible. With longer transport the competitiveness of the company can be increased, as one LEA-compatible plant could serve an extended area. In case of smaller countries – presuming a high-level infrastructure system – one or two strategically settled mixing plant could serve the whole country.

3.1.2 Emission saving throughout service life

The mitigation of GHG concentration is not only reachable through the energy and emission effective production methods as the LEA process shows, but also through innovations which are targeting the carbon sequestration directly from the atmosphere. The carbon capture and storage (CCS) can be mostly reached on a local or regional level. Global results could also be influenced by world-wide afford, mostly through revitalization of natural landscape like reforestation, or at least slowing down the scale of nature destruction and water pollution. Engineering innovations are mostly targeting the local mitigation of hazardous gases in highly polluted cities, industrial areas or along busy traffic roads. Some innovations stayed with the most effective design for GHG absorption and using plants, algae or moss for carbon sequestration, while others are offering artificial equipment for optimal and sustainable absorption of GHG. Both types of products could be used as complementary equipment for road pavements, as the further chapter will present, but their role can be played by the pavement material with adequate additives. As the practical experiment of researchers at Eindhoven University of Technology in the Netherlands proved, combining conventional pavement with titanium-dioxide could drastically reduce the concentration of poisonous nitrogen oxide gas. Nitrogen oxide is not one of the greenhouse gases but it is responsible for the formation of ozone, which is declared as greenhouse gas by formation artificially closer to ground level – opposite to natural ozone in the stratosphere, which is essential for life on earth and has a cooling effect for the atmosphere. NO_2 is not only dangerous because of ozone production, but also through its poisoning potential. It is toxic through inhaling, responsible for smog (like Los Angeles smog), and contribute general acidification of soil and the water circular, which is mostly identified through acid rain formation [29]. NOx (which contains NO nitric oxide, and

[38] Not only compatible with current transport vehicles and finishers, but also has a non-sticking effect on the machine surfaces, which means less waste and easier cleaning method for the vehicles.

occasionally the GHG gas nitrous oxide N_2O) can be produced through oxidising of nitrogen molecule during any king of combustion process. The main producers of NOx are the traffic and industry, that is why its practical to mitigate at the location of the emission itself, reducing poisonous gases and indirectly GHG too.

Titanium-dioxide is a quite cheap additive, which will be impregnated in asphalt or concrete material to eliminate 20-45 % of the vehicle gases. The process is photocatalytic, based on a chemical reaction catalysed by sunlight, which transforms nitrogen oxide to nitrate that later could be extracted from rainwater drainage system, or absorbed by the soil. This Eco-paving system was been proven through practical tests which shows 19% lower nitrogen oxide concentration on eco-paving road compared to titanium-oxide-free control pavement, as well as 45% in ideal weather conditions, defined by the amount of visible and UV light [30]. Similar effects were being proven in Poland, Nowa Sol, where nanoparticles of titanium dioxide were used on pavement surfaces reaching 25 % reduction of pollutants. Even though conventional pavements materials are suitable for Eco-paving, the high porosity and surface roughness of previous concrete pavement allow more particles to contact with UV light improving the removal efficiency, as well as protecting the particles from traffic loading [31].

3.1.3 Alternative pavement materials

The overwhelming role of asphalt and concrete in the infrastructure sector is currently unquestionable, but there are other options with a totally different concept to construct practical and sustainable road structures. As seen in the further chapters, the alternatives can be used combined with present structure elements, like composite pavements, and there are alternate road systems to supervise the whole infrastructure, but first let us have a look on road structures, which not only have similarities with the subground and base layers, but show new innovations for pavement structures. The ideal candidate to switch the hegemony of asphalt and concrete is the recyclable plastic as a quite endless source of material and a useful consequence of recycling.

PlasticRoad

The first candidate of plastic road structures have no smaller objective than offering three times longer service life of a plastic element-based road with only a couple of days construction work and minimal maintenance demand. The KWS company recycled plastic waste into lightweight prefabricated hollow elements. That means easier transport and construction with less heavy equipment needed to deliver and construct plastic roads, that means significantly smaller GHG emission compared to conventional methods. [32]

Figure 3.1 – Plastic Road concept [32]

The hollows in the plastic elements can be used for drainage of excess water by heavy raining, and even in case of flooding, increasing further the safety of the traffic, and also have the purpose to offer space for cables and piping of traffic equipment and potential future innovations.

The element concept offers easier and sustainable repair works, as the damaged element can be easily replaced and refurbished or recycled into a new element, which prolonged life expectancy contributes to a circular economy. the first PlasticRoad in the world was opened on September 11th, 2018 in Zwolle (the Netherlands) as a 30-meter-long bike path [32]. The other feasible applications of the PlasticRoad are still being examined for residential and provincial roads, or even for highways and airports. The biggest concern against the use of PlasticRoad for vehicle traffic is to define the legit stiffness, with surface coating, or sand and crushed stone addition to the plastic material. The problem of vibration and noise pollution are also investigated even as a source of generated power within the plastic hollows.

3.1.4 Composite pavements

Not only the composition of the material (RAP) and the producing technology (LEA) can be changed for alternative pavement, but the combination of older and up-to date pavement materials also causes composite alternatives. The goal of the combination is to obliterate the disadvantages of each component and ensure the positive effects. Composite pavements are the semi rigid pavements with rigid (mostly Portland cement concrete) base course and bituminous waring course, or the combination of flexible asphalt pavements with photovoltaic surfaces. If the combination of two or more methods induces a pavement with lower environmental effect (defined for example through Life Cycle Analysis) than the methods used alone, it is an effective composite alternative for paving. Its effectiveness can be measured in the energy saving through recycling, redeemed material manufacture or transport aspect. If the planned road does not have a full innovative layer structure (like the presented ideas in the next chapter) the developed method mostly concerns the surface layer, and the mandatory bounding with the binder or base layers – mostly made from concrete or asphalt.

Solar Panels as road pavement

One promising example for composite pavement is the SolaRoad innovation in the Netherlands. SolaRoad's product is a combination of pre-produced concrete plates covered with photovoltaic panels. These panels generate electricity with 75% efficiency compared to rooftop solar panels, and their transparent coating offers same skid resistance as asphalt surface layers, with less exposure to deformations. [33]

Figure 3.2 - SolaRoad photovoltaic surface [3333]

One of the main benefit of this technology, is that not only environmental aspects but also economic view was taken into account by developing it, so the total costs of the SolaRoad are quite similar to other road structures, and the investment for the new design can be covered by the sale of electricity.[39] On a pilot basis many bicycle lines were constructed in Netherlands – as well as in Nantes, France - to examine the energy efficiency of the SolaRoad, and since 2019

[39] In the following chapters will be presented, how important is this aspect for the potential spread of an innovation.

the first attempt for heavy traffic were made, confirming the bearing capacity of the surface. With similar goals but distinct structure was the Solar Roadways established. In their case, the solar road does not consist of pre-produced plates, the structure of the pavement follows the original flexible pavement concept until the binder layer, and only the surface builds up from solar panels. The panels consist of two layers of tempered glass surrounding the energy producing electronics. The thick glass layers are protecting the solar panels from all impacts – just like bulletproof glasses – but it does not reduce the efficiency of the solar rays reaching the surface. The Solar Roadways can be adapted to many urban and peripherical conditions. It could be used in light loaded transport surfaces, like walkways – with the benefit of de-icing in winter – bike lanes or parking lots. But the load-bearing capacity of the Solar Roadways can withstand the weight and movement of heavy traffic, which makes it a useful alternative for driveways and motorways. On the other hand, it should be clarified, that the tempered glass surface of the Solar Roadways is only available for flat surfaces, which reduces the usability at driveways. It is preferable to see Solar Roadways as an element of the complex system that consists of asphalt and solar surfaces with a perfect surface bound. The flat surface expectation induces a possible application at airports, where not only the de-icing technology would be useful, but the incorporated LED-signals can help the plane guidance too. The small, hexagon shaped panels are easily replaceable in case of damage, which also correspond to the expectation of automated alternative roads.

China's first solar highway – parallel the first photovoltaic highway section of the world - was already on test phase as the first 0,6 miles long route was opened in 2017 in Jinan, south of Beijing under the development of Qilu Transportation Development Group. The round 6000 square metres of solar energy producing surface is capable of generating up to 1 GWh per year, which is planned to be used mostly for traffic lights, billboards, and cameras. The road is built up from three layers. The top layer is a transparent concrete layer which allows the penetration of the sunlight to the lower – energy producing - layer, while protecting it from the loads of the traffic. Its flexibility can resist to the pressure of even larger vehicles by high speed, which makes it suitable for highway traffic. The second layer contains fragile amorphous silicon boards which are producing the photovoltaic electricity supported with an insulation layer. In case of success the technology would be used in two lanes of every expressway in China, combining the innovative alternate with conventional road structures. During its first 14 weeks in operation, the road generated 96MW of energy [34].

3.2 Alternative Road System

3.2.1 FOR

According to the Forum of European National Highway Research Laboratories[40] (referred to as FEHRL) the transport infrastructure needs a whole redefinition in the 21th century, and the new concept must involve pavement materials, construction, and infrastructure as a complex system, such as seen by R5G. The name of the program is the Forever Open Road (FOR), which describes roads as adaptable, automated and climate resilient parts of the infrastructure. With these characters the alternative pavement material or method could be an effective solution for transport challenges, like ageing transport network, economic pressures, threats of extreme weather events as well as the vision of automated driving. Road network needs to be a part of an integrated transport system, not only connecting interdisciplinary specializations of road traffic, but also defining its connection with railway, water, and air transport. The major goals of the project can be seen on their official logo. (Figure 3.3)

Figure 3.3 FOR Logo [35]

The Adaptable Road: focusing on ways to allow road operators to respond in a flexible manner to changes in road users demands and constraints.

The Automated Road: focusing on the full integration of intelligent communication technology applications between the user, the vehicle, traffic management services and the road operations.

[40] FEHRL is an International Association formed in 1989. It coordinates the operation between more than 30 national research centres. It initiated the FOR Programme as the core of its Strategic European Road Research Program V from 2011 to 2016. The cross-modal research and implementation Plan for SER was defined for the time period 2017-2020.

The Resilient Road: focusing on ensuring service levels are maintained under extreme weather conditions and man-made events [36].

The Forever Open Road concept involves many national programmes mostly from the area of the European Union but also cooperating with countries like Norway and the USA. These national programs can identify a specific, local goal, like the E39 coastal highway route in Norway, or determine general challenges for the national infrastructure system, like the R5G (Route 5 Generation) in France or the R21C (Road in the 21st Century) in Germany. Through the close tie between the FOR concept and the R5G national concept, the main challenges of this alternate road network system can be represented through the basic goals of R5G.

3.2.1.1 5th generation roads (Route 5 Generation - R5G)

The whole comparison of different phases of road building history is based on the concept of the road generations from The French institute of science and technology for transport, development and networks of the Gustave Eiffel university (IFSTTAR) [37]. Compared to the other two groups of possibilities, the R5G maintains the major challenges of the modern road networks. The R5G has been launched by the IFSTTAR as a national concept of modern road networks, but it has close ties with the European vision of Forever Open Roads. Alternative pavements with potential energy exchange, automatization and changeability belongs mostly to the R5G but it does not exclude any kind of innovative road pavement methods, as the whole network must be an integrated system. The project's main environmental goal is to preserve natural resources and minimize pollution due to road construction maintenance and traffic, but there are many other aspects of a R5G, specially:

- Economical aspect (in connection with the main goal)
- Resiliency to climatic impacts, storms as well as earthquakes and underground changes
- Energy efficiency
- Self-diagnosing and repair
- Automatization
- Cooperativity, Communication between infrastructure, network and vehicle
- Safety

The ideal guideway to the deployment of a R5G compatible road is shown on the Figure 3.4.

Figure 3.4 - R5G chain [3737]

Economical aspects

To reach both economic and environmental advantages, the life cycle of the road must be extended with less repair works. To achieve this goal many innovative materials should be developed to find out the most fitting solution to the traffic and climatic situation. At the IFSTTAR new mixes like epoxy asphalt, and new materials like High Performance Cementitious Material (HPCM) with steel fibre reinforcement will be developed. [38]

Resiliency

Resiliency means the assurance that service levels are maintained under extreme weather conditions and man-made events. The resiliency of the road against weather conditions, has undisputed importance for traffic safety and economy. The FOR concept focusing the adaptation to climate changes according to the EU Strategy which estimated no less than 250-billion-euro cost by missing the adaptation process, that is why it becomes a key element by TEN-T European network development.

To develop resilient roads the geographical position, the local parameters of the area and the climate for the location of the road must be well examined and specified. Since it is not an exact science, the climatic effects against the road structure, and the whole road network will be defined with the help of risk evaluation. With the help of hydrological risk assessment, the possibility of damaging effects through extreme weather and their possible return period can be illustrated. With these evaluation, the necessary and sufficient defence of the road structure (and the ideal structure design against the natural disasters) can be identified. As a major point of the risk assessment [41], the possibility of the damage could not reach zero (the case of impossible effect), which means, it is not possible to design fully resilient roads, but with the statistical knowledge of former impacts, the probability of the damage can be minimized. In case of earthquakes the possibility of high amplitude effects can be – at least countrywide – adequate forecasted. But the geological impacts with smaller scale of damage, like sinkholes, landslides or erosion are effective in almost every location. The major problems begin with the hydrological effects. As floods, storms or hurricanes were quite easily forecasted long before their impact, the quick changes in the global climate unsure these statements. Extreme weather conditions will be even more frequent and unpredictable. There are already warning signs nowadays, just as the Ciara and Dennis storms in 2020, which not only reached the coastal countries of Europe but also the inside of the continent. These kinds of extreme storms will be more common in the next centuries, which means that a today planned road network with at least 30 years of life cycle must be examined for less likely, or even yet unforeseen impacts. The impacts of climate change reveal themselves not only on extreme level, but also with smaller scale effects, that might not destroy the structure, but could cause short-term or even long-term malfunction in service. Stronger, more intensive storms can easily overload the drainage system, saturate unbound layers and subgrade indirectly reducing the durability of the structure. Extreme heat indicates deformation like rutting and building of shrinkage in asphalt and concrete layers and could directly disrupt the set of automatic infrastructure systems. The milder climate might decrease winter maintenance requirements, and on the other hand it increases the number of frost-thaw cycles. Not only alternative – smart road – system need vulnerability test methods against climatic events, but long-used structure materials must also test for wilder range of climatic effects.

According to the FOR the resilient road also need to be examined for ageing, constant transport service level, land use planning, safety, and security.

Energy efficiency

In the case of R5G energy efficiency is mainly focused on the service life of the pavement. It is still important to find out an energy saving production method for R5G pavement materials, like the recycled and low energy asphalt, but the main point of this challenge is the energy production during the use phase, and the road is regarded as an energy source. The already

[41] The definition of risk is the multiplication of the possibility and the caused damage of an event. That is why events with low possibility but major results could been let out of the investigated spectrum. On the other hand, the planners must find a rational balance between resiliency and effectiveness.

developed method of energy-asphalts make use of the opportunity to produce heat energy through the warming of the dark surfaces. One example is the so-called asphalt-collector, which was developed in the Netherlands. A pipe-system with small diameter but high density of pipes is implemented in asphalt pavement to absorb the energy from the hot – in some cases even 70 ºC – asphalt and leading the warm water into the pipe systems of near buildings [39], not only producing heat energy, but also reducing the heat island effect, and extending the life cycle of the pavement through cooling. In winter the system can be reoriented, and the circulation of warm water could substitute the winter service similarly working as a floor-heating. However, the efficient, and long-term storage of asphalt-collectors heat in artificial reservoirs is not fully developed, which makes it useful only for urban areas with high average temperature.

The vision of R5G takes the energy efficiency on an even higher level with producing electricity, which could be used locally for the infrastructure equipment – illuminating signs, operating traffic lights – to transport for urban usage or – as most of the projects are dedicated to that – charging electric vehicles. Reaching this challenge is an interdisciplinary project between civil engineers, infrastructure engineers and mechanical engineers. The probability of spreading this kind of road system is principally based on the potential spread of electric vehicles. In the urban transport system there is already a wide use of electricity – with trams and electric buses – but the rate of electric vehicles in cars and lorries is still surprisingly low. The reason is the short cruising range, long time recharge and high costs, which might be upgraded in the near future but today they are overshadowing the huge potential of electric vehicles – and the energy efficient roads with them. The growing tendency might give reason for hope, but it is still hard to answer, if the rate of electric vehicles will be soon high enough to operate a car charging pavement system efficiently.

The formerly mentioned IFSTTAR has several experiments to insert the car charging technology into pavement structures. The FABRIC[42] [40] project working on the large-scale adoption of electric vehicles (EVs) in the transportation system, and reach advanced on-road charging solutions, potentially with contact-free solution.

Not only within the EU can find potential innovations in energy efficiency. The world's first demonstration of power transfer between tires and pavement surface linked to the Toyohashi University of Technology in Japan. [41] In this project steel belts were imbedded in the tires and a dielectric coupling transferred the energy wireless from metal plates in the pavement to

[42] Feasibility analysis and development of on-road charging solutions for future electric vehicles

the tires. With this innovation the scale of accumulators in the electric vehicles can be reduced, the recharging can be solved during the travel, and longer distance can be reached with electric cars. If this innovation can be applied into practice, it could enable electric cars and R5G to be competitive alternatives to gasoline-based vehicles and classical asphalt or concrete roads. The KAIST's Wireless Power Transfer Project Group from South-Korea developed on a Shaped Magnetic Field in Resonance (SMFIR) which allows to transfer the energy from the pavement power lines to the OLEV, on-line electric vehicle, over 20 cm gap wireless. This invention can be used mostly for public transport, mainly in buses and trains. [42]

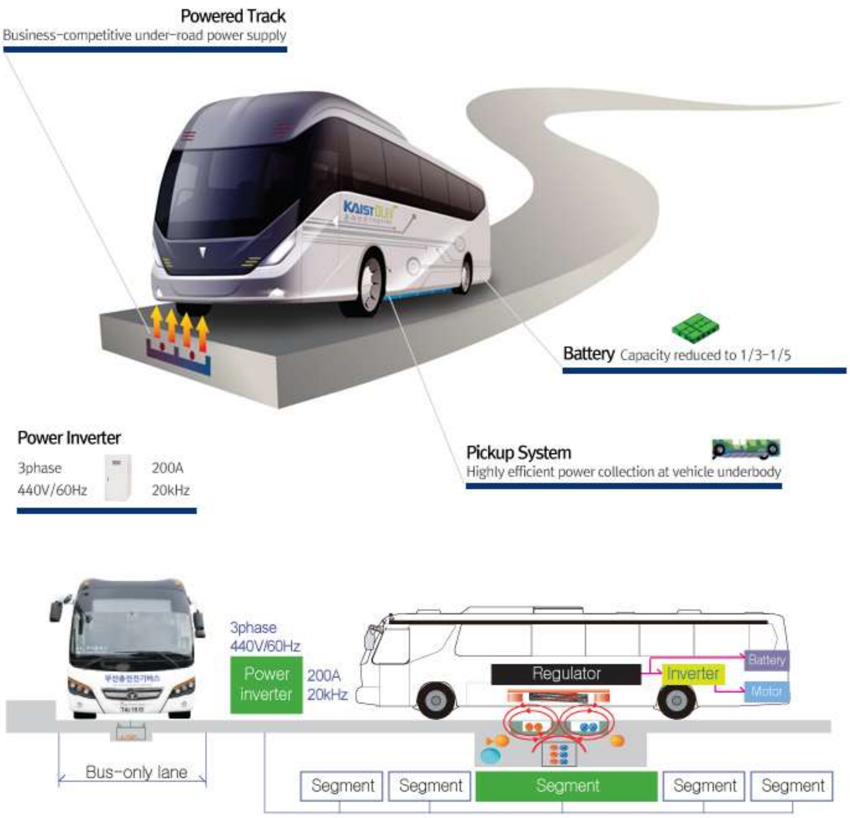


Figure 3.5 - Kaist Vehicle and energy source pavement concept [43]

Self-diagnosis

The technological innovation needed to make the road service life energy efficient goes hand in hand with the expectation of self-diagnosis of the structure and the connected communication with other parts of the road network. Structural Health Monitoring (SHM) aims to provide continuous information about a structure capacity to identify the actual loads from traffic, evaluate its impact on the structure strength and define and monitor onset damage [44]. Self-diagnosis would offer better a solution to optimize the maintenance with proper forecasting of the ideal time of maintenance and reparation works through intense monitoring of the impacts, which could cause reduced life-cycle costs (further explained in Life-Cycle Analysis part). On the other hand, it needs a large number of sensors and monitoring devices (optical fibers, photonics), with prudent – with this regard also long-term and investment-intensive – installation, up-to-date digital system and the maintenance of the monitoring-system too, which can overshadow the reduction costs. Therefore, a proper assessment needs to be done during the planning phase to see the short- and long-term effects, and necessity of self-diagnosis system. In the case of energy efficient road structure, the monitoring system could be built out easier with the charging and communication system, but there are such situations when the classical pavement structures might offer environmental and economic advantages in a systematic level.

Automatization and Connected Road Network

Not only energy but also information must be exchanged between the infrastructure and the vehicles, as well as between users, and traffic control. These exchanged data can not only be related to the technical state of the structure – collected through self-diagnosis monitoring – but also climatic and traffic conditions of the located area. In a connected road network, the vis major cases like damage of an infrastructure equipment, car accident or climatic disturbance, could be identified and located at current state, which offer immediate intervention from the traffic control. Counting with electric vehicles could offer an alternate route plan to avoid problematic areas, not only solving roadblock situations but also helping the work of damage control, public security and ambulance. The connected road network can also serve some energy saving advantage, through intelligent traffic control which could define the necessary working of the whole network system. For example, the power of streetlights, traffic equipment and other supplementary instruments can follow the weather and traffic conditions. In case of empty road sections, the lighting system could turn automatically of – or at least on standby mode – until the information of oncoming vehicles reaches the section. In urban areas there is a great benefit of the connected network to help the infrastructure system. Nowadays this method is mostly based on the connection of the traffic equipment system – under the direction of the traffic control – but it would be beneficial to combine it with the pavement system itself. As the most important aspect of the infrastructure is the safety, the automatically changed control system can only be used in case of a totally connected road network with minimum risk of failure, and applied safety interventions – even manual override – within the system.

Intelligent traffic management also helps the environmental goals by urging drivers to reduce their fuel consumption, as well as calculating emissions [45].

Safety

Not only the safety of the vehicle traffic, but the aggregate transport of the different members of the traffic must be harmonized, eliminate all foreseen and unforeseen (probable) accidents from contact points of different means of traffic. From this point the speedway systems and most of the high-ranking periphery roads are easier to organise without level crossing of other traffic flows or contact points with other level of traffic members. At urban area, the most important task is to avoid the collision of vehicles with vulnerable road users such as pedestrians and cyclist. This is mostly the task of the traffic control, but an R5G self can make mandatory interventions. The self-diagnostic system in the road also can identify dangerous and forbidden pedestrian crossings, not only warn the non-compliant behaviour, but also alert the on-coming vehicles extending response time. On highways one of the greatest risks of collision comes from the wildlife crossing which could be reduced and controlled with fences, green bridges and tunnels – with a huge amount of investment to build and for a constant maintenance – but could not be totally avoided. When large, herd-type animals crossing – considered from the view of safety also as vulnerable road "users" - the warning of the drivers just a split second before the visibility to the naked eye can probably avoid the collision, mostly at night or during other low light conditions. (Figure 3.6)

In the – might not so - distant future all connected system between the infrastructure and the vehicles could detect the over speeding events and other non-compliant driving events and warn both the offender and the authority through the traffic control. The forecasting of the speed limit for the actual street, or road section is quite common for new, GPS-assisted vehicles, but in the near future communication between the vehicle and infrastructure might enable the automatic reduction of speed, making it impossible, to reach an over-speeding event.

Figure 3.6 - Wildlife Crossing concept of Solar Roadways [46]

3.3 Connection with traffic technology devices

As a highly interdisciplinary area of technology, economics and politics, the green innovation of road pavements not only involve the issue of road material construction but the trends in the development of traffic engineering. The R5G concept views the road construction as a solid, related system connecting road pavement, road markings, traffic signals and lightings, barriers and finally the vehicles. Most of the innovations aiming the concept of autonomous driving and the complex information system through traffic signals to support their operation. Most of the road vehicles are still operating without automation based on only human driver performance, but as the car industry changes to produce more and more vehicles including drive assistance or partial automation, the road signals must be visible and detectable not only for human drivers but the sensors of these new generation of cars.[43] [47] The MarketWatch research detect the time of high and full automation of cars at least a decade later, which means enough time for the technology devices to evolve for the modern requirements, but the vision of full automation of the traffic is highly impossible from the present situation, that is why the traffic device system – and the road structure in general – must be suitable for both full automation and non-automation vehicles. These innovations are mostly requirements of high-level traffic safety and traffic comfort but have indirect effect of the emissions and energy use, which the optimal road structure can support. Vehicles with higher automation are most likely fuelled with more

[43] The first and second level of automation means steers or controls of speed, as well as Lane Departure Warning System (LDWS), Lane Keeping Assistance (LKA) separately (1. Level) or combined (2. Level).

sustainable energy systems – as the widespread of electric cars evidenced – and the steering and control of speed provides an opportunity for optimal fuel usage. The flexible changing signs support the on-time information preventing not only potential accidents and hazards but also manoeuvres with higher energy demand – like sudden speed changes or breaking. As seen solar pavements grant flexible changing signals powered by solar power, but conventional pavements have the same opportunity through complementary innovations. LED spotlights are rapidly deployable and easily extendable solutions for asphalt surfaces with high durability and bearing capacity against even highway traffic. Intelligent LED systems can replace the more energy-demanding road lightings offering lower level of light-pollution. Combined and remote-controlled system will be able to define the present traffic level not only granting valuable data for traffic engineers but allowing to change the amount of light by the necessity for the current traffic. In some cases, both LED and conventional lighting systems can be replaced with renewable light sources, like the innovation of Studio Roosegarde in Netherland. The researchers of the company invented paint contains "photo-luminising" powder, which can be charged by daytime sunlight and glow at night eight-ten hours long.

These examples are mostly made for traffic safety purposes using elements of road system, which are inevitable for operable traffic, but the opportunities for further complementary equipment are quite limitless. The positive effect of emission absorbing pavements, like the titanium-dioxide containing eco-pavement can be extensible with further air-cleaning devices. The company Global Research Technologies is developing a machine called "synthetic tree" made from resin, which reacts with CO_2 trapping and storing it by adding water[44]. The stored CO_2 can be sold for industries like oil drilling, to replace a significant amount of artificially produced GHG. Similar efforts to snare manmade CO_2, released primarily from the combustion of fossil fuels, are not yet viable at a large scale, but some scientists think they hold great promise in tackling climate change [48]. The rate of absorption is potentially a thousand times faster than natural trees, and suitable for high GHG emission areas, like highways with heavy traffic (Figure 3.7).

[44] The concept based on the chemical reaction of CO2 with the hydroxide-laced filters of the synthetic tree which produces bicarbonate ions. The added water lowers the affinity of the filter for CO2 causing its release as stored in the liquid.

Figure 3.7 - Concept of Artificial Tree planting along highways [49]

Not only the solar energy can be used along the road, but the unused energy of the traffic. As one of the requirements for road pavements, most materials are designed to reduce noise and vibration from traffic like porous asphalt surfaces or different sealing technologies used on surface layers, other innovations are aiming to use this untapped energy source. The Innowattech Energy Harvestin System is using generators with piezoelectric crystals to generate energy from the vibration of the vehicles [50]. The piezoelectric generators (IPEG) using the mechanical energy from changes in weight and vibration, as well as heat energy of the pavement to produce electric energy used in-situ for the lighting and traffic signs or feed back to the electricity network. The system must be installed round 6 cm under the surface and works very well with asphalt and thin concrete layers, as well as composite layers. One of its advantage compared to solar road systems or even wind plant the easy and relative cheap installation during new road construction or maintenance. These generators can be installed not only roadways, but also in railroad or aprons. Even pedestrian lanes have the opportunity to produce electric energy with these generators, but the small amount of production makes it less profitable. Not only the direct mechanical energy of the traffic can produce energy. Same to the concept of wind turbines the movement of the air, generated by the ongoing, heavy traffic can produce electricity. The concept of the Turkish Devecitech called Enlil [51] is a smart wind turbine with vertical axe and bended rotor blades (Figure 3.8) It has been designed to harvest the energy of natural wind and the one generated from the traffic [51]. The smart system of wind turbine ideally installed between the highway lines to make full use of the wind energy. Because this position the system can be potentially extended or combined with other devices like solar panels and traffic management systems. This application can be installed independently from the pavement structure, but its potential could be higher combined with solar or smart roads of the R5G concept.

Figure 3.8 Enlil Vertical Axis Wind Turbine [5151]

3.4 Occurrent difficulties

"With this regard their currents turn awry, And lose the name of action" William Shakespeare

In this chapter some promising alternatives have been represented for road pavements, shown that both conceptual and practically tested options are being developed presently all around the world. As seen, many companies and investors are interested in innovation of products with high environmental and economic benefits, which shapes a feeling of a new technical revolution in the sector. However, the presented results and promises must be explored from a less optimistic, more critical view. It is important to refer to solid facts and evidences by presenting new methods and to outline the difference between scientifically proven results and concepts. As in many other sectors, the environmental revolution has also numerous ideas on infrastructure, concepts and visions to solve the urgent problems of our world, but that is only the first step to a solution. The importance of the first step is inevitable, without a genius idea no further efforts solve any problems. It is a necessary but not sufficient condition to reach the defined environmental goals, and many innovations are not being able to reach the next step and prove its hypothetical benefits in reality. Even with certified evidence, most of the innovations will not reach even nationwide prevalence – not to mention worldwide prevalence which would be necessary for tangible results – because of the economic and social situation. Let's see some facts about the presented methods.

As a scientifically proven and by the EU legally certificated product, LEA is one of the few examples, which already reached the second step, and its mass production already began. The LEA has 45 licenced partners who had established 350 000 tons of Low Energy Asphalt [52]. since its certification in 2005. In 2016 15 743 866 tons of asphalt was produced worldwide, according to UN Data, which means 45 times more asphalt in one year, than LEA in 15 years. There is a representative example in Hungary, were Duna Aszfalt Kft (Donau Asphalt Ltd.) as licensed partner of LEA-Co already redesigned its mixing plant for LEA and began the production. Since offering these alternatives in total three village roads and a 10-kilometre-long peripheral road was constructed with Low Energy Asphalt. Despite being harmonised with national and European technical specifications, being easier and faster constructed and even cheaper than conventional methods, the spread of the innovation depends on the customer's choice which still prefers conventional – and already known – materials, not only within the competition of companies, but also out of the products offered by one company.

The number of recycling cycles of asphalt and concrete materials are still limited, and mostly replace 20-30% of newly produced product (50% in few cases). There are also sustainability issues with the transportation and reheating process, which causes most of the used asphalt and concrete materials to end up in landfills.

PlasticRoad reached 2018 the test phase with bike lines but needs further investigation to define if the method is able of bearing heavier traffic as the vision was in first place. Questions arose not only about durability but floating and connection problems, which must be solved before mass production. The 100% rate of recycling is also seeming to be unsustainable in long-term production.

Even becoming cheaper and more efficient in time, photovoltaic technology still does not seem to be an effective replacement of asphalt not only from economic but also from environmental concerns. Despite being oddly popular among the public, most of the energy experts are sceptical about solar energy roadways, as they represent a much more problematic use of solar energy, than rooftops and empty fields. One of the failed concepts in the area was the WattWay test in France, which performed roughly half of its expected electricity generation, and even with highest efficiency would cost 13 times as much per kilowatt/hour than large-scale rooftop installations.[45] [53] Solar Roadways are still under development, but a project in Idaho investigated, that most of the panels are not capable of generating the 48 watts stated capacity.[46] [54] If LEDs and heating elements are involved, they might consume the entire generation of capacity. As most of the installation were used in public walking area until that day, the durability performance and safety – pursuant the friction between rubber tires and pavement surface – under heavy traffic must be proved before literal mass production. SolaRoad already tested its durability under heavy traffic, but it is still in development stage, as well as Solmove Smart Solar Streets in Germany. They are promising exceptions, but there is still no solar energy using pavement which totally and without any doubt proved its capability both as pavement and solar energy producer.

China's photovoltaic highway was facing surface failures after five days of testing under real traffic circumstances which delays the mass-production and construction of this pavement as further developments are required.

The Artificial Tree concept was defined in 2010. The initial units will be able to capture up to one ton of CO_2 per day at a cost of less than $100 per ton. By driving costs down to $50 a ton or less, carbon capture can become a cost-effective option for companies looking to meet regulations emerging in Europe, North America and elsewhere," The realistic view of planting the first working artificial trees is in the year 2030 as earliest.

The effectiveness of wind turbines in traffic use are being questioned. The high price and lower efficiency of energy production could force them into economical handicap opposite to solar cells.

Forever Open Road concept of the EU is a long-term vision still in the stage of theoretical development. As a high-scale of a project, FOR and its national partners could not be seen similar to defined road paving methods and needs a higher amount of theoretical for-planning, but the constantly deferred results might give a reason for sceptical view. 2020 – the year of this thesis – was defined as a second milestone of the FOR project to achieve resilient TEN-T Network sections, with the technology that already proven to be climate resilient and adequate

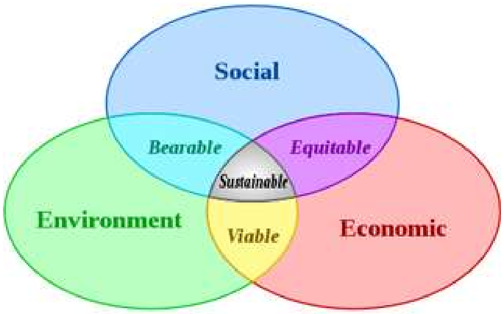
[45] WattWay's silicon resin-strengthened PV panels cost 17 Euro per kilowatt-hour at highest efficiency toward rooftop solar panels with 1,3 Euro per kilowatt-hour.

[46] Sandpoint Project, Idaho

to the other FOR premises. As the technology is still not proven even for part of the tasks – like energy production, weather resiliency or communication – further research and development is needed with new milestones till 2027-2030 as seen in the FOR Programme. [36] The importance of theoretical development is unquestionable, but the long-continued vision of forever open roads might question the effectiveness of developing a complex system – still without solid evidences of its future operation – instead of testing less ambitious but easier testable and provable alternates, which could explain its positive effects during the development of further aspects. With this regard the local progresses – even with continental or global know-how cooperation – might lead sooner to results, than continent wide visions.

4. Sustainability

The most important tasks of an invention can be classified in many ways, but in most cases, they can be separated as technical, economical, and legal aspects. These three aspects have equal importance and shown some similarity with the three pillars of sustainability, which are the environmental, economic, and social pillars. The classical view of the sustainability is the interception of the three area, with even relevance, on the other hand the new interpretation of the sustainability shows the social and economic pillars as subsystems of the environment, with intersection and relative complements or the whole economics as part of the social pillar (Figure 4.1). These new concepts represent the subordinate part of the social and economic aspects against environment because any system can only be sustainable in a long-term manner if its material flow fits fully and completely in the circle of the nature.



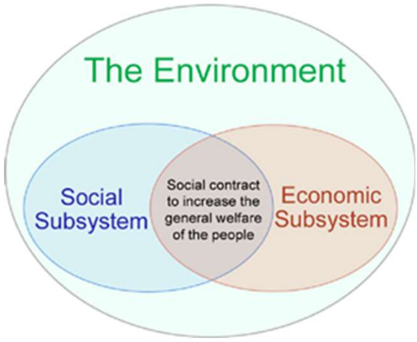


Figure 4.1 - Sustainability concepts [55] [56]

In case of road pavement design performance, cost and environmental impacts define the quantitative sustainability of the project. (Figure 4.2) One of the best tools for comparison of different construction products or methods in the view of sustainability and environmental impacts is the Life Cycle Assessment (shortly LCA).

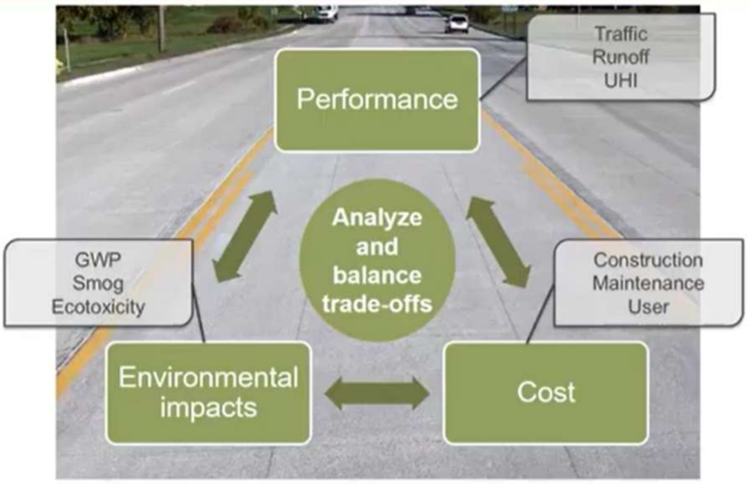


Figure 4.2 - Quantitative sustainability of a road pavement [6666]

4.1 The Life Cycle Assessment and its utility in road building methods

The Life Cycle Assessment is scientifically based method to evaluate the environmental impact and burden of a product or service, with quantitative results. It is an international recognized assessment tool, which provides major decision support during the planning phase by comparing different products or methods based on their utility. This fundamental decision is majorly environmental, but the recognition of the life cycle can also provide information about the economic opportunity through energy-demand, recycling potentials and estimating the total price. The theory of the assessment based on the "cradle to grave" aspect, which considers an aerial and temporal accurately defined and bounded system.

The standardised methodology of the assessment requires a high degree of accuracy during the definition of the system boundaries, data collection and management of significant figures. Dealing with the uncertainty of data is a major challenge during the procedure, that needs adequately referred sources and punctual computation to present realistic estimations for the different technologies.

A successfully conducted Life Cycle Assessment offer the advantages of: [57]

- Legit comparison of the environmental performance of similar products
- Better understanding of production processes and systems for product development and optimization
- Definition and potential reduction of the negative impact of new products and technologies
- Identifying future improvement in existing products
- Avoid modifying one aspect that may cause more significant issues at another stage in a product's life
- Proper help for the environmental management
- Basis of economic and political decisions
- Better external communication of the corporate

A life cycle study requires the definition every material- and energy flow throughout the raw material production, construction works, use (within maintenance), demolishing as well as the transport between these phases. The system boundary could not be constrained, and the law of conservation must be represented in the study. That means products, materials and energy can be changed during the procedure but cannot be disappeared. Defining the life cycle could be easier by products and methods in so called linear economy, which means, their life cycle follows the linear route from raw materials to residual waste. The beginning and end of their lifespan can be easily defined, in consequence the "cradle to grave" aspect can be fulfilled. As products single-use plastics are the widely known examples. In road construction, concrete pavements are the example of these kind of life cycles, with negligible percent of recycling, asphalt pavements show better recycling quality, which means potential feedback loops in the life cycle. For computation purpose these examples might be preferred, but from an environmental view the circular economy has the most potential to fit in the natural cycles. As its name shows, the life cycle of product or method should be circular without any flows left the system, but with many alternative disposition pathways. [58] Reuse returns the product to the use phase, remanufacturing returns to the manufacturing stage, and in last case, recycling takes the product back to its raw material, which can be processed into any other product, beginning a new life cycle of a new product.[47] That is the "cradle to cradle" aspect which entails the risk of incorrect definition of the system boundary – as it is quite questionable, from which stage can we speak about new material, so where are the boundaries of the two systems built upon each other.

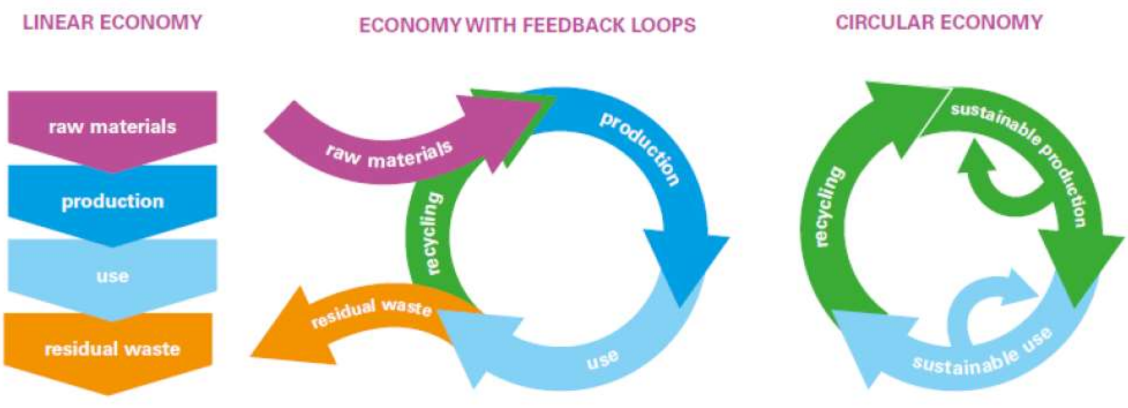


Figure 4.3 - Constructing a green circular society [59]

[47] Next to the three explained feedbacks, repair and maintenance of a construction site can be seen as a feedback loop as well, which retains value. Reverse flow arrow for „Re-design" is also important to represent product failures or iterations. By alternative pavement technologies these steps are involved by the research and development, starting with the initiation of the idea, research, iteration, which are leading to multiple prototypes and the choice of the final design. These steps must be involved in the analysis too, showing the importance of the Life Cycle Assessment already in the planning and design phase.

As Figure 4.3 shows, from environmental point of view the highest expectation of an alternative road pavement – next to the technical adequacy – is the goal of the fully circular system. [59] Fully closed, circular systems might only possible in the nature, but the life cycle of the pavement must approach this goal as near as possible, with minimalize the residual waste – as well as emissions of pollution to the air, water, or land - and replace raw materials. Recycled asphalt pavements can reach these goals in the material flows, while energy producing pavements can cover the energy-demand – as electricity, heat, or both – their production, and produce more energy if it is necessary.

4.1.1 LCIA

The expedience of a new, eco-friendly technology can be measured through its impact to the environment within its lifespan. Many inventions have the external communication of being energy saving, or eco-friendly through recycle or unconventional new production method, but if these results are minimal next to other impacts, the new technology will probably fail. Some of the presented green alternatives could not successfully spread world-wide because of undiscovered negative outputs. For example, if an energy saving pavement requires higher energy level by production, or a recycling technology causes more pollution through transportation and recycling, the invention will fail as environmentally friendly technology.[48] The best tool for complete definition of the impacts is the Life Cycle Impact Assessment (shortly LCIA). *Impacts of resource consumption and generated emissions in a product life cycle are classified and quantified based on a limited number of impact categories. These categories can be weighted based on their importance* [60]. The LCIA results are becoming from the selected impact categories and indicators, which are classified and characterized according to specified models. For the better representation, grouping and weighting of the results are also recommended, but only as optional elements. The four major group of impacts are the air, soil, water, and resources which are equally examined. The impacts on the soil is divided regional and local, mostly by the construction or reconstruction works of a new road.[49] Water is mostly seen as regional destination of impacts, as well as renewable resource (both

[48] Even if the positive impacts outnumbered the negatives, but these effects cannot be recognized in the earlier stages of the life cycle – means years, or decades long pay-off of the energy production – the invention might fail because of the lack of investment.
[49] By taking the necessity of newly built or expanded asphalt plants, factories for the technology also into consideration.

groundwater and surface water). The impact on air must be considered in both regional and global levels, through toxic gases, particles, and global warming potential.

After defining the impacts, the results must be confirmed in such form and unit, that makes the comparison of the examined products or technologies clear. In that case all of the impacts will be transformed into one single category, which describes the whole life cycle of the examined component through an equivalent impact. There are six major impact categories usually used for LCIA: Acidification Potential (in sulphur-dioxide, SO_2 equivalents), Eutrophication Potential (in kg phosphate-eq.), Ozon Depletion Potential (in kg CFC-11), Photochemical Ozon Creation Potential (in kg ethylene eq.), Primary Energy Use (in GJ) and the most important Global Warming Potential (GWP) [61]. *GWP is an index to measure the contribution to global warming of a substance that is released in the atmosphere* [62]. It shows how much CO_2 emission would be equal to all impacts of the component, during its life cycle. At the end of the LCIA phase the following issues should be reported as decision help:

- the relationship with the LCI results
- a description of the data quality
- the category endpoints to be protected
- the selection of impact categories
- the characterization models
- the factors and environmental mechanisms
- the indicator results profile.
- relative nature of the LCIA results
- reference and description of value choices [5761]

4.1.2 LCC

The feasibility of a road pavement technology depends on not only the environmental and technical aspects but as much on the social and economic aspects correspond to the three pillars of sustainability. From economical point of view, the cost-effectiveness will always be preferred against the other aspects, which could mainly incapacitate the spread of new but less effective ways. This problem is also relevant even if the cost-effectiveness only long-term reachable, or its advantages are not mainly presented. With this regard the necessity of Life Cycle Cost Analysis (LCCA or LCC) is relevant to choose the technologies with the most economic potential [63]. *Life Cycle Cost compares the cost-effectiveness of alternative investments or business decisions from the perspective of an economic decision maker such as* *a manufacturing firm or a consumer* [63]. This description shows the main difference between LCA and LCC. LCC could not be part of the LCA, and not even an addition to it, but should been treated both as equals, to understand the reality of a future technology or project. Both should be conducted in the early stage of the project development. As LCC managing the direct costs or benefits of the defined activities, its end-unit will be monetary. On the contrary of the LCA the timing is critical, and the scope does not cover the whole lifespan, but a specific time horizon, mostly because of the time-consuming and labour-intensive way to define every single cost detail.[50] The level of detail must be consistent with the level of investment. Outside of the horizon any other costs and benefits are ignored, which means by shorter horizon that the long-term cost-effects – both positive and negative – will be left out of consideration. To avoid the manipulation of the results by random choice of the time horizon, there are some basic rules to define the examined timespan of the road. *As a rule of thumb, the analysis period should be long enough to incorporate at least one rehabilitation activity* [64]. The FHWA's September 1996 Final LCCA Policy [65] statement recommends an analysis period of *at least* 35 years for all pavement projects, including new or total reconstruction projects as well as rehabilitation, restoration, and resurfacing projects [65]. Some cases, this period could be reduced, but not in case of alternatives with more than two rehabilitation within the period. The Figure 4.4 shows a potential method to describe the time period within the pavement life, while the Figure 4.5 compares two different strategy. It clearly shows that from LCC view the "A" alternative is the preferable one – if the two versions have similar technical and environmental parameters.

[50] The LCA and LCC could not been mass produced as every construction project are different from each other, but there are primary pavement management strategies, that could been used as models for new LCC for the same time-saving reason and to avoid unnecessary repetitiveness.

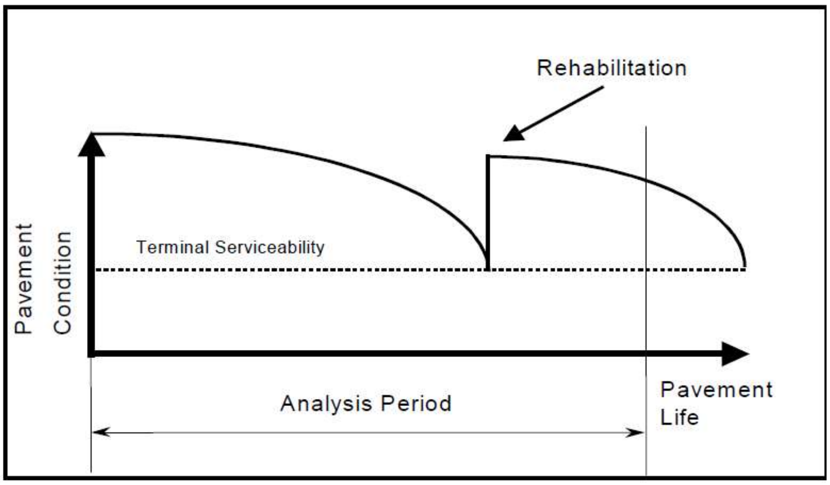


Figure 4.4 Analysis period for a pavement design alternative [64]

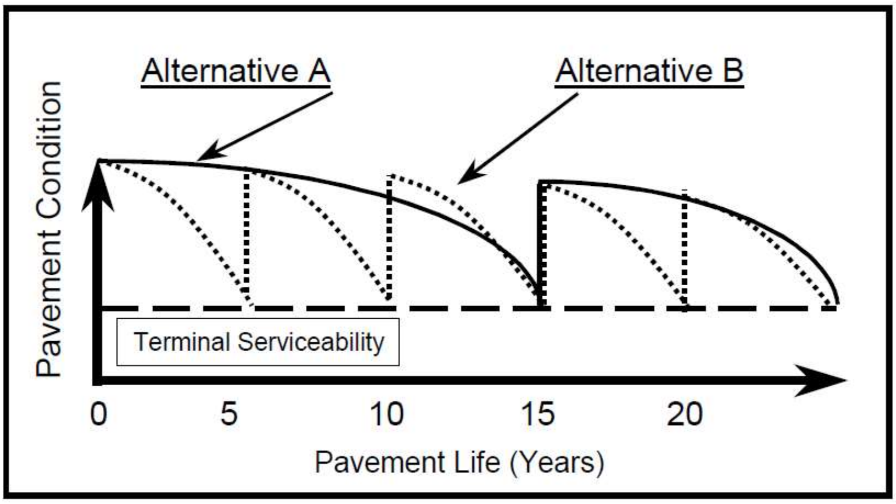


Figure 4.5 Performance curve versus rehabilitation strategy [64]

The rule of thumb, as well as the recommended time period was being defined in the nineties, mostly used for asphalt or concrete pavements. As in this time the fifth generation of roads were not be considered, the new and future pavement could rewrite some of the LCC definitions. The lack of data for serviceability, rehabilitation and even lifespan of solar roadways make it impossible to define proper results of these systems, and even most of the alternative asphalt materials are younger than 35 years, which means, that proper examinations are only made for classical asphalt and concrete products. The major changes in the life cycle of the alternatives only can be estimated, which could disrupt the comparison opportunity.

4.1.3 Life cycle thinking in road building

Life cycle assessment and life cycle costing are typical processes by technology development. In case of technologies related to road building the environmental performance can be evaluated by understanding the impacts associated with the pavement material, construction activities, and other activities that occur on the pavement during its lifetime of use, like maintaining, removing and disposing of the pavement material.

After full and inclusive mapping of all activities the required energy, resources and raw materials and set of emissions will be quantified. Their combination called Life Cycle Inventory. The MIT CSHub[51] dedicated to improving infrastructure science through LCA methods [66]. Their probabilistic LCA model (Figure 4.6) defines the most important components of the Life Cycle Inventory[52].

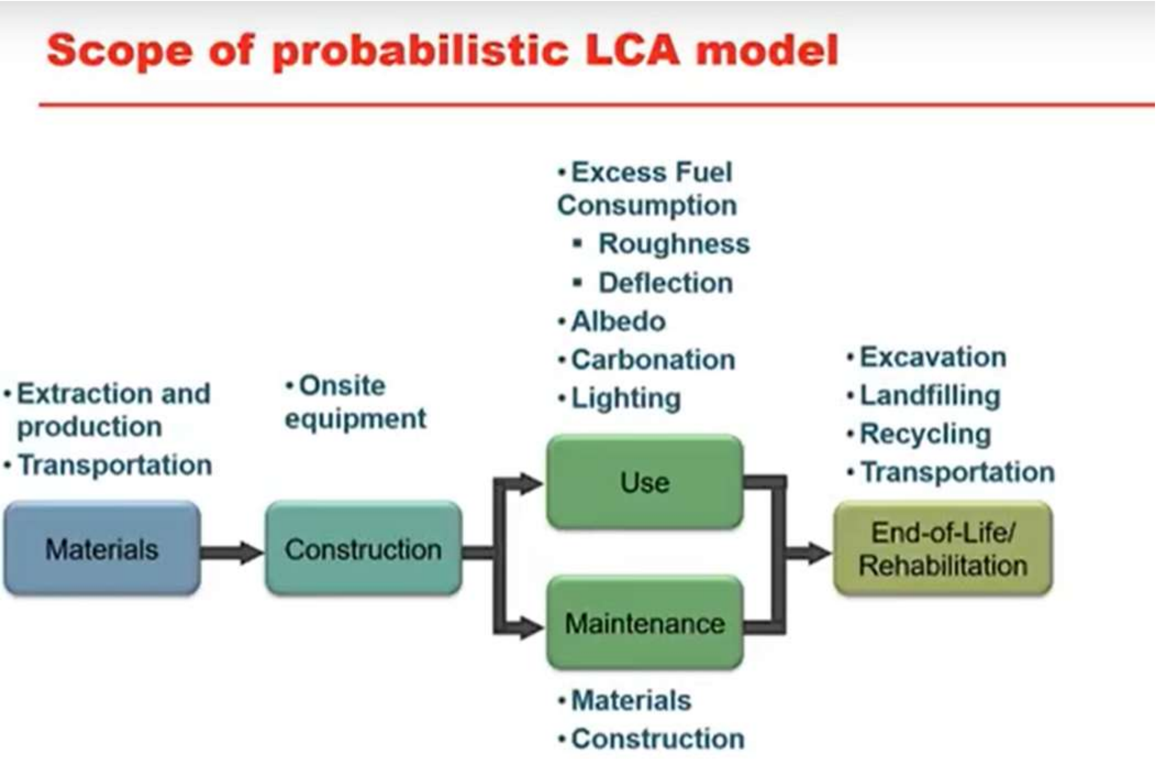


Figure 4.6 - LCA Model for concrete pavement [66]

The Figure 4.6 shows the life cycle model through the five main phases of the pavement construction and maintenance, specifically raw materials and manufacturing, construction,

[51] The Concrete Sustainability Hub of the well-known Massachusetts Institute of Technology (MIT CSHub) are working on infrastructure science, engineering, and economics in connection with concrete pavements and buildings. In their researches Life Cycle Thinking is heavily involved as a main tool for encouraging environmental aspects in construction sector through partnership with Ready Mixed Concrete Research & Education Foundation and Portland Cement Association.

[52] The model refers to concrete pavements as the main focus of their project, but schematically can be used for all major pavement materials.

usage, maintenance, and end of life. The components of the model show direct environmental impact of the pavement, in which supporting processes – like the usage of equipment for construction – are incorporated.

Phase 1, 2 - Raw Materials Extraction and manufacture

The first phase of the life cycle begins with the extraction of raw materials - such as aggregates, binders, and additives – followed by the production, and will take until the final product reaches the construction site. This phase involves the impacts of transportation between resource deposit and plant (or factory), and between plant and construction site. These impacts can be significantly reduced by high level of logistics, environmentally effective plants, equipment, and vehicles or by using mobile plants (described in 2nd chapter). The energy demand of extraction and manufacture is barely enough as decision tool in favour of one or another product according to the life cycle thinking, otherwise it still contains major information about the technology and foreshadows the environmental potential of an alternative. The energy consumptions of the most used pavement materials are summarized in the Tables 2.4 and 2.5 in the 2nd chapter. Through examination of the presented data some major correlations can be established. Expressed in ranges the aggregates are showing a smaller distribution between 20 and 40 MJ/t (only exception is in-situ recycling). Binders have wider distribution, which describes the high energy demand of reinforced concrete – with peak result - and cement concrete, and the energy saving opportunity of the recycling methods. With higher percentage of RAP, the energy spent on binder production is naturally sinks approximately lineal. This trend could not be followed, as seen on the line graph (Figure 4.7) because of the technical difficulties by higher RAP percentage. That is the reason, the road base asphalt concrete with 50% RAP presents the lowest energy demand for binders (equally to the thermal recycling).

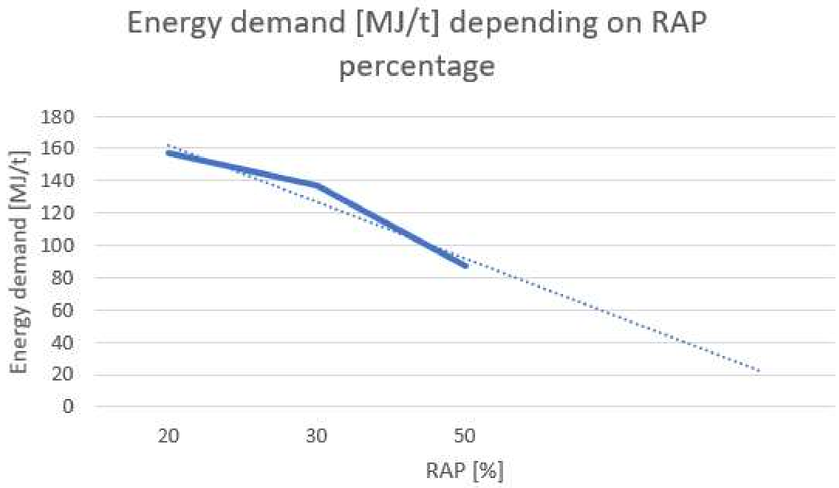


Figure 4.7 - Correlation between energy demand and RAP amount of asphalt binders

The advantage that recycled asphalt pavements have on material production are lost on the manufacturing phase against CMA and some of the cement-bound materials, on the other hand they show markable similarity with bituminous asphalts, mostly because of the heating demand. With present technical development recycled asphalt pavement can only be used for road base asphalt pavements with warm mix production. The ideal solution would be a recycling method which significantly reduce the heat demand by the production phase – approximately like CMA – taking the advantage of both recycling and heat saving. As the necessary product quality of the RAP – by present knowledge – only can succeed through heating; radical innovative procedure would be requisite to reach this goal. Some chemical additive might generate such improvement at ambient temperature, or at least lower temperature then WMA, but the environmental burden of the additive probably compensates the advantage. The transport and construction work, within that the laying procedure is balanced by the most products, only the thermal recycling shows significant derogation in both column and compensate its advantages in production and transportation with the high demand during the installation. Comparing the total energy demand of these product might indicate some preferences from the energy saving side, but the total results apply only for the first phase of the pavement life cycle. Deciding only by these results would counter with life cycle thinking and with the rule of thumb of the LCC by ignoring the first rehabilitation.[53]

[53] The other problem - arises by the definition of the life cycle - is to decide the role of the recycling. By RAP the recycled material – with energy demand for excavation, transport and reheat - can be seen both as the end of the life cycle for the rehabilitated road pavement and the beginning of the new project. With this regard there could be overlapping between Life Cycle Assessment.

Phase 3. Service Life

The usage of the pavement constitutes longest part of its life cycle. This phase shows significant demands of emissions even without the maintenance and rehabilitation for both asphalt and concrete pavements, between 66-72%.

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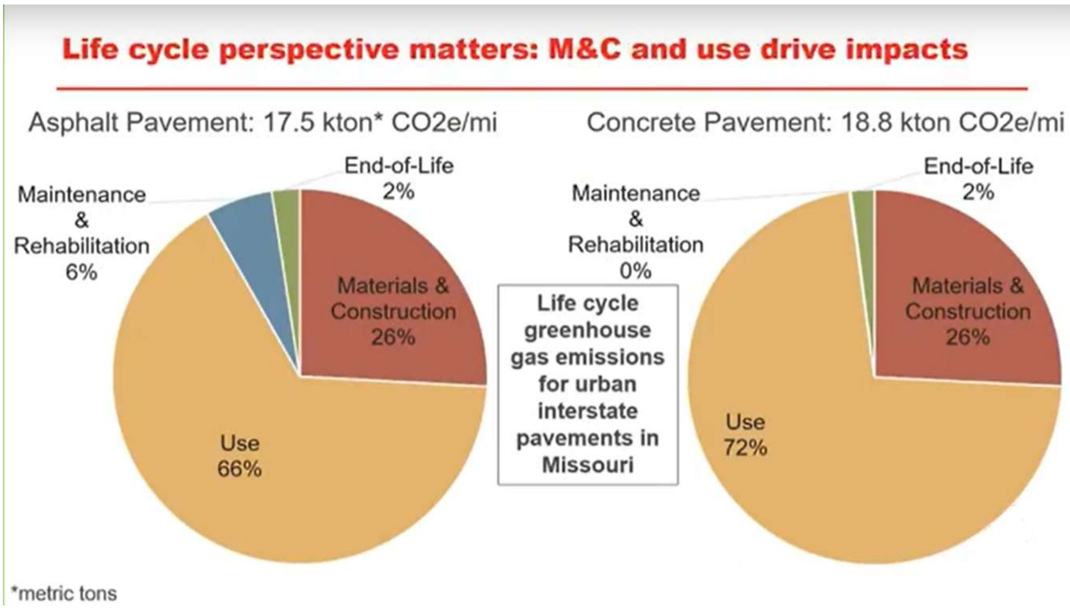

Figure 4.8 - Emission of phases of the life cycle [66]

As one of the most actively innovating phases, most of the developed alternatives produce their effect within this phase. Not only the solar roadways, but the innovations for asphalt and concrete surfaces induce huge impact of the life cycle emissions, through direct effects of the nature and also with the relation of the surrounding area, ground and traffic technology devices water network, traffic light or lighting. Based on the asphalt and concrete surfaces there are three major aspects[54].

1. Albedo and lighting
2. Pavement Vehicle Interaction (PVI)
3. Carbonation (relevant for concrete pavements) [**Error! Bookmark not defined.**]

The surface characteristics have implication for the appropriate level of lighting. In this aspect, concrete surfaces have advantage against asphalt because of the lighter colour. Light grey, tan or white colour intensify the reflectiveness of the surface, indicates cooler pavements and higher albedo. Albedo (from Latin word, "whiteness") is the measurement which describes the reflection of solar radiation and heat. It could be defined for construction surfaces like

[54] These are applying for fifth generation roads too, completed with other aspects, irrelevant for these two basic pavements (for example electricity efficiency).

pavements, roofs or walls, or whole planets and moons as well. It is a unitless number between 0 referring to black body (with total adsorption) and 1 for total reflective surfaces. Dark pavements, like asphalt can absorb 80-95% of the sunlight aggravate urban heat islands as local effect and contribute global warming too. [67] They required 50% more lighting power than light surfaces to achieve illumination for the traffic [68]. If the pavement has no heat and radiation adsorbing function like solar roadways and asphalt solar collectors, the higher albedo is preferable. With lighter tone even 17 ºC cooler surface temperature can be reached. *Pavement reflectance can be enhanced by using reflective aggregate, a reflective or clear binder, or a reflective surface coating.*[55] CoolSeal by GuardTop® is a great example for reflective emulsion sealcoat. It was used with high percentage on the streets of Los Angeles, which induced a measurable reduction on the city temperature. These products not only reduce the heat island formation and radiation – which causes saving of high energy costs in other sectors - but improves water and air quality, comfort and safety through better visibility for drivers – and induces less street lighting necessity at night.[56]

The energy used for street lighting is an interesting cross-border of the life cycle analysis. The environmental impacts of the street lighting are considering of the road system project – or from production side as impact of the energy sector – but certainly not to the life cycle of an asphalt or concrete pavement. On the other hand, the spared energy through foreseeing pavement design can be considered as a reduced impact on the environment. In that case the energy which must be needed to produce for street lighting of a darker surface is considered as a negative energy demand in the life cycle, likewise the energy that would be produced by a solar roadway. Like these overlapping life cycles part of the fuel consumption – with all its complex environmental burdens – considered in the pavement life cycle.

The traffic fuel consumption considered in the life cycle of the whole transport sector, but same as by the lighting the surplus of fuel consumption caused by incomplete surface context (mostly through roughness and deflection) considered as the impact of the road pavement product. From other point of view the saved fuel through properly produced and laid pavement product must be considered as positive (in this case with negative sense counted) environmental impact. This effect considered in the Pavement Vehicle Interaction (PVI) method. PVI shows how the characteristics of the pavement impact the fuel used by driving through that specific pavement.

[56] On the other hand, all of these innovation must be tested for such technical conditions of the surface layer, like skid and polishing resistance, noise emissions, resistance to temperature caused deformation, to fuel and chemicals (through climate change expected extreme weather conditions the resistance to high and low temperature – as well as de-icing agents – will also be a key measurement)

PVI aspect of the use phase is influential in sort of defining what the environmentally preferred solution is, because PVI can be more than 90% of the use phase burden, which was already the highest in the life cycle phases. The roughness is the dominant mechanism within PVI, but the importance of deflection cannot be underestimated. In PVI roughness means the presence of all type of cracks and potholes, and deflection is the bending of a pavement under the weight of a vehicle. Both can be reduced with propriate pavement design – within proper subgrade and subbase compression and/or stabilization, and proper pavement layers – but the choice of the surface layer material has also a great impact on PVI. The fuel consumptions and pollutant emission through PVI can be calculated with different modelling methods and simulations (like Motor Vehicle Emission Simulator (MOVES))

Phase 4. - Maintenance

Even with the best constructed pavement design and best quality of the materials, the deformation of the pavement during its lifespan is unavoidable because of the aging and fatigue of materials, deformation of ground etc. To preserve the safety and comfort of the traffic as well as keep environmental impacts down, these effects must be compensated through maintenance and rehabilitation.

The rehabilitation of a rough pavement segment has higher potential of decreasing fuel consumption and GHG emissions as the material production and construction phase [69], which confirms the high percentage of impacts during use and maintenance phase against the two earlier stages. The effect of the rehabilitation is superior by higher volume traffic compared to lower volume traffic, which indicates the importance of the highway and motorway maintenance.[57]

There are countless rehabilitation methods for road pavements. Because of the local situation, unique circumstances of the pavements, there is no single solution, which is recommended for every single rehabilitation case. With this regard comparing all maintenance methods in general is impractical. Thus, there are many studies for the comparison of a few methods, which can serve some rule of thumb, at the time of deciding the ideal maintenance.

Thenoux defined that the lowest environmental impact is achieved by cold in-place recycling (CIR) with foamed bitumen opposite to asphalt overlay and reconstruction [70]. The National Technology Development, LLC [71] compared the effects by using recycled asphalt for

[57] In environmental sense. In sense of transport security all type of roads are equally important to maintain.

reconstruction, and concluded, that the RAP usage in HMA has the best energy saving potential at high content of RAP and love moisture content. For energy demand the in-situ recycling is always preferable to avoid the impacts from transport. As for recycled concrete aggregate in-situ recycling is mostly impossible, or at least unpayable – in opposite to asphalt recycling – the impact recycled concrete is heavily dependent on transporting distances.[58] Weiland and Muench [72] investigated some contradictor conclusion by rehabilitation of Portland Cement Concrete (PCC), as the removing of existing PCC pavement and replacing whit HMA has the highest energy consumption, but still has lower global warming impact, than the replacement with new PCC pavement. In these cases, more points of the different methods must be considered to make the right choice, which also contains the preferences of the impact. For example, if the energy demand can be fulfilled – at least partly - by renewable sources, it makes advantage for the first version. The presented maintenance methods have the connotation of removing the existing pavement and constructing a new one – preferably with recycling the deconstructed materials. There are maintenance activities on smaller scale, which can prevent the full reconstruction of the pavement, or at least shorten the number of necessary rehabilitations through restoring the pavement serviceability. These Pavement Preservation Treatments – or preventive treatments prevent the distress development in the pavement, to improving the functional performance and prolonging lifespan. Wang and Gangaram [69] considered four treatment for flexible pavements like: HMA thin overlay, Crack seal, Slurry seal and Chip seal, and calculated that the thin overlay have the highest energy consumption and emission, but resulted the greatest reduction in consumption and emission at usage stage. Just like HMA overlay, other preservation treatments are also generating high amount of burden associated with the maintenance but causing an improvement of the use phase. A great example for that is the diamond grinding method which improves the PVI because of the better performance of a smoother pavement, even with higher environmental burdens during the maintenance phase. These connections also show the importance of life cycle thinking, as all the impacts must be analysed combined with their effects on the other phases. With this method in the final phase, at the end of the life cycle we will have a summary documentation of the global burdens, and the knowledge of all connections between the assessment complement can

[58] It is also a main reason, why concrete recycling is not so widespread in any part of the construction sector, even if it has high technical potential.

help, to find the best alternative method – or combination of production, construction and maintenance methods - from the available opportunities.

5. Technical obstacles

An alternative road paving material or method must face many expectations and fulfil technical regulations, economic advantages as well as winning the political and social support to become a competitive and effective option in the construction sector. Technical expectations are being divided to environmental and performance-based properties. As seen in the description of sustainability and life-cycle analysis, the new products must perform with significantly better environmental attributes during their life cycle to belong to green alternatives. These conditions are less regulated by national and international standards. Even though there are promising steps to support alternative methods from the start of the design till the implementation, while simultaneously fining the more polluting processes – according to the polluter pays principle in the environmental law - these steps are being only at the preliminary stage showing less dominant influence to actual changes in the economy. Performance-based properties of the product are more strictly regulated by international and national standards. Economical-political priorities for alternative methods are harder to define as these expectations mostly ruled by the actual economic situation and the operation of the state. The competitiveness mostly depends on the cost-effectiveness of the product, but there are other influencing factors – investor arrangements, interest of lobby, good economic repute – that are hard to scientifically define. The obstacles of the spread of a new method are mostly overlapping environmental, economic, and social properties, as the sustainability is defined by these three factors. For example, good bearing capacity and durability of the pavement are not only technical expectations. Less maintenance has clear economic benefits for the company, moreover, energy-effective production could mean cost-effectiveness, which spared capital can be invested for further environmental developments. Similarly, less emissions from the production and construction have immediate, local advantages on the human health etc.

In this chapter the major expectations and the technical economical-political obstacles they are generating will be described. These are the major challenges an alternative concept must face, and the difficulty of meeting these challenges outlines the lack of a real breakthrough in this area. Technical suggestions with the attempt to solve these conflicts in order to promote the spread of promising alternatives in the near future are also outlined.

As the presentation of the alternatives and the chapter of the sustainability already summarizes the most important environmental issues, this subsection focuses on technical performance of the products in relation to its essential characteristics. In the case of all road construction products the harmonized European Standardization was based on the Construction Products

Regulation (CPR) which made it obligatory for the manufacturer to confirm the Declaration of performance (DoP) and CE marking. DoP containing all information about the performance of the product, confirmed, and guaranteed by its manufacturer. *CE marking attests conformity of the construction product with the declared performance in relation to the essential characteristics, covered by the harmonised standard or by the European Technical Assessment which relates to the construction product* [73]. The European Standards must be fitted in the National Law Framework of the member states. For construction materials there are seven basic requirements [74] published by the European Committee for Standardization:

1. Mechanical resistance and stability
2. Safety in case of fire
3. Hygiene, health, and environment
4. Safety and accessibility in use
5. Protection against noise
6. Energy economy and heat retention
7. Sustainable use of natural resources.

It is a significant improvement, that after the former construction products directive (CPD) in 1989, the CPR in 2013 put a greater emphasis on environmental issues, with an introduction of BRCW 7 about sustainability and a complementation of BRCW 3, 4 and 6 with new requirements.

5.1 Mechanical resistance and stability

The most important characteristic of the pavement material is to ensure the safe and effective implementation of the defined level of traffic, for which the long-term resistance to mechanical impacts is essential. In case of conventional materials, the official, nationally adopted standards for the physical characteristic of the final product, as well as its component like the aggregate and binder agent are defined. The general empirical and performance-based test methods for verifying the compliance of the product are also regulated by the national standard – which is adopted from the EU standardization in the case of member states. Empirical test methods had to be carried out for modelling the behaviour of the material under laboratory circumstances. Without material specific properties these methods perform a simulated behaviour of the product to define its reactions during the lifecycle. Some of these tests identify the properties of the mixture (like compatibility, density, bulk density, or grain size distribution), while others confirm its appropriate resistance under different external effects (temperature changing, effect of fuels and thawing agents)[59]. Performance based test methods fulfil the determination of material specific properties under similar conditions as in the field – meaning actually simulated stress-strain situation - using a full spectrum of temperature and loading. These methods mostly describe the mechanical resistance and stability of the end-product. In case of any kind of asphalt mixtures from HMA to HWMA, also including alternatives like polymer modified asphalts, LEA or asphalts with different amount of RAP, the same general methods must be fulfilled as a minimal requirement when it comes to mechanical resistance, which must be complemented with other, product-specific test methods.

Thermal Stress Restrained Specimen Test [75] (TSRST according to EN 12967-46) is used to define the cryogenic tensile stresses due to cooling with restrained shrinkage. The cooling test determine the cracking susceptibility of asphalt concrete in case of strong cooling in winter. The pavement specimen - usually sampled from the surface layer - is restrained in longitudinal and transverse direction, and the constant cooling rate (with 10 Kelvin pro hour) increases the cryogenic stress and relaxation, until the failure of specimen at crack temperature. This value of the temperature resistance defines the quality of the binder content, binder and filler rate and mix design, and can confirm the adequacy of a new binder agent using reclaimed or modified materials or additives.

In case of Uniaxial Tensile Strength Test [71] (UTST EN 12697-46) the temperature dependent tensile strength and the respective strain will be defined. The test method will be fulfilled at constant temperature – but repeated at different temperature values to cover the whole spectrum – and the strain will be increased with a constant of 1 mm per minute. The regression over the mean values at different temperatures describes the evolution of tensile strength, which gives information about the material behaviour of the mixture at surface and binder layer at low and intermediate temperatures. The combination of these two methods can define the tensile strength reserve, as the difference of the two curves.

Triaxial cyclic compression test [7175] (TCCT EN 12697-25) determines the resistance to permanent deformation at high temperature. The cylindrical specimen is being tested at 40-50 ºC (higher temperature by surface layer because of the direct exposure to heat and submitted to axial and radial pressure with cyclic loading. The permanent deformation – which is dependent

[59] These aspects are defined in the fourth basic requirement: safety and accessibility in use.

on the number of load cycles - results the creep curve, which is able to compare different pavement materials by their resistance to permanent deformation - like rutting.

The dynamic stiffness and resistance to fatigue of the asphalt mixture – usually the bonded base layers – are defined through the 4-point bending beam test (4PBB EN 12697-24 and -26). A prismatic specimen will be loaded on two central points in vertical direction, perpendicular to the axis, while the vertical position of the end points stays still. The loading is cyclic, and sinusoidal, keeping the amplitude constant. The dynamic stiffness of the material is defined as a function of time and frequency. Conversely to the former tests, 4-point bending beam test is a no damage test. To define the fatigue resistance the number of load cycles will be measured until the dynamic stiffness is being reduced to half of its start value.

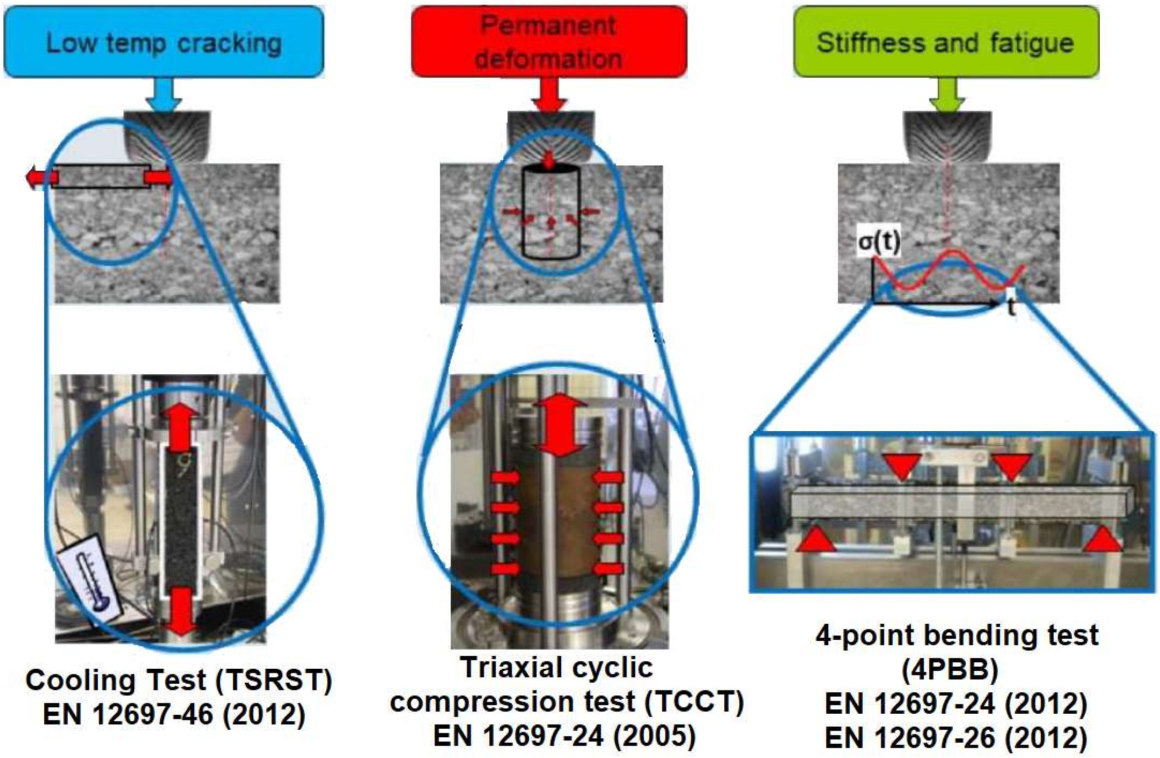

Figure 5.1 - Performance Based Test Methods on Asphalt [75]

Empirical tests, like the Wheel Tracking Test (WTT EN 12697-22) or the Marshall Test (EN 12697-34) also defining mechanical resistance. WTT simulates the cyclic loading of the traffic, through a loaded wheel and define the permanent rutting after 20 000 loading cycles. The Marshall test defines the stability in the sense of compressive strength, which gives the maximum resistance of a cylindric specimen of compressive loading. The quotient of this stability, and the indicated deformation – defined as flow value – gives the Marshall quotient (M=S/F) which is an important tool to define the optimal binder content of the specific bitumen product for an ideal resistance. [7175]

Other functional parameters can be defined through additional performance-based test methods, like defining the skid resistance as an important part of the mechanical resistance of the pavement. In case of asphalts the optimal skid resistance must be performed by the surface layers, which has to meet the requirements such as grain distribution and consistence, opposite to concrete which does not have separate layers, indicates the necessity of the ideal surface characteristic from the whole mixture itself.[60]

The material of the concrete pavement must be tested for strength, which depends highly on the strength of the binder agent and the water-cement ratio (W/C Ratio). The compressive strength (f_c) of the material is defined in laboratory conditions on a cylindric or cubic test segment pressured until failure. The material is being tested at the age of 2 days and 28 days. The concrete material – conventional or alternative version, with or without recyclate – must withstand at least 700 kN compression as first step to prove mechanical resistance. Most pavement has a compressive strength between 20-35 MPa [76]. The significantly smaller tensile strength of the concrete can be calculated from compressive strength as $0,3*f_c^{2/3}$. This calculation is mandatory for every kind of concrete structures, but concrete pavement must be tested for further mechanical characteristics. The necessity of testing the flexural strength through technical exam was being replaced with split tensile strength test, conducted on cylindric sample with constant vertical load perpendicular to its axis. The American Concrete Institute's Concrete Code gives rules-of-thumbs for calculating split tensile strength ($6,7\ \sqrt{f_c}$) and flexural strength ($7,5\ \sqrt{f_c}$) [77] defined from compressive strength. From the stress-strain diagram of the material, the modulus of elasticity of the concrete can be calculated as the quotient of $\Delta\sigma$ and $\Delta\varepsilon$.[61] Opposite to asphalt, concrete must be tested for plastic and autogenic contraction (caused by loss of water during hydration or low W/C ratio) and creep.

The conventional pavement material mixtures are simple to test under laboratory circumstances, test segments can be produced directly from the mixture, and can be cut out of the final pavement layers too, which must be done at specific distances. Alternative pavements like plastic roads and solar panel roadways could not be tested similarly. Therefore, in their cases

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[60] The mistake of the mixing or compaction could cause unhomogenized vertical distribution of the grains – because of the sinkage of greater grains – weakening the concrete near to surface.

[61] Where $\Delta\sigma$ is $\sigma_a - \sigma_b = f_c/3 - f_c/30$ stresses defined from compressive strength and $\Delta\varepsilon$ is $\varepsilon_a - \varepsilon_b$ strains at a and b stresses.

the mechanical resistance must be calculated first theoretically and examined in-situ after the construction work will be finished. The lack of established and practiced test methods for these innovations bring some difficulties when the practical use comes in question. In case of solar pavements, the mechanical resistance of the panels must be proven without any doubt for long-term phases within the lifecycle. Ideally the failure of the surface as consequence of repeated, mechanical load arises not earlier than the necessary maintenance of the structure itself. Solar panels are already managed to resist mechanical loads mostly from weather conditions like snow load, storm, and ice, but these impacts are lower concerning time period and mechanical load than the traffic loads the pavement must bear. There is the reason to cover solar road panels with protecting layers without narrowing the effect of the photovoltaic energy production. If the panels are covered with protecting layers, their mechanical resistance can be tested in lab conditions, but the performance of the structure, must be tested in-situ. The SolaRoad project is already in the testing phase and examines the effect of the vehicles on a 30 metres long test pavement gathering data from that performance base test.

China's first "photovoltaic highway" has a test route with transparent concrete layer which proved its resistance to the pressure of even large vehicles, theoretically. After five days of testing the route had to be closed because of surface damages of some panels. A two metres long, 10-15 centimetres wide section of the protecting layer was missing. Other seven photovoltaic road assemblies were tampered. The first suspicions were talking about vandalism and theft of panel-elements, but the police investigation revealed that the damages were caused by the undercarriages of cars impacting the road's surface on a downhill section. [78] The form and state of the damage excluded the possibility of being cut by a machine, as the police stated. The transparent concrete tends to handle 10 times the pressure than a conventional asphalt road – according to the developer Qilu Transportation Development Group - which was proved by test methods, but as the example shows, not only the part of the structures must be tested for mechanical resistance, but also the composition of these layers and the bonding between them must withstand the test. [71]

In the case of Solar Roadways, the solar panels are reinforced with bullet-proof glass panels. The concept had faced constant scepticism from the scientific community mainly because of the lack of mechanical testing. The first ever built Solar Roadways at the inventor's own yard, followed by an opened parking lot for real-world testing of the early-stage product. The durability of the solar roadways are not fully proven, as the Department of Transportation used a 3-D modelling analysis, and the practical tests were conducted with static loads, showing the necessity of further field-traffic evaluation to determine safety and durability performance – as

Eric Weaver, the research engineer of the Federal Highway Administration claimed. As he suggested the concept might be used under lower load [79], like pedestrian walkways or cycle-lines, - such as the SolaRoad concept was used in the early-stage of testing - to define the further opportunities of the structure [79]. The biggest concern from the viewpoint of the mechanical resistance of Solar Roadways is whether the glass protecting layers are able to bear the cycle load of the traffic without breaking or even present damages which could limit the effectivity of the photovoltaic sensors. In case of solar panels, the transparent concrete seems to be more durable even with the need of further developments as the Chinese case shows.

Same problems are shown by plastic material pavements. As plastic is a blanket term for numerous materials with a wide range of quality characteristics, to find the ideal composition of recycled plastics would need a lot of energy consuming preparation a pre-production to extract plastic materials with non-suitable properties. Polyethylene terephthalate (PET) is one of the mostly recycled plastic materials, but its temperature expansion and viscosity changes due to ultraviolet light exposure and makes durability unsuitable for road structure material, which becomes more brittle[62] with the number of recycling cycles. As complementary materials for asphalt products – like polymer modification, or rubber modification – some types of plastic are suitable for road construction, but pavement structure totally built of from recycled plastic do not seem to bear the load of highway traffic. The development of these concepts – just like Plastic Road – require further researches and endurance tests to prove the durability. More durable plastics, like Fibre Glass Reinforced Plastic (FRP) might offer a solution for that problem but face the economic problem of higher price and lack of recycling abilities.

Solution

As mechanical resistance and durability are essential characteristics of an operable road pavement, these properties of the road pavement layer – and the whole structure too – must be proved without any doubt for adequacy. In case of asphalt and concrete products the test methods are already mandatory requirements[63] for the authorisation of the production and construction. The effects of additives on the mechanical performance - like in polymers or chemicals for energy consumption reduction, or RAP for recycling method – are defined with the same methods. New structures might adapt some performance-based test methods if the circumstances are similar to the conventional technology, but a new method must also define

[62] Similarly, to RAP but with shorter time and higher rate of loss of durability.
[63] With differences dependent on the national guidelines

its proper verification. As the performance of fully plastic roads and solar pavements are not fully demonstrated, until further developments, the green versions of the conventional materials are preferred. As asphalt roads are not sustainable because their high energy consumptions and emissions, but fully recycled plastic pavement has concern about durability, ideal solution could be the combination as a balance of the two methods, in form of rubber modified asphalt mixtures, or asphalt products with high amount of recycled plastic to replace part of the bitumen need but verified for mechanical resistance through the presence of resistant aggregate – which also could be partly recycled material. Solar panels might be more durable with transparent concrete surfaces, than tempered glass surfaces, but until there is evidence of an efficient performance as energy production devices and traffic surfaces, the ideal solution for bearing capacity can be found even with new transparent materials.

5.2 Safety in case of fire

Fire resistance is a key element of the building materials to ensure safe use of the structure. From the viewpoint of safety, fire resistance is the most important in infrastructure tunnels, where fire resistance could potentially save lives at road accidents, but from the viewpoint of maintenance and optimal damage reparation the heat and fire resistance of the pavement is an important issue in the whole infrastructure system. Asphalt products are less capable in case of extreme heat or fire because of their higher temperature conductivity than concrete. The damage is mostly appeared in form of surface deformation – like rutting – but loss of mechanical resistance is also possible. Asphalt material has the fire resistance classification of B [80] meaning effective protection against moderate fire exposures and not readily flammable material, which was defined for Asphalt Shingle Roofs. For asphalt pavements the applicability for tunnels is the most important part. The fireproof property can be defined at laboratory level through the cone calorimeter test [81].

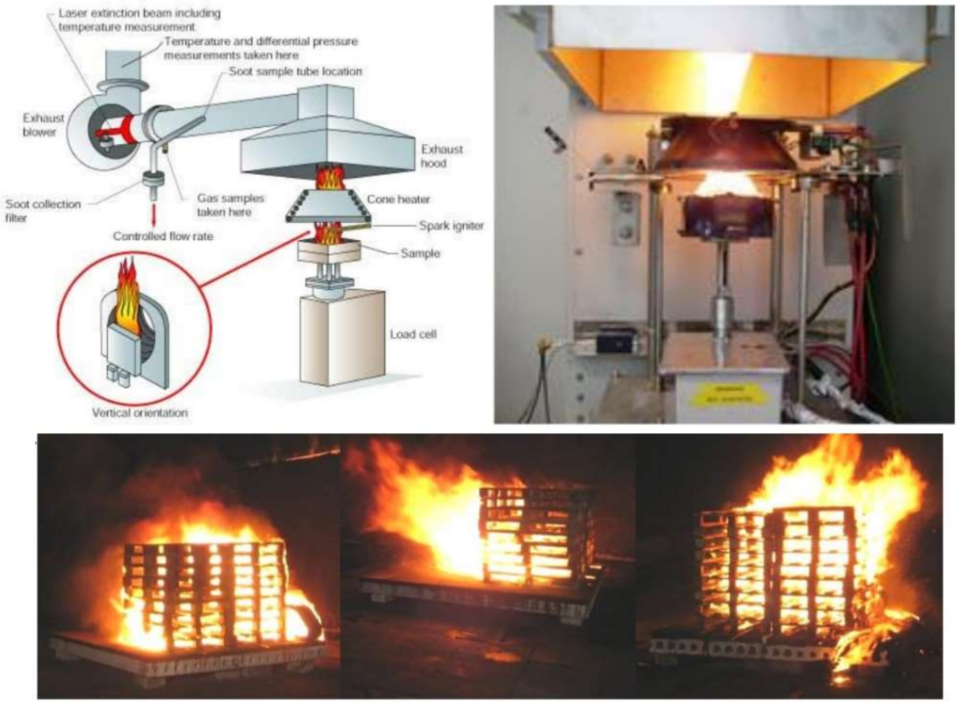

Figure 5.2 - Schematic representation of small-scale cone calorimeter test, and full-scale test in tunnel [82]

The method makes it possible to evaluate fire properties like heat release rate, total heat release, mass loss rate or specific extinction, reflecting the smoke production [82]. The test can be carried out on a small scale (with a 100 x 100 x 10 mm asphalt specimen), medium scale (with 410 x 260 x 50 mm specimen), or full scale in a specially designed tunnel testing asphalt pavement with different fire loads. (Figure 5.2). From the results the fire resistance of modified mixtures can be defined and compared with conventional asphalt layers. In case of inappropriate fire resistance values, the behaviour of the mixture can be upgraded with so-called flame retardants additives (FR) such as aluminium and magnesium hydroxides or various phosphates as binder modifiers.

Concrete is one of the best performing building materials in case of fire, classified as A1 – aka highest fire resistance classification – under EN 13501-1:2007-A1:2009 [83]. As a non-combustible material with no toxic fume-emission in case of fire or heat, concrete pavements require no additional fire-protection in form of chemical additive or protecting layer. The ultimately fireproof property can be explained by the low thermal conductivity of the cement-aggregate chemical bond. Its shielding effect from heat and fire mostly useful in building construction, but the high classification makes it optimal for pavement constructions too in case of road accidents with potential fire damages. Transparent concrete materials combining optical glass fibres with concrete – without loss of durability of the strength – are classified as A2 meaning no significant contribution to a fire load or fire growth, this makes it optimal surface material to protect solar panels in potential solar pavements.

Even though solar systems rarely set on fire – showing no significant difference in the risk of fire than any electric device - the fault of installation practice can increase the risk of potential system fire [84]. Properly installed solar system with live update system of the potential failures for proper maintenance – which is the concept of the FOR innovations – can be defined as fire resistant solution for solar pavements. The biggest sources of fire risks are the electrical faults like arc faults, short circuits, or grounding faults. The test area of Solar Roadways installed at a public square in Sandpoint, Idaho [54] caused smoke because of a failed electric cable, in March 16. 2017 after two weeks of test work. Although the source of the smoke came from the operation box of the system, and not from the pavement elements themselves, the failure must be defined as fire risk from the road pavement system. Using electric devices on the road surface and nearby made it necessary to expend the safety guidelines of pavement materials for electric devices, increasing the responsibility of proper installation and capable maintenance and control of the devices. Overheating of the panels is also an issue which must be prevented with thermal isolating materials to minimize both energy loss and risk of fire overheated electric cables.

From all solutions, recycle plastic waste has the lowest fire resistance and the highest risk of toxic fumes emission through fire damages. Some flame retardants can be used to higher the resistance in case of fire, but chemical additives in plastics – like brominate flame retardants are proven to be highly toxic. To define ideal flame retardants for the pavement, the actual components of the plastic waste recycled for pavement must be defined which could make the preparation of the ideal composition of recycled plastic pavement even more energy and cost consuming.

Solution

From the viewpoint of fire safety, conventional materials - especially concrete - are preferable until further development of the alternatives. For asphalt mixtures proper test methods and necessary additives are available to define of fire behaviour and potentially upgrade these properties by any type of bituminous mixtures counting recycled plastic-containing asphalt products as well. Solar panels could not be counted as totally fire-proof systems but adopting the competent and appropriate installation method used by solar panels might minimize the probability of system fires. Solar panels combined with transparent concrete could offer safer service and a decreased damage in case of inner fire through the fireproofing properties of the concrete.

5.3 Hygiene, health, and environment

This point of the seven basic requirements can describe all by itself the necessity of environmentally friendly, green technologies. As this point, while being concerned with the minimalization of the environmental impacts – involving the effects on human health, regional and global ecosystems – the whole life cycle of the road pavement material must be taken into account. This requirement shows similarities with the importance of life cycle analysis as the result of the analysis is being converted mostly to measurements showing the GHG emission (like CO_2 equivalence) which describes the environmental effect of the product. The highest emissions – as well as the greatest impact on nature and health – are done during the first phase of the pavement material's lifespan, through extraction, production and construction, and the demolition phase[64] which are already presented in the 3rd chapter. The hygiene and health effects of the pavement during its service life are lower – not even comparing it with the environmental effects of the traffic - but it does not make it less important, considering an alternative product. The effects are mostly classifiable into the water polluting and air polluting impacts. During the service the contact of the surface with the vehicles causes settlings of many pollutants, solid particles from the tyre rubber, metals from the undercarriage, oils and fuel residues even pesticides, which are accumulated on the surface and mostly washed off with the rain water. It makes the importance of proper water drainage through the whole road structure outstanding to separate and clean the heavily polluted rainwater before its return to the natural water circle. It could happen through collecting and leading the surface water from the road to wastewater treatment plants – like in most of the urban areas – or achieving the cleaning through natural processes locally. Porous asphalt [85] and concrete layers are great examples for decreasing the level of water pollution in the road structure itself reducing or even eliminating the need for further water drainage.

[64] Which is ended with the process of recycling in best case.

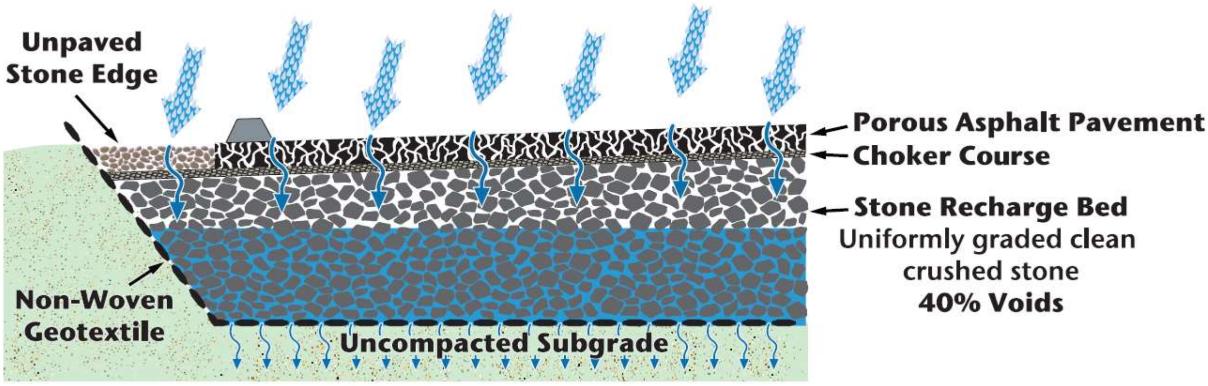

Figure 5.3 - Schematic of the porous asphalt [86]

The high void structured porous asphalt allows the water to penetrate through the pavement to a stone reservoir which serves to the stormwater as storage and slow infiltration into the soil below. The full-depth porous pavement is being able to eliminate metals like lead or zinc and petroleum of more than 90 percent, and components like nitrogen and phosphor of round 60-80 percent from the stormwater. [81] Porous asphalt pavements are mostly used for parking lots, but the material is adequate for road surfaces with high level of traffic too. Also, they show other advantages in use like avoiding water spray effect, and air pumping, and reducing noise. Pervious concrete could be used with the same hydraulic concept, as the lack of sand fraction allows high void content (15-25%) in the surface layer. The structure of pervious concrete allows at least 200 L/m2/min water flow, without leaching any petroleum. [87]. Most of the concrete and asphalt products have a negligibly small loss of solid particles – opposite to the pollutants from the vehicles – but alternative materials must be proved for similarly low waste of the material through direct contact with the vehicles or other impacts, like UV radiation or temperature. The general scientific view is against the use of recycled plastic for pavement as not only the production and recycling process but also the use of the pavement allows a huge amount of microplastic pollution, which cannot be separated through porous sub-bases or most of the conventional drainage systems. Microplastic can pollute the air too making it dangerous for the local area even when operating normally. Considering the effect on human health and nature through emission during the service life, the fire resistance is heavily contacted to that point of requirement. Not only the risk of potential fire must be decently low but in case of unavoidable fire the emission of toxic fumes should be minimized. CO_2 and CO emission is inevitable when building material burnt, but further – more toxic gases could be avoided. Solar panels have many components showing dangerous, toxic properties – like cadmium or silicon production - in case of incomplete production and installation, but these are not showing dangerous level of toxicity even in case of direct burning.

5.4 Safety and accessibility in use

Even with the increasing importance of sustainability in road building the safe use of the pavement is an essential condition that could not be by-passed, not even reduced. Many former criteria overlap with this requirement since it is the elementary condition of a road structure. Mechanical resistance minimized emission, hygiene, and fire-proof structures are all contributing to the safety of the road users, inhabitants, and nature. In addition to them the safety and accessibility in use ensure the flat, stable surface for road traffic according to the location and function of the road and the level of service (LOS). Level of Service is related to the quality of traffic service, based on performance measure like speed, density, and delay [88]. Skid resistance is one of the major characteristics to ensure sufficient road safety based on the long-term existing friction between the vehicle tyres and the surface. Road surface must ensure friction to help the vehicles acceleration, deceleration and changing direction without sliding risks that could lead to accidents. This roughness originates from the macrotexture of the surface, described with the friction coefficient which is the sum of the two acting forces at the contact surface [89]. [65] The macrotexture depth should be at least of 0,5 mm to decrease the risk of accidents [90]. While microtexture is sufficient at dry weather conditions to ensure safe friction between tires and road surface it loses the effectiveness even in case of a thin water film layer between the two, contacting surfaces. Ideal macrotexture (round 1-10 mm) could dissipate the water pressure under tires on wet and flooded surfaces and offers ideal friction at wet weather conditions, with less splash and spray effect which also increases traffic safety and comfort.

Skid and polishing resistance of asphalt mixture can be measured in laboratory conditions and in the field too. One of the laboratory experiments to define resistance based on the Wehner/Schulze method. The device used 3 cone-shaped rubber rollers to simulate the polishing effect of the traffic. 3 sliding rubbers are for recording the skid resistance up to 100 km/h traffic velocity.

After defining the ideal aggregate composition for the asphalt surface layer, the asphalt road structure do not need further treatment after the construction, on the other hand the skid

[65] Friction coefficient is the quotient of friction force (F_x), which is parallel to the surface, and normal force (F_z) perpendicular to the surface. $\mu = F_x / F_z$

resistance must be controlled right after construction and at pre-defined intervals throughout the service life. In case of decreased resistance, the structure can be repaired through layer exchange, rebuilt, or with use of surface treatment. Surface treatment usually means in the case of asphalt mixtures thin layers like seals (Chip Seal, Slurry Seal), OGFC (Open Graded Friction Course) or UTBWC (Ultra-Thin Bonded Wearing Course). There is a wide range of devices for skid resistance measurement in the field. *The principles are divided in three groups: longitudinal friction measurement principle, transverse friction measurement principle and stationery of slow-moving friction measurement principle* [89]. *Most of the measurement devices defining the longitudinal friction coefficient (like ADHERA, GripTester, RoadSTAR, GripTester, SRM, TRT).* For sideway friction coefficient SCRIM and SKM devices are the most usual, while VTI Portable Friction Tester is for Slow-moving measurement, and Dynamic Friction Tester is used to define rotating friction.

In case of concrete pavement, the in-situ treatment of the surface is necessary after the construction method, to establish the ideal macrotexture. This texture is provided by small channels and grooves formed in the plastic concrete (with or cut in the hardened concrete.) Ultra-Thin and Open Graded courses (like OGFC and UTBWC) can be used for concrete pavements too, but the macrotexture usually developed with diamond grinding or grooving. Measuring the ideal surface texture on concrete pavements could be implemented with the same devices, like SCRIM or GripTester, but laser-based texture scanners are also available to estimate texture parameters of concrete surfaces.

In case of plastic road surfaces and solar pavements, the measurement methods for skid resistance are not fully established yet, and the use of conventional test devices must be tested in the future. Transparent concrete as surface on solar panels can be treated at the production to reach ideal macrotexture, but further in-situ treatments are highly limited opposite to conventional concrete products, as some of the interventions on the surface – like grooving or grinding – potentially damages the optic fibres decreasing the effect of transparency and indirect the energy production efficiency of the panels. Tempered glass panels can be designed for ideal texture, but the polishing resistance is still not totally proven.

Possible solution

The sufficient traffic safety is a major challenge for road building with increasing difficulty at higher speed. Conventional pavement materials and most of their alternatives have already proven the opportunity to develop ideal macrotexture for safe tire-pavement contact at high speed, being ideal for highway and roadway constructions too. As the alternatives are not tested at all conditions of tire-pavement contact, until further innovations their use might be more effective at limited speed areas, roads with lower speed limit, parking lots, pedestrian areas and bicycle lines like most of the new alternatives (PlasticRoads, Solar Roadways) start their practical testing.

5.5 Protection against noise

The optimal macrotexture of the road surface has elementary part not only in skid resistance, but also in noise production. Noise pollution is an important – but less attention gaining – part of pollution. In as much as around 80% of the noise pollution arises from the traffic sector. Road building is playing an active role in protection through minimizing the negative effects from noise which is being caused by the mechanical contact between the vehicle and the road surface.

The generation of noise mainly determined by five major mechanisms. These are the vibration in the tyres (generates noise in the frequencies from 500 to 1500 Hz), the air pumping effect (as air pressed out of the cavities of rubber blocks), horn effect (from the contact of the tyres pattern with the surface), absorption under propagation and from the effect of stiffness (surface macrotexture) [91].

The protection against noise is feasible through either the modification of the source of the noise, or the limitation of the spread. Road building has the most impact on the rolling noises of the vehicle but indirectly the mechanical noises induced by the vehicles can be reduced with the help of pavement design. Mechanical stability of the structure has also a wider role in noise formation as localized settlements and yield, or surface deteriorations from temperature, load, or fatigue indicated deformations are not only decreasing the safety and accessibility of the pavement but also increasing the amount of noise. The statement of the pavement surface from the listed impacts is defined as mega texture, which indicates not only external tire-pavement noises but also in-vehicle noises which also decrease travelling comfort and ride quality [92].

A major advantage of asphalt pavements is the possibility of continuous construction, opposite to the other alternatives. The construction from panels (like concrete pavements, solar panels, or most of the plastic road concepts) creates the risk of enhanced noise production at the jointing. The joint building of concrete is necessary to control the cracking, isolation of the structures or provision of load transfer. Proper joint design and maintenance can reduce the negative effect on the travelling comfort and noise production, which is already defined for concrete structure, but need further investigation in case of solar and plastic pavements. Noise formation is inevitable even on perfectly constructed, flat and smooth surfaces, but the level can be limited through surface treatment. Luckily, most of the interventions on the pavement surface for safety purposes are effectively reducing noise pollution to. Treatment like, grooving or diamond grinding primarily used for improving ride quality and skid resistance, but also helping to reduce tire-pavement noise.

Compared to conventional asphalt concrete pavements Split-Mastix Asphalt shows 1-3 dB noise reduction, while porous asphalt shows 2-4 dB reduction. [93] The consistency of the asphalt mixture has major effect on noise and vibration production, through high void content (5-6%) low sand content, maximum 5,6 mm aggregate size and mostly cubic aggregate for example.

Possible solution

Proper surface treatment, joint design or further development of conventional pavement materials can effectively minimalize the produced noise. Porous pavements have clear advantages opposite to mixtures with full grading curve while coating and sealing products could also be used on less proper pavement surfaces. As this question is still opened for plastic and solar pavements, there is an interesting new concept combining conventional and innovative technologies. The second version to fight against noise is the using of noise protection walls – noise barriers - to shield the wayside buildings or natural areas. These traffic technology devices can work well with the road structure to reduce the noise which could not be avoided with pavement innovations.

The solar pavements already show some weak points as a green innovation: using panels as pavement not only causes the need of mechanical reinforcement (with tempered glass or transparent concrete surface), but the energy production is highly limited through the traffic and the stable, mostly horizontal state. Many sceptical views on solar pavements might support the idea to utilize the mostly unused area next to highways, and plant continuous solar tracker[66] lines along the road, where the geography and building density allows it. The gradient of these solar panels can be adjustable to maximize the effect of solar energy production, but they could serve other purpose and complete – or with further development even replace - the noise barriers along the road. Sufficiently high panels – or standard panels on noise production roads or high foundations - are granting noise protection by reducing the sound pressure level of its shadow

[66] Solar panel systems with movable photovoltaic panels – which are turning around a horizontal axis - called solar trackers as they are tracking the suns movement throughout the day. This automatic tracking movement allows to maximize the produced electricity reaching higher efficiency than stable panels.

zone, even in slant position. There are no general specifications of the height and position of noise barriers, as the effective noise protection depends on too unique parameters, like the level of traffic, position of the road structure, position and distance of the protectable items (receivers) etc.[67] The calculation of the height and position of these trackers – or solar tracker-noise barrier combinations – is based on mathematical theories involving Fresnel integrals (like optical diffraction theory [94]) which agrees very well with the measurements. The determination of Path Length Difference [85] based on basic geometry, described with the height and location of the barrier, and the heights of the source and receiver (Figure 5.4). On the figure the direct path ("D") shows the shortest way from the noise source to the receiver, which must be fully blocked with the noise barrier – to avoid the negative effect of the transmitted noise waves. "B" shows the path of the diffracted – bent – sound waves. Larger PLD results in more effective reduction of noise, which can be achievable with longer distances between the source, barrier, and receiver, or with higher barrier.[68]

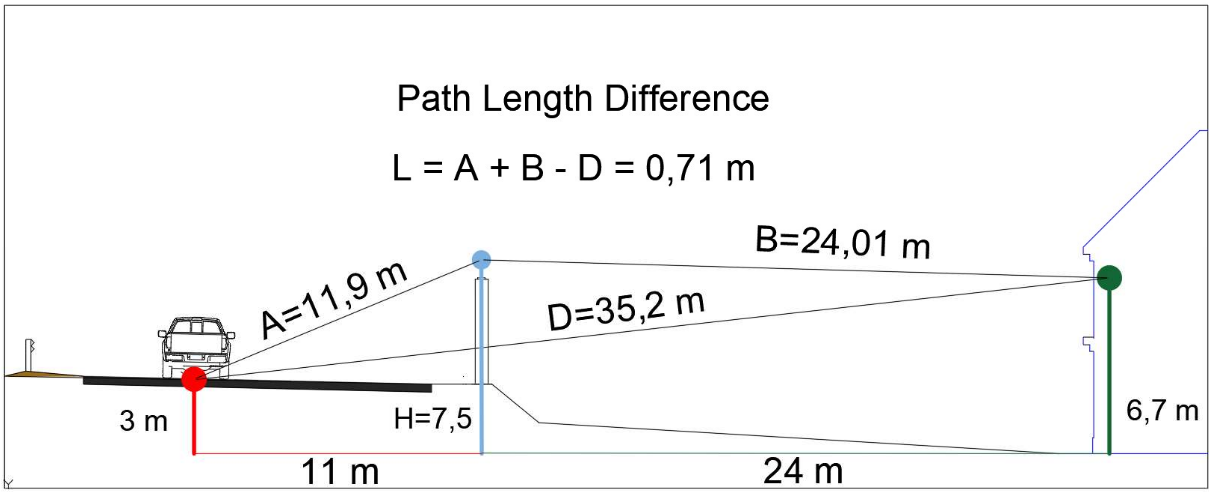

Figure 5.4 - Path Length Difference determination on common highway cross section (based on the example of Tom Paige) [94]

Reflection from near-by objects – like buildings or even opposite standing noise barriers - can reduce the effectiveness of the noise barriers, which must be considered in case of both side planning of protection walls. Barriers must be constructed of solid, non-porous materials, mostly steel or pre-cast concrete, but the concept of solar trackers can be feasible with some surface reinforcement. The protection of solar panels is still necessary from potential

[67] Even with similar situation the specification of the minimum height of an effective barrier can be different by countries.

[68] Both criteria have limits as the barrier height must be statically safe and economically exploitable, while after a certain distance between the noise source and receiver, the building of barrier became unnecessary due to the low rate of effectiveness.

mechanical damages from the traffic, as well as from the effect of the noise itself, but it is lower than in case of using them as pavement materials. The maintenance or repairing work is also simplified in their case. The mechanical movement of the panels during their service life might need some part of the produced energy, but the rate of effectiveness is still higher even considering this energy demand. After sunset, the solar trackers could stand down in perpendicular position to maximize the noise reduction in the high priority time-period.[69]

The positioning of solar trackers on noise barriers offers the same area saving benefit as the solar pavements, without the disadvantages of the mechanical impacts of the traffic. As the concept mostly usable at roadways near to populated areas, the produced electricity on these sideway solar panels can be transferred easily to the area of use.[70] Produced electricity along highways could also be collected and used at highway petrol stations promoting the sideway loading of electric cars without the transport of heavy silicon-electrical accumulators.

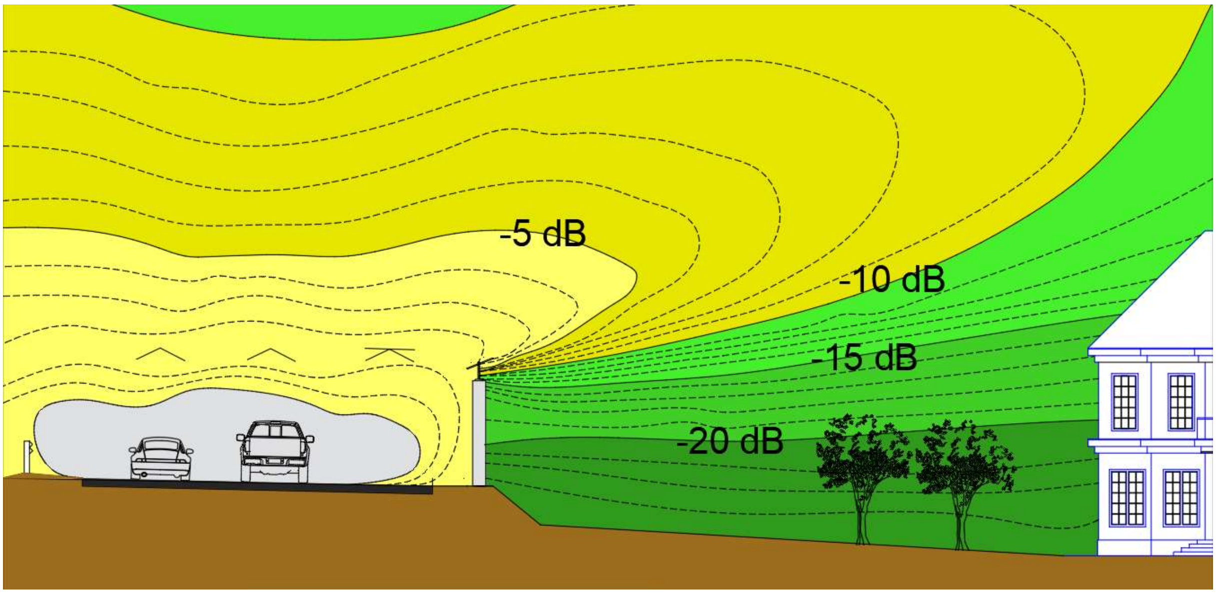

Figure 5.5 - Concept of solar tracker supplemented noise barrier (based on the concept of the Handbuch Umgebung - Bundesministerium für Land- und Forstwirtschaft, Umwelt- und Wasserwirtschaft) [93]

The maximum theoretical limit for barrier attenuation is 24 dB, but the practical values will always be less due to practical limitation. [85]. As the Figure 5.6 shows, the noise barriers can

[69] Solar trackers mostly locked in a horizontal position during night or inefficient weather conditions. Designing solar trackers with mostly perpendicular state in stand down position must include the calibration of wind loading resistance caused by natural movement of the air, as well as traffic induced air pressure on the panels and the barrier. Wind also must be considered as it could volume up the noises in case of proper direction.

[70] In light of higher electricity production than the demand for road service devices and lightings.

effectively reduce traffic load with around 15-20 dB. The tracker needs smaller re-designed changes on its form to serve the noise protection purpose even in slant position, which could be reached with a complementary panel at the h2 (Figure 5.6) height of the holding device without obstructing the free movement of the panels. For it to work effectively, this panel could be designed as a movable part too, linked with the solar panel, to follow its movement.

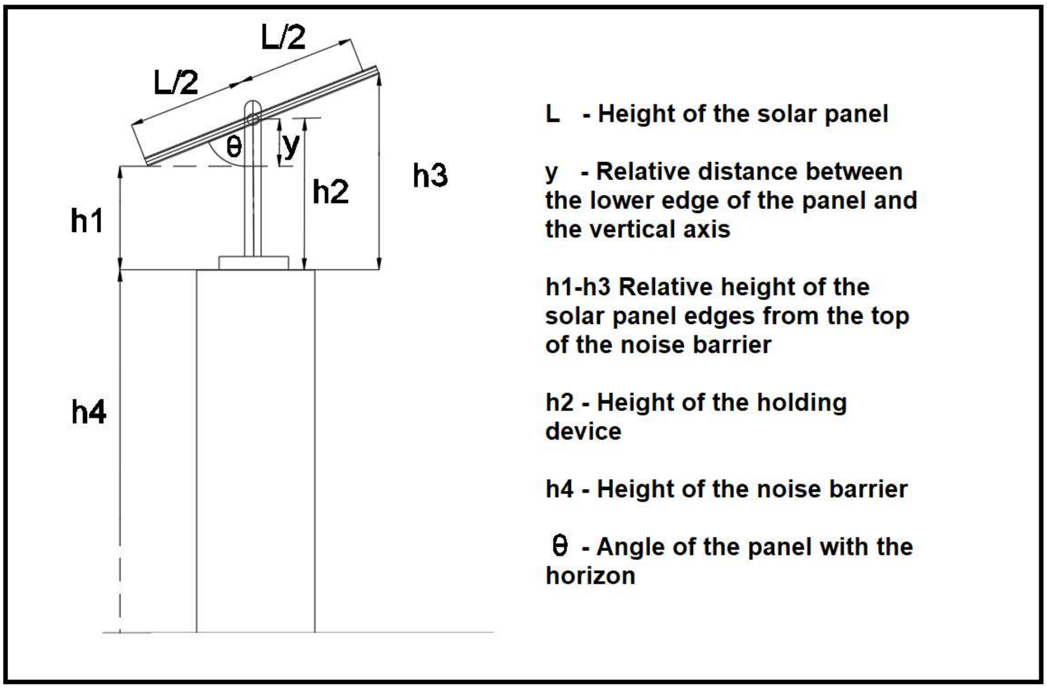

Figure 5.6 - Parameters of a Solar Tracker on Noise Barrier (pre-cast concrete) (based on the concept from Chin) [95]

For the optimal soundproof effect different types of panels were tested, such as wing, zigzag or curved type. Curved type noise barriers are widely used in Europe, positive examples can be found from Denmark, Copenhagen, to Vienna, where bended steel noise barriers are used at the A4 highway. [91] The unusual form might make the production of these barriers more complex opposite the flat surfaces, but concrete and steel panels are easily formed to the required shape. Curved transparent materials – even glass – can be used too, to reduce the blocking of the view, both for the receiver buildings and the drivers[71] In case of curved types, the design factors are the depth of the panel ("a" from Figure 5.7) – towards the cross section of the road structure – and the curve length ("b"), which helps minimize the reflection noise with maximum 1,2 dB replace the need of absorbing material used on the inside of the panels. Using curved noise barriers as holding devices for solar trackers, might raise some doubts from static view, but

[71] To avoid the unanimity of the view causing loose of vigilance of the drivers.

with sufficient basement and width even the curved forms are able to hold trackers, or static solar panels. The latter option is structurally preferable as the static load of the panel weight distributed on the surface of the top of the panel - which is mostly ended as a lineal console – instead of the lineal distribution of the tracker axis. The solar panel can be fixed on the surface of the steel or concrete panel, but it also be used as a complementary layer within the panel. Concrete or steel barriers build up mostly from prefabricated panels fitting between posts. Steel HEA-panels are ideal to hold these panels, even in curved form. Using the concept presented in the Figure 5.7 allows a statically more stable version with easy access to the panels, for maintenance or repair works. With non-tracking elements, this concept can only be used in case of proper orientation of the road (close to West-East orientation).

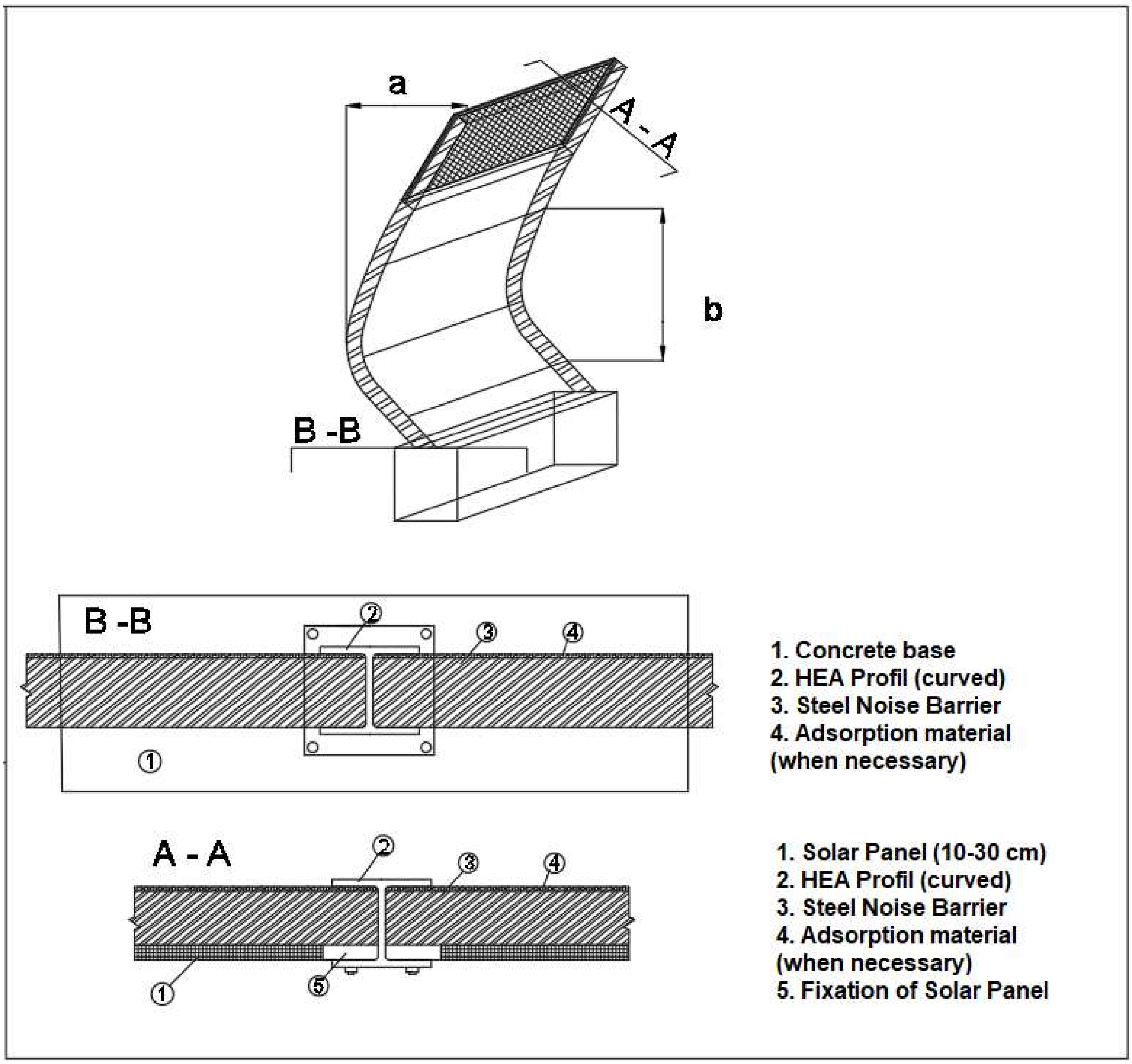

Figure 5.7 - Concept of a curved noise barrier completed with stable solar panels

5.6 Energy economy and heat retention

The energy efficiency and thermal performance of a pavement can be analysed separately phase by phase during its lifespan. For conventional pavements, the energy consumption during the raw material extraction and production phase is clear and comprehensible. The energy demand of the product mostly comprise the fossil fuel consumption used by the transport and construction machines. Ideal energy economy can be accessible by optimizing the logistic of raw material and product transportation, developing the efficiency of the machines and mostly by reducing the heat demand of the production phase. As the plastic and especially the solar alternatives demand more complex product composition, their energy economy is harder to analyse. For example, a solar pavement production most be examined for every component of the photovoltaic cells, the wires, electric devices, insulation materials and reinforced surfaces, and describe the energy demand of the whole production change. It is elementary to define these steps, as an energy producing device is only considered efficient when the produced energy covers not only the energy demand of the maintenance but also the production, and the investment has a high and short-term return. The construction has the same condition from the point of view of energy efficiency, that is why rapidly deployable, easily accessible pavement structures are preferable just like the R5G criterion describes. The demand of easily accessible structures most not be reached at the expense of mechanical resistance and stability. On the other hand, the structure must adapt to renewed situations and offer easy and energy efficient solution for maintenance work and – when needed - changing the damaged parts. Asphalt and concrete surfaces would be partly or fully disintegrated in case of structural damages. Solar panels need to be easily movable in case of technical failure – both in case of repairing work or change of unrecoverable panels. These steps are part of the technical characteristic of the pavement structures to reduce the energy demand through maintenance works.

Heat retention also plays a major role in the basic requirements, as not only the production chain of the product should minimize the heat demand, but the thermal behaviour of the pavement during its service life must be optimal too. The thermal performance of the pavement is mostly influenced by properties like albedo, thermal conductivity, surface convection etc., but the effects of the environmental conditions are also heavily affecting it. In case of concrete, asphalt or even plastic surfaces ideal thermal performance means high solar reflectance, dependent on the albedo. Concrete surfaces, or asphalt surface layers treated with light paint offers ideal high albedo. Conventional HMA, rubber or polymer modified asphalt layers on the other hand are too dark for solar reflectance heavily involved in the building of heat island, which must be reduced. (as the 4th chapter presented) Even though concrete pavement has preferred reflectance opposite too asphalt pavements, the two types show changes in time with opposite direction; concrete losses 5-10% of its reflectance, while asphalt pavements has higher reflectance after 5-6 years in use [96]. Heat retention has a different meaning in case of solar pavements, which are constructed to reach as much solar impact as possible, that is why the panels have mostly low albedo with dark colours. The sufficient illumination starts the photovoltaic process in the cells, causing the energy production and increasing the temperature within the panel. The transparent surface[72] must assure both process for efficient production, but the absorption of the heat should be solved within the panel itself. The working cells should not release the arising heat to the other parts of the panel, to minimize the danger of fire, which could be solved with insulation layers. Most of the heat will be released back to the atmosphere through the reinforced surface.

5.7 Sustainable use of natural resources

The importance of sustainability must be acknowledged for the whole life cycle of the product from the outset of the planning. To analyse a building material's specific data, long term performance and effects for the probably decades long lifespan is a complex and – with the presented steps of the sustainability and life cycle analysis in mind – probably impossible challenge.[73] This point of the list could contain the six former basic requirements as part of the sustainable process. It was not considered as an autonomous requirement in the former Construction Products Directive (CPD) from 1989, but one aspect of the sustainability must be analysed separately since it is a major point to save natural resources. Recycling has a direct effect on the amount of raw material extraction. This effect was presented as a step of green development in case of conventional materials and must be a peak in the innovative material concepts. On the other hand, the effects and advantages are not so clear and easily achievable as the first impressions suggest, and the obstacles and weak points of recycling must be independently presented.

Technical and economical obstacles of recycling

As one of the most important tools for sustainability and part of the solution for circular economy, recycling has a leading role in environmental assessments and represent an aspect of

[72] Transparent concrete is useful in this case for its mechanical resistance instead of its solar reflectance
[73] Not even talking about the impacts of the social and economic aspects.

production and construction that every single sector must consider. The definition of recycling became an everyday used idea, we can encounter in our life from common products like food packages and PET-bottles to complex structures like buildings or machines. From this generality the word recycling became a synonym for many processes which are different or at least showing some contrast at the level of intervention to the production chain. To better understand the differences between the steps of retaining value the so-called “value hill” of the usage must be defined through the aspect of circular economy. [97] In the case of open-circle economy the usage will be precluded with the steps: extraction (like aggregate extraction or binder production), manufacturing (concrete or asphalt production), assembly (laying of the road) and retail.[74] These steps are in the pre-use phase, which must be done before the start of the service life of the product. In open circle recycling there is no opportunity for feed-back loops - or the amount of these are negligible next to the raw material flows - which indicates the loss of value after the use. At the end of the post-use phase, the material will become waste, which is called C & D, Construction, and demolition material within the building sector. On the contrary the value hill of the circular economy retains value at the post-use phase, avoiding waste production and reducing input flow through feedback loops to every single step of the pre-use phase (Figure 5.8) Circular economy corresponds to the theory: *“There is no such thing as waste; only resources in the wrong place”* [98].

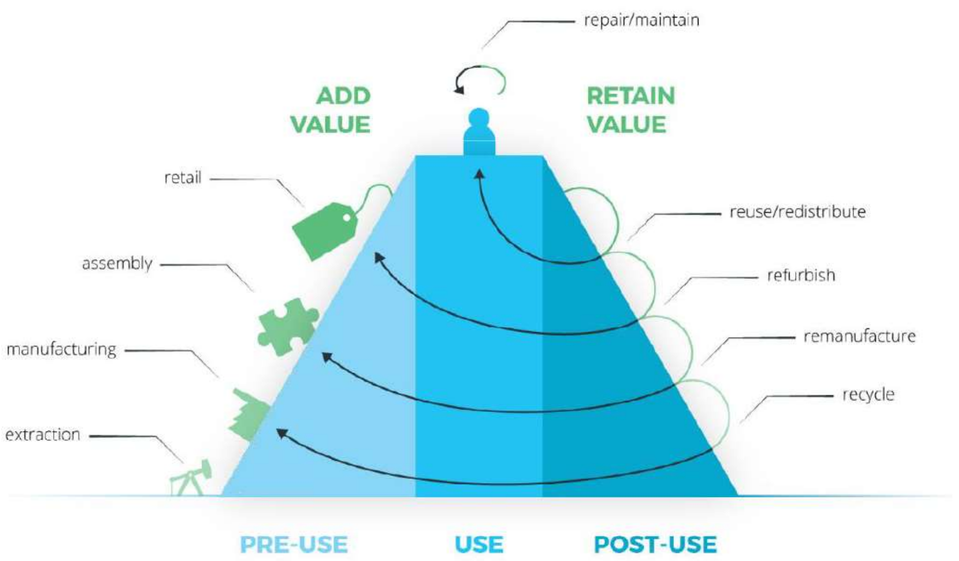

Figure 5.8 - Value hill in circular economy [97]

[74] For most of the products the retail is the final step, but in case of construction investments the retail preludes all of the other steps or takes place within the pre-use phase dependent on the contract according to the assignment.

After the phase of use – defined by a technical report through the loss of one or more certain properties which could not be repaired through common maintenance – the downhill will be slowed down to utilise the remained useful resources of its material. *This Value Recovery involves using recaptured materials, providing refurbished products, selling second-hand products, and facilitating remanufacturing and recycling* [97]. It also enlarged with the steps of rethink and refuse which make together the so called six Rs system[75], product designers must keep in mind regarding the environment. The next examples explain the steps through pavement materials.

Rethink – invent an alternative of the production or construction process to reach higher level of sustainability without any economical or technical disadvantage compared to the original. As a first step all the presented alternatives and innovations are belonging to this group.

Refuse – refusing to accept or support products or companies that harm the environment by changing habits. Without competitive alternatives this step is not accomplishable for asphalt or concrete pavement materials.

Reduce – reducing the amount of resources used for the pre-use phase, as well as reducing the produced material quantity. In the capitalist system it is only reachable from demand side, but economically not accomplishable for pavements materials as the production numbers are continuously increasing worldwide.

Repair – maintaining the pavement material after the loss of one or more technical requirements without redesigning the whole structure (pothole repairing, concrete surface grinding).

Reuse (**Repurpose**) – reuse the material of a product at its life cycle end for another purpose, like reusing asphalt layers as crushed stone aggregates in base or subbase layers.

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[75] As seen in the example the definition of six Rs system is not defined through common consent, as the **R** definitions are not exact. There could be overlapping between the definitions, which could be redefined or complemented with new methods dependent of the product. Some studies also define the step of Renew as the use of renewable source, which also can be considered as part of the Rethink step. That is why at least eight **R**s can be defined only for pavement materials.

Remanufacture – maintaining the pavement material after loss of requirement – like durability or bearing capacity – which indicates the redesign of the whole structure. In-situ recycling belongs to this group instead of recycling.

Recycling – feedback loop of the demolished material back to the production chain (pre-use phase) possibly without further need of energy.

As seen from the Figure 5.8 the retaining interventions slow down the downhill phase but never had the chance to stop it, which lead of to the main obstacle of recycling and the whole sustainability system. The biggest problem with the concept of circular economy, is that except natural energy and material circles of the eco-system, a fully circular system without energy and material output and only once input flow is impossible to reach. Circular economy defines a main target for the production sectors, which will never be reached, but still a duty to aim. Even with the best afford in order to promote green innovations for circular economy – which are mostly overwritten by economic-political decisions – sustainability is only an accessible but not reachable goal, which could be a "breeding ground' for sceptical opinions in the civil and scientific community too. Recycling asphalt pavements is only possible with a restricted amount and defined number of re-recycling. As the bitumen content of the reclaimed asphalt pavement tends to become brittle with the re-heating cycles, after two or three recycling phases it will lose its quality as a binder agent and could not be used as an asphalt pavement layer anymore. After the run out of durability as an asphalt pavement layer, the demolished material will be used as crushed aggregate in base and subbase layer in asphalt or concrete pavements. It looks like a closed cycle for the material – without the use of its full potential, as the brittle bitumen became part of stone aggregate too – but it is also just matter of time to find its way back to the nature – mostly through transportation to landfills as the end of the life cycle – which means that the contained carbon of the bitumen will be sooner or later released and get back to the natural carbon cycle. From strict definition recycling involves no energy input that is why RAP mostly mentioned as reclaimed and not recycled asphalt pavement. From this point of view, the definition of In-Situ Recycling also false, as the method remanufactures the structure of pavement at constriction site with less but still demanded energy than RAP. Colloquially the word recycling is used for every feedback loop in the production chain, that is why this thesis addressed these methods together in that chapter.

Creating a circular system has two major ways to help the eco-system, reducing waste material from output flow, and reducing the need of new materials – and their energy demand from extraction to construction – from input flow. As seen in the presentation of conventional asphalt and concrete, both materials have the potential for waste reduction, not only through using their own recycled materials, but also using other Recycled, Co-Product or Waste Materials.[76] The majority of construction and demolition waste still ends in landfills, but through international regulations at least the attempt to reduce the waste, and increase the ratio of recycled materials had begun. In the statistics there is a major improvement showing the recycling ratio of asphalt and concrete pavements. From that point the innovations and national regulations have already shown their effect in the waste management for road pavement materials and other RCWM-s, except building demolition materials like building concrete because of their high amount of polluted contents. From the input view the very limited amount of RAP ratio has less impact on the raw material consumption and their energy need. If we established a curve from the asphalt production of the world from the last decade, we would get a monotonously increasing curve. The data seen in Table 5.1 is from the UN and summarizes the asphalt production of the six highest producer's data between 2010 and 2016 in thousand metric tons. According to this interval, the last five years data, as well as the next five years were calculated showing the increased rate of production, estimating an ongoing trend from the last years.

Table 5.1 - Asphalt production per year (based on data.un.org) [99]

Asphalt production (2010-2016) of the six biggest producers [thousand metric tons]							
	Total	China	USA	Russia	India	Germany	France
2010	51,16	12,639	22,971	4,778	4,536	3,775	2,461
2011	52,09	14,114	21,998	5,422	4,638	3,402	2,516
2012	53,723	16,187	21,064	6,054	4,658	3,869	1,891
2013	53,805	17,937	19,365	6,193	4,785	3,595	1,93
2014	54,338	19,531	19,251	5,751	4,632	3,41	1,763
2015	57,183	20,078	20,358	6,246	5,157	3,525	1,819
2016	60,025	21,715	19,721	7,633	5,185	4,065	1,706
							Source: UN

[76] Even if this method postpones the solution of waste material handling for future generations which clearly contradicts to the principle of sustainable development.

Table 5.2 - Forecasted ratio without and with considering RAP (based on data.un.org) [9999]

Evaluated asphalt production tendency (2017-2025) (based on UN Data)				
[thousand metric tons]				
	Forecast	Lower Confidence Bound	Upper Confidence Bound	Forecast considering 20% less need
2017	61,20	59,19	63,20	48,96
2018	62,53	59,83	65,23	50,03
2019	63,87	60,62	67,12	51,10
2020	65,21	61,49	68,92	52,16
2021	66,54	62,40	70,68	53,23
2022	67,88	63,36	72,40	54,30
2023	69,21	64,34	74,08	55,37
2024	70,55	65,35	75,75	56,44
2025	71,89	66,38	77,39	57,51

To demonstrate the effect of recycling it was assumed that 20% RAP use was introduced as obligatory for all asphalt mixing plants which means a reduction of newly produced asphalt mixture demand. In this highly hypothetical case, the introduction of this new rule would make a small step back in asphalt production, but without further elevation of RAP rate in new mixtures, the trend of increasing production would not stop, and would easily overtop the present rate within five years.

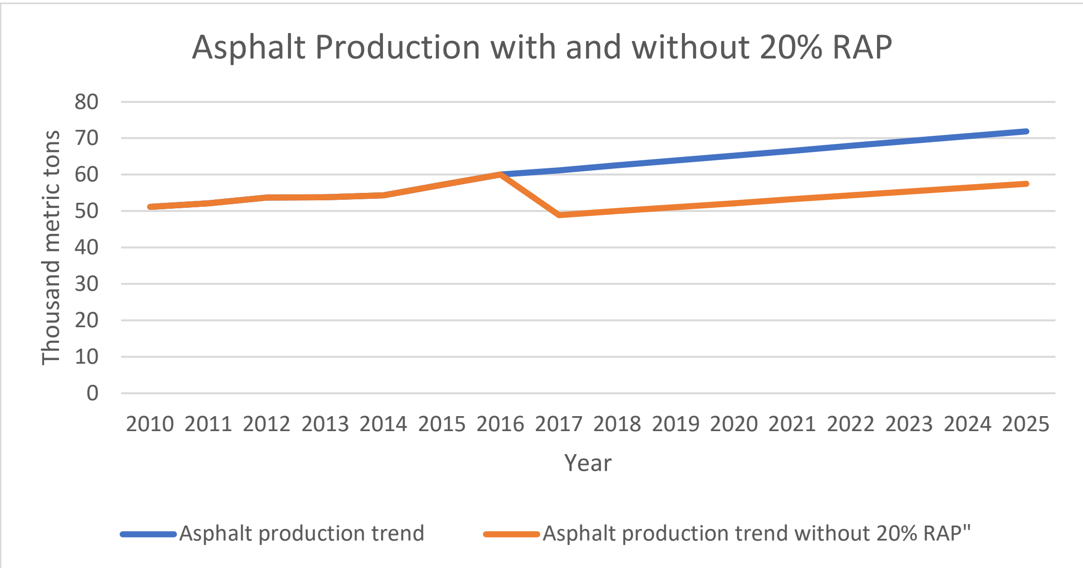

Figure 5.9 - Asphalt Production with and without 20% RAP

The complex the material conglomerate is, the harder is it to effectively recycle it, or the more energy it needs to divide its compounds to be reuses. In case of asphalt, the cold recycling is a sufficient solution to recycle the mixture as base layer, without an actual division between binder and aggregate. RAP is reheated at the mixing plant during the mixture process which allowed to sieve the crushed stone aggregate by fractions and melting the bitumen from its surface to re-coat the aggregate in the mixture, but it does not really divide the two component. One example is the trichloroethylene, a chemical compound used for examination of the ready asphalt mixture before its construction. Trichloroethylene mixed to the ready asphalt mixture eliminates bitumen from the aggregate – offering the redefinition of its grading curve for control purpose. The aggregate could be used again – after washing and drying – but the mixture of liquid bitumen and the chemical could not- Conversely, it has a status of hazardous substance because of its poisoning and carcinogenic potential.

As seen in the 3rd chapter, concrete production is responsible for a huge part of GHG emission, which could be drastically reduced with a proper effective system for concrete recycling, for which the necessary processes had been already developed. Still the lack of proper recycling in the concrete production industry is alarming as the tendency of increased production tends to continue in the next years. The insufficient recycling of concrete mostly applies for building materials, and less concerning in case of concrete pavements, but the material should be examined as one for all sub-sectors. As presented, building concrete is not allowed to reuse in concrete pavement but developed recycling methods could make it possible in the future. The lack of recycling is mostly explainable with insufficient or incomplete national legislation, the technological underdevelopment of demolishing processes and the economical handicap of recycling, compared to new production. Most of the recycling processes concentrate on the aggregate content of the concrete, used directly as base or sub-base layers or in other fields like as railway track ballast. Some of the common demolished concrete recycling plants make it possible to retrieve stone fractions and other materials like steel separately, but mostly without any recovery of the most valuable – and energy efficient – cement. As the Construction and Demolition Waste Management Protocol of the European Commission suggests, the waste hierarchy with priority of the prevention at source must be the primarily act in case of construction and demolition wastes, but with the ever increasing tendency the recycling rate must also be expended. "*In particular, Article 11.2 stipulates that "Member States shall take the necessary measures designed to achieve that by 2020 a minimum of 70% (by weight) of non-hazardous construction and demolition waste excluding naturally occurring material defined in category 17 05 04 in the List of Wastes shall be prepared for re-use, recycled or* *undergo other material recovery"* [100]. Most of the countries comply with this regulation – some of them even exceeding the 70% target – but there are still materials, like concrete which recovery rates hardly reaches 50% in countries like the UK.

In case of solar innovations next to the aggregate and binder agents – usually used as lower layer for energy producing surfaces – the materials of the electrotechnics must be considered for future recycling. Photovoltaic cells are mostly containing silicon for semiconductors, aluminium, glass, cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) as band gap material. [77] Silicon has a two-level process, one at high temperature to burn off oxygen (that creates metallurgical grade silicon) and a chemical-rich process to reach higher than 99,6% pure silicon which will be mixed with copper and hydrochloric acid. [101] This acid helps produce trichlorosilane gas, and then silane gas, used to create the waited silicon crystals. Cadmium has a water polluting and carcinogenic potential, but it is necessary in order to make cadmium telluride thin film. CIGS have the highest efficiency among all thin film materials, which makes it reasonable to use in second and third generations of photovoltaic cells but its production with vacuum process make it energy and cost consuming. The production of photovoltaic cells for solar roads involves many dangerous materials and processes with high energy consumption and low material efficiency. Only half of the cadmium used in the process will be placed in the film, the waste material has the hazard of water and air pollution with certain health dangers too. Silicon production is energy intensive and materially wasteful as around half of the silicon is lost in form of dangerous gas, not even talking about the explosive silane gas usage during the process. The development of the third generation of solar panels had the first steps for a smaller ecological impact through reducing silicon layers with heavier glass panels – which were given the high proportion of PV with round 89% of the mass - but further steps must be taken, to make these production processes affordable from an economic and ecological view. The proper recycling of these dangerous materials is not only necessary to decrease the production impacts but also get rid of hazardous waste from landfills.[78] Even though solar panels have the advantage of a longer life span, around 30 years with only 6-8%

[77] We differ three type of cells; the first generation of solar panels use different crystalline silicon; the second generation complement them with CdTe and CIGS while the third generation is the combination of numerous thin films.

[78] Most of the un-recyclable electronics (WEEE – Waste Electrical and Electronic Equipment) land on landfills, where only the metallic compound could be sold as reused materials, which causes the burning of a huge amount of electronics to extract metals (in case of solar panels, mostly the copper) emitting numerous poisoning gases from the burning of plastic and silicon compounds.

of efficiency loss in the first 25 years as some practical experiments had shown, but the planning of future recycling is inevitable by longer life cycle too, not even speaking about the life shortening impacts when the panels would be used as road surfaces. In this case the easy and energy efficient change of disabled or worn out panels must be executed – as the adaptable road requirement also expect by fifth generation roads - with the practical treatment of the changed panels mostly as materials for recycling. The longer life cycle also means a sharp increase of PV waste in the near future as the beginning of mass production and wide spread of the solar panels can be estimated at the late nineties and early 2000's. The increasing rate of solar panels is hopeful from the energy production view but warn for the expected increase of waste material. According to the evaluation of Greenmatch, the amount of PV waste was already 43500 ton in 2017 and can reach an incredible amount of 60 million tons in the year of 2050 when the present planted solar panels will reach the end of their life cycle [102]. Planning solar roadways as the main road surface pavement for TEN-T networks would increase this already high level radically. The official recycling process for silicon PVs offers a total reuse of metal components and 95% reuse of glass, but the reuse of silicon and plastic modules (round 85%) need thermal processing at 500 °C and further melting processes which means further energy need.[79] In case of thin film based (third gen) panels the shredding of the parts offers to separate solid and liquid material through a rotating screw. At the end of the dewatering and separating, 95% of semiconductors could be reused in a more efficient way from to point of view of energy. The reused materials could replace raw materials for new solar panels, but they effectiveness as recycled solar road pavements must be entirely tested.[80]

Possible solutions

The impossibility of reaching total sustainable development could not be an argument against trying, as the main goal must be changed to the extension of the life cycle as long as possible. Within a defined period, every production process can be seen as sustainable, and the challenge is to extend this time period. Circular economy claims to retain the products added value in this extended time. The product must be long lasting without the need of maintenance or repair, but still offer the possibility of extending its life cycle with maintenance. From that point of view, concrete pavement achieves this challenge better than asphalt pavement with longer lifespan

[79] In some cases, the energy demand for plastic evaporation and module separating can be used as heat source for district heating or for further production processes.
[80] This process is still not fully finished for solar panels as road materials primarily.

and less maintenance needed, but both pavement materials tend to be repaired instead of demolished.

The innovation to divide the components to their raw material form after the recycling would be a turning point for all the recycling processes. If these methods could reach a cost and energy effective level - including the transport - the effect of global recycling in the sector would be visible also in the statistics of newly produced materials. The full recovery of the pavement material contents would cause a downturn on the raw material demand. The replacement of a significant portion of the bitumen or cement production would decrease the emission and energy-demand of the whole process.[81] There are many aspects that are must be considered for the optional recycling process in addition to environmental aspects. The process must be easily and quickly achieved to keep up with the construction need. Potentially should be achievable in mobile recycling plants to cut off transportation costs and time gaps and must perform the same technical measurements as the new materials, without causing performance obstacles or environmental hazard, like the presented trichloroethylene does. As fully recovery is a hardly reachable goal – just like full sustainability – the bitumen component would still be suffering fatigue through the numerous recovery cycles, but if the ratio and the number of cycles could be increased, the effect of the recycling would be greater with order of magnitude beyond today's level. Not only with full recovery, but the current recycling methods could be improved further to encourage higher RAP ratio in the mixtures. Some countries already allow a higher amount of RAP than 20% without experiencing performance obstacles in HMA, but the alternatives could also improve to allow higher RAP addition. Some of WMA-s like LEA allow a higher level of cold RAP addition, but the effect can be increased with polymer modification or chemical additives.

Opposite to asphalt recycling, end of life concrete (EOL) is easier to divide back to its components in a concrete recycling plant to use concrete in circular way. For processed concrete, the concrete debris will be separated back to gravel and sand, which method is possible also in mobile plants. There are different innovative ways like Advanced Dry Recovery (ADR) which is using mobile mechanical crushers to separate coarse and fine materials, after the metal reinforcement and potential other components are removed. [103]

The recovery of different aggregate fractions for new concrete is essential to limit the amount of newly extracted aggregates, especially for the sand fraction, which plays a bigger role in the concrete grading curve, than in the case of asphalt. Although natural aggregates seem to be

[81] That is why an energy effective level of full recovery is impending to replace raw material production.

renewable – at least on the scale of human application period – a shortage on the available sand proper for construction works will occur within decades, as the extraction overdoes the natural replacement. Most of the natural sand – like desert sand – is not suitable for concrete production because cement could not bind the smooth surfaced grains, which highly limits the natural resources to sand from riverbanks. As extracted sand also a raw material for glass and electronic production, the recycling of aggregate and high proportional reuse in concrete is essential for the sector. Not only the exhaustion of natural sand could be prevented through higher recycling proportion, but also the illegal extraction can be limited because of the lower demand on natural sand.[82]

Current guidelines allow up to 45% of the mixture to contain processed concrete rubble (recyclate), but further investigations are running to increase the maximum proportion. The practical tests of the *Krieger u Söhne KG* are showing that a sample cube with a reused concrete aggregate can withstand nearly in a 100% the required 700 kN strain defined through compressive strength test. Further tests indicate that recycled concrete is also more resistant to frost and chemicals than previously stated in the official guidelines. [104]

Similar to asphalt recycling the biggest step for recycling would be the efficient removal and reuse of binder agent, as the largest saving on energy and emission would be the reuse of cement instead of further production through the conventional energy-consuming way. Even though total retrieve of cement is not technically and economically accessible yet, there are promising developments for cement recovery, like the method of the TU Delft within the European C2CA project, which gently mills the crushed concrete to remove most of cement paste from the aggregate surface, making it reusable for low-CO2 cementitious binders [105]. Despite this slim breaking technique being tested and proven on laboratory scale and in practice – even with mobile smart crashers on constriction site – the reuse of cement from EOL is not a widely spread technic and the concrete recycling is mostly limited to aggregates.

As a quite new territory for road pavements, solar roads are facing new challenges in the topic of recycling, which means lack of proven processes. On the other hand, the ongoing testing of solar cell pavement surfaces brings a great opportunity to develop and test these innovations for the whole life cycle including the effects of recycling and designing the future solar pavements suitable for recycling. The efforts of solar panel recycling could be used as example

[82] The danger of illegal extraction and exhaustion of riverside sand resources can be presented on the Chinese and Indian examples, as both the Mekong and Ganges are suffering from the enormous overdemand on sand from both ecological and social point of view. The exhaustion of riverside sand would redesign the world-wide sand trade and transportation and might encouraging the development of recycling, but this should be reached before the point of the worst-case scenario.

for start, but further developments are required to get to a higher level of sustainability. From this point of view solar pavements have the advantage opposite to conventional materials to evolve with recycling methods bearing in mind and not posteriorly developing them in need. The potential lack of sustainable recycling also must be considered as a reason for exclusion of solar pavement production, even in case a suitable and working service life is proven.

As presented through the examples, the technical opportunities are already in progress for making recycling techniques more suitable and potentially get rid of their weaknesses, but – as in most of the cases – the technical development is not enough for practical progresses. The social reaction for these innovations is just as important as proving the operability of the methods. First step, the standard guidelines for the allowed proportion of recycled materials must be supervised and in case of necessity rewritten to exploit the full potential of recycled materials within the technical opportunities[83]. These standards should be internationally recognised and equalised bearing in mind the local differences of climate and economical case. Further researches should be politically encouraged and supported with special financial help and foundations, as well as the legal framework for the proportion of recycled materials must be defined, to require by the law the mandatory minimum and maximum amount of recycled materials by new construction process. Sadly, these steps are requiring a full mentality shift in the construction sector which means not only the redesign of the legal framework, and political organisation but also the economic system which characterizes the sector for decades.

[83] As the test of Krieger Gruppe proved.

6. Economic, political, and legal obstacles

The presented technical obstacles and environmental challenges are essential to overcome, since the main goals of the road pavement and road structure are to effectively ensure its function within the infrastructure and take steps towards sustainability. Even though the modern interpretation of sustainability is placing economic and social aspects inside the field of environment, in reality not even the equality of the three basic pillars come true. In a well working society, the need of achieving technical requirements is inevitable[84] but the environmental aspects are frequently being neglected. The economic aspects such as ensuring continuous economic growth, mobility of goods services and labour and increasing productivity have been top priority as opposed to environmental aspects. As the most important motivations of political decision economic and political aspects must be considered as strongly connected even though their connection is more complex to simplify them as similar aspects. Legal conditions aim to protect the fundamental rights and liberties of both legal and natural persons, which also includes the protection of human health and safety which heavily involves the human right to a clean environment. The right to a clean environment includes clean air, clean water, wildlife and habitat, pollution prevention, development and cooperation, education and participation, sustainability, climate change reversal, scientific research, effective remedy, healthy living and quality of life. [106] These criterions are strongly connected to the presented environmental issues of road building. Law has the purpose of establishing standards, maintain order, resolve disputes, and protect rights and liberties. [107] These goals set the clear framework for different road pavement materials – defining the technical requirements and their test methods, the development of the road building process (for the whole life cycle) and the properties of the constructed road structure. Safety and technical compliance cannot be overshadowed by economic considerations, the relation and balance between economic and environmental aspects, however, could be different in each country, mostly to the detriment of the environment. Legal aspects like assurance of free competition might overshadow the environmental view, the latter of which was strengthened only in the last couple of decades. The lack – or at least overdue – reaction of the human society to the global environmental impacts only can only be explained with a branched network of reasons, the analysis of which could account as a whole dissertation itself. These aspects go beyond the scope of civil

[84] Ignoring the common trend of political influence on road building sector, which might lead to imposition with technical consequences like inappropriate road surface, shorter life cycle, sooner fatigue.

engineering, but the connection between these sectors should be considered from both sides for a clear understanding of the system and reaching the ideal level of development. In this chapter I will present four aspects in a nutshell, which show the greatest effect on the potential wide-spread of green innovations. As the final pages of the 3rd chapter show, most of the green innovations – in any stages of development from concept to mass produced products – are enduring serious difficulties from economic-political, legal and social aspects. These aspects can be demonstrated through the practical case of the LEA product in Hungary.

6.1 The case of Low Energy Asphalt in Hungary

Low Energy Asphalt is a practical attempt to reduce the energy demand of asphalt products by changing the components of the bitumen and reorganizing the structure of the asphalt mixing plant, as the 3rd chapter described. I have chosen this product as demonstration because its advanced stage of development. Opposite to other alternatives within the early stage of concept, protracted test phase, or even with not-proved or rebutted suitability, LEA not only proved its effectiveness during laboratory and in-situ testing, and getting its certification, but was also produced in many countries with success.

During my research I made an online interview with Zoltán Lehel the innovative chief engineer of the Duna Aszfalt Kft. (Donau Asphalt Inc.) to inform myself on the past and present of LEA in Hungary. The company was established in 1996 and expanded to Donau Asphalt Group of Firms, with the main activities of road and bridge building, infrastructure development, utility construction and environmental projects. [108] The company group is heavily involved in the development of innovative technologies to make road building more sustainable and green, and they have invested into buying the licenses of the LEA product in 2009 – only four years after the innovation was developed in France by the LEA Group - and got the right to be the exclusive consumer in Hungary. As a huge investment, two asphalt mixing plants (a Benninghoven TBA-200K in Dunaharaszti in 2011 and an Amman Uniglobe 240 in Lakitelek in 2014) were reconstructed to be able to produce LEA complemented with recycling system – while the production of conventional products is still possible. The investment at the price of around 60 million Hungarian Forint (round 220 000 Euro at the past conversion rate) was implemented by the company on its own, while the further projects were developed with the help of HAPA (Hungarian Asphalt Pavement Association). As the area of use and the technical parameters and test methods of the product corresponded to the Hungarian Standards[85], there were no more legal barriers to spread the product in Hungary. An 8 kilometres long reference-work was built to assure a necessary project reference for procurement procedures. LEA shows a slight price reduction opposite to other products – by small amount of production the price-difference is not significant - but the significant savings came from the saving of energy during the production phase. According to the company the maintenance work of a 581 metres long (20 cm thick and 6,5 metre wide) road would cost 1 tonne less CO_2 emission with LEA opposite to conventional HMA products, which would mean 1 carbon credit saving for the country. [109] It had been seen that every circumstance was ready to spread LEA in Hungary, but the reality was different. Even though the conditions are ideal since 2011, only 8000 tonnes of LEA were used for one project in 2013, zero tonne were ordered in the last seven years. As the legal and technical conditions are ready, the situation can only be changed from the site of the customers. The company only can increase the marketing procedure to publishing the economic and environmental advantages of the product. The return of the investment would be reached in a couple of months[86] in case of procurement for LEA, but without the interest of the contracting authorities of road works – mostly public and local authorities – nothing seems to be changed in the next years, which also prevents further investments to innovative reconstruction of other mixing plants. According to Zoltán Lehel Green Public Procurement could increase the interest in WMA products like LEA. The reform of the "Hungarian Act on Public Procurement" allows more decision factors (like environmental impact) next to price, without meaning illegal selective economic advantage for the Duna Aszfalt Kft. as other companies are also able to produce WMA products with low environmental impacts.

The LEA proved its competence as an alternative road building material, during the 8000 tonnes of LEA production, the reached fossil fuel savings were even better than the prescribed standards from France, and the Duna Aszfalt Kft. reached 66% saving instead of 50% ratio. As the Figure 6.1 shows the two redesigned asphalt mixing plants were able to serve many big cities in Hungary (including the whole area of the capital, Budapest) counting with the increased two hours long transport period within LEA stay buildable. In case of further investments –

[85] Standard Highway Specification (ÚME – Útügyi Műszaki Előírás) ÚT 2-3.301-1 about the area of use, and ÚT 2-3.301-1 about the parameters correspond the Asphalt Concrete. Slight changes in the Standard Highway Specification makes it allowed to build in green asphalts, like LEA.
[86] The time period of the return of the investment can be even shorter with parallel production of LEA and crushed asphalt.

thinking about strategically chosen mixing plants – it would be easy to cover the whole area of the country with no more than four mixing plants[87].

Figure 6.1 Asphalt Mixing Plants with LEA production and their potential served area (original map from www.roughguides.com) [110]

6.2 Economic and Legal Obstacles

As the example of the LEA product sales is also showing, the green innovations have extremely difficult task to show up on the market, even after the successful proving of their suitability for the technical requirements. Most of the innovations, presented in this thesis are still in the concept phase, which means, their path to successful spread is only at the beginning, and will probably continue only with the help of great amount of financial investment from the company or the state too. The LEA is an exception with the official certificate about the suitability and the successful production and construction as reference project. The lack of consumer interest can be originated from economic aspects and setting exactly the wrong precedent for future projects. To execute a working version of a green innovation always needs start-up capital for a long time period for the investment to return. The combination of these two aspects usually deter the investors, limiting the opportunities of the new method. As I mentioned before the

[87] Assuming increased production capacity

financial support of green innovations from the state[88] could get the innovation through this situation to lay the foundation of a successful production phase. As major decision factor in procurement, the price has the most important part to progress the success of a new product. As thumb rule it could be claimed that most of the new technologies have – at least slightly – higher production costs opposite to conventional – long-used production-method disposing – technologies. In case of slight modifications in the process of production or construction to reach the awaited level of sustainability, the investment could be smaller, and return faster, as the example of LEA shows, where smaller and – on the level of road building sector – cheaper redesign of the mixing plant was enough to switch to the new production method, and made the company able to achieve this goal by themself. This economic advantage allows higher chance for green product variations like WMA asphalt products opposite to brand new technologies, like plastic or solar pavements. Even though solar panels show a promising reduction of unit sale price (Figure 6.2), the mass production of potentially working solar pavement panels would need heavily extended or brand-new production facilities with unique technology, devices and knowledge making it necessary to include high amount of start-up capital. [111] The expense of changing for a new technology as well as the production costs are not enough for a successful start-up as the product must show a significant price difference from conventional products to get the opportunity to have a substitute function. Products with higher price and long-term return of the investment are mostly in enormous competitive disadvantage, making it extremely hard to succeed on the market.

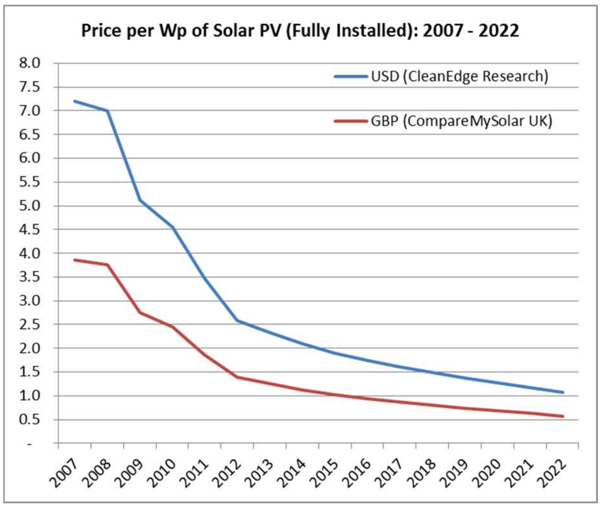

Figure 6.2 Price reduction of photovoltaic panels (per Watt peak) [111]

[88] Or further investors inside or outside of the company.

As Zoltán Lehel highlighted, the competition is hard even in case of lower prices. As the LEA offers the same quality in slightly lower price, the change of investor behaviour towards the new product would be logical, but this improvement did not happen in Hungary in the last seven years. This practical experience claims that the lower price – at the same, offered quality – IS the necessary but not sufficient condition for market benefits. In the case of asphalt alternatives, the costumer choice to stay with the common, well-known products instead of the alternative, can be explained with brand-loyalty and the uncertainty relating to new innovations. As its own, lower price might could refer to quality failures or other hidden defects of the product. Even though official certifications have credibility about the quality, the product needs more recognition to get consumer trust, which could be achieved through marketing procedures and more reference projects. Tools for life cycle management like LCA and LCCA can help to highlight both economic and environmental strength of a product also offering a comparison based on the utility of the products, to provide decision support for both consumers and investors. In Hungary, the Green Development of a technology or even a company has not got enough attractiveness towards the consumers to play a major part in corporate identity, but in other countries positive changes had begun to scale-up the importance of green innovations even during economical decisions. These changes are promising but means only the first steps to a sustainable economy. According to the scientific community for the goal of preventing climate change or at least reducing its damage for the whole human population, drastic changes in economy must be fulfilled in the next couple of years. Steps like the proposed package of United States legislation called Green New Deal (GND) can combine economic approaches with processes for sustainability - such as renewable energy or resource efficiency – to promote the general economic interest of promising innovations. The economic obstacles depend on the political decisions and legal conditions. The obstacles of free competition according to the market economy could limit the opportunity to support one company over others. In public procurement procedure the price is a mandatory, often exclusive award criterion after submission of the bids. There could be further qualitative criteria, time period, warranty or maintenance considered, but the criteria of low environmental load apply an unobjective argument, leaving the procurement procedure open to legal challenge. For this legal obstacle, the mentioned Green Public Procurement – or green purchasing – could serve a solution by taking environmental protection into an award criterion. With this – until now voluntary – instrument, the consumers can make contribution to sustainable consumption and production. GPP can be supported with the Ecolabel concept of the EU. The EU Ecolabel criteria take the main environmental impacts of a product into account, as well as the technically possible improvements. Procurers can refer to the requirements underlying the EU Ecolabel in order to specify their needs. The European Commission is developing new tools for Life Cycle Cost Analyses, to support the green purchasing. [112]

6.3 Political obstacles

It is hard to set unambiguous line between the political, legal, and economic aspects, as they lean on each other, and significantly affect the decision making on every level. Political decisions and their underlying reasons depend on countless attributes like the political system of a country, the actual economic state or the role they are playing in the global economy. The political system of a country specifies its policy towards environmental aspects and its place and role in the environment protection, making it unavoidable to reach green development on the level of political acts. On the other hand, it could be contra productive to watch environmental questions clearly from political view instead of scientific approach. The trend of establishing new political parties with the main goal of green development of the society is a welcomed change that in the last decades shows the importance of environmental protection, but could also empower the false tendency of thinking, that these questions are not affecting every part of the society. If the aspect of green development linked only to specific parties instead of being one of the main points of the campaign of all parties, the scientific view of green innovation necessity could be overwritten as political conviction, potentially causing misalignment and division in a topic, that needs cooperation on both national and international level. International approach for the global call to action also brought back hope in the last decades – only need to refer to the Paris Climate Agreement – but from a more sceptic view, the actions taken as consequences of these agreements might be not strict enough or was set too late to accomplish the goals and objectives for green development. Even in case of goodwill the results can be significantly under-implemented. The Forever Open Road concept from the European Commission is a great example for a plan with great potential for the future, but the topic might cover a great part of the question – to show effective changes the whole TEN-T network in Europe for resilient, adaptable and automated roads – to show effective changes in the near future. Conservative, till untenable deadlines for the goals could also delay the effective action, however the scientific community have reached a strong consensus that in the absence of measures to reduce GHG emissions immediately, the changes in climate will be substantial, with long-lasting effects on many of Earth's physical and biological systems. [113] As David Attenborough said "*We cannot be radical enough in dealing with this issue. The question is* *what is practically possible."* [114] It is especially true for green innovations. As the alternatives presented in this thesis show the procedure to change a promising idea to a really working and everyday used, green system could take years or even decades, which makes the immediate action and support of this issue even more urgent from the political view too.

6.4 Social obstacles

Political decisions mostly taken on economic purposes have the greatest effect on the possible future of new innovations – and the global system of economic, environment and society too – but the impact of the social opinion could not be ignored. The attitude of the people towards the issue of climate change and environmental protection provides a significant contribution to the chances of green innovation. Even with proper democratic voting system the biggest political power of natural persons derives from their purchasing power[89]. Consumer decisions could have a large impact on the economic tendencies achieving bottom-up changes in the economic system also exert pressure on the political decision-making. Boycotting heavy polluting companies and bringing the purchasing power to companies promising more sustainable substitutes is the most effective way to support the widespread of green innovations. But in reality, the situation is much more complex, and as the case of LEA shows, the energy saving, and green indicator is still not attractive enough to change the attitude of consumers. Behind these decisions there are many social, even psychological reasons which could divide the society by their vision on the environmental issue. Even with the positive changes in the general public attitude towards the urgent problems, the effort made by the scientific community and the social groups trying to point out the need of a quick action still seems to be too small to achieve realistic changes in society. Even though the climatic facts were established long ago, and the public opinion also begins to find consensus in this case, the denying views are still strong enough to prevent further processes. As the official evidences are incontrovertible about the manmade climate change, the view formerly called climate scepticism was changed to climate denying as their argument misses any kind of scientific proof to contradict the evidences.[90] [115] Even without proper evidence, the climate crisis denying

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[89] It also called *„Voting with Wallet" Theory.*

[90] Scepticism has two imperatives, the first is the imperative to doubt ("*nullius in verba" – "take nobody's word for it" as the motto of the Royal Society says)* the second is the imperative to follow the evidence, and give more credibility to claims that are well justified than those which are not. (Ellerton, 2019)

trend has a negative impact on the much-needed change in climate policy. The denying has different levels from:

- denying the existence of climate crisis
- claiming global warming is a natural process without any causation with human activity
- denying the effect of energy saving, green methods on climate change
- seeing climate change as a long-term process without any necessity of action in our lifetime
- or simply transferring the liability on other responsible states, companies etc.

The common point of these various opinions, that neither of them sees the necessity of taking actions, considering green innovations and methods needless.

The climate denying can be empowered by political propagandas, lobby, and economic campaigns, which also could lead to the frustrating trend of common distrust in science. Even though our current scientific capacity is not being able to punctually forecasting the future of such a complex system like the climate of a planet, the measurements and calculations from both input (GHG emission) and output side (average global temperature rise, sea-level rise, carbon concentration in atmosphere, microplastic concentration etc.) are allowing to establish scientifically proven facts for the near future of our planet, which are alerting for immediate action. The impact of denying can be traced through the trend that the formerly used definition "global warming" is proposed to avoid even in scientific papers to prevent the easy and clearly false disagreement, that claims: colder weather is a rebut for global warming. Nowadays the definition climate crisis is the preferred one instead of climate change pointing out the need of immediate action.[91] Sadly the political and economic propaganda - claiming to spread climate denying for preventing more strict and economically speaking disadvantages climate laws - has a breeding ground in the human society mostly caused by the systematic patterns of deviation from norm or rationality in judgment, called cognitive biases. [116] Cognitive biases - like Dunning-Kruger effect - are heavily involved when the attitude of society to the climate crisis come into question. There are more than hundred different cognitive bias, some of the most important ones could also enable denying processes and even conspiracy theories. The mentioned *Dunning-Kruger effect* is one of the most famous biases, causing overestimated

[91] Also preventing the argument, that climate is always changing so human activity has nothing to do with it

confidence in a field without deep knowledge. It is related to *illusory superiority*[92] and comes from the inability of recognizing the lack of ability in a specific area. The second denying process is a good example for Dunning-Kruger effect, when small, out of their context taken information allows to get far-reaching and probably wrong conclusions. [117] The periodic trend of the global average temperature on the earth really changes by its own following colder and warmer periods, from which it would be easy to conclude on the fact that this is happening right now, without our help. Even though we are in a natural warming phase, the exponential acceleration of warming from the last fifty years could not be explained only through clean natural processes. Other important bias for the social view of climate crisis is the *backfire effect*, which means a common obstacle for every scientific process developed to rebut former theories and concepts. [118] Backfire effect means that an encounter evidence – even with detailed explanation and scientific proof – could be rejected and even strengthen the support of the original – provenly false – statement. Backfire effect is in the subtype of confirmation bias, which means that the information that confirms existing preconceptions or hypothesis will be favoured instead of new, encounter information. The common presence of confirmation biases shows the danger of false statements spreading faster than ever, thanks to the technologic revolution and social networks, which could undermine any scientific methods, even with the most evident ones (like the near[93] globe form of the Earth). *Hyperbolic discounting* is also evolutionally integrated in the human brain, meaning that the safety of present has priority to the safety of future, which bias even works for near future events. The greatest danger of the climate crisis is: that its clearly discernible impacts will appear only in the future, and even though thousands of local evidences shows the process's actual state, until greater threat to the global society and economy, the danger of the crisis will be secondary for most of the people. Even though at this point the action against the crisis will probably be too late. That is the reason why in most of the climate policies climate adaptation and resilience are the keyword making effort to get used to the new situation instead of trying to prevent it.[94] Some biases like *the naïve realism* make us believe that we see the world objectively, and those with other opinion are uninformed, irrational, or biased, make it even more difficult to notice if our opinion not

[92] Overestimating their own qualities and abilities, in relation to the same qualities and abilities of other people.
[93] The mathematical figure of the Earth called geoid, after Carl Friedrich Gauss.
[94] At this point the effect of climate change is inevitable, which makes the resilience necessary but still not sufficient effort, as the 2 ºC maximal increase of global average temperature (compared to the measurements before the industrial revolution) could not be overstepped to keep adaptation in future still possible.

representing the reality. [119] There are countless other biases influencing our opinion and thinking and the whole view we so the world each other. It is hard to identify these instinctive backgrounds of our opinion, but not impossible. The most important is the high level, independent education system, not only building on the scientific facts, but also their substantiation, teaching the process of logical thinking on every level of the education process (teaching how to think instead of what to think). There are legal tools to prevent the spread of miss-information and conspiracy theories but with the rapidly evolving technology it is hard to keep pace. The producing companies of green innovations has also opportunities to change the false view of unnecessity their products by using marketing and campaign to highlight the local and immediate effect of their production methods, setting the short-term goals and forecasted results for the publicity.

7. Conclusion

In my thesis, I made an attempt to comprehensively cover the present situation of the road building sector from the aspect of environmental protection. The complexity of the topic could not allow to reach every details of the problem I raised in my thesis, that is why I tried to summarize the most important parts and highlight the strengths and weaknesses of present methods and developing concepts. I hope that my work would help for those who wants to be informed about the current situation of road building industry as well as its potential, which hopefully will not be unused in the future. My goal was to focus the attention of the importance and actuality of the global environmental crises and take afford to encourage the possible green development of my own field. As a civil engineer with the specialization of infrastructure development I have a direct view of the technical features of road paving material production and construction as well as the physical characterization of the materials, but I find essential to achieve a wider point of view of the topic, understanding the economic-political, legal and social tendencies which are heavily involved in the question of green innovations. This interdisciplinary attitude might help to use the whole potential of some innovations and help the widespread of green products and methods, which has not really happened until now. During my research I was both amazed and frightened seeing the present case of road building. The number of new concepts, innovations and ideas in the area were amazing, not less the effort engineers, scientists or even civil inventors made for the green change of road building. On the other hand the necessity of immediate act and the lack of major success on this area is frightening, that is why I wanted to highlight not only the technical and social obstacles of major innovations but also try to find possible solutions to overcome them.

The monopoly of conventional materials – if we are counting both concrete and asphalt pavements – is unquestioned as any other substitutes could reached only the test phase, or small amount of exact construction. Even with the presentation of the technical differences, there is no evident choice between concrete and asphalt. Concrete pavements are useful in many different cases, but the surplus of asphalt makes it legitimate to start the environmental changes with this product – while the further development of concrete mostly helps to reduce the impact of other parts of the building sectors. The surplus of HMA products in asphalt building industry must be reduced step by step leaving scope for less conventional asphalt products. WMA, HWMA and CMA products have the most potential to effectively reduce the environmental impacts of the production, without compromises of the technical requirements. Even the economic benefits could appear in a short-term, as opposed to other innovations, if further obstacles are not setting back the development, like in the presented case of LEA. Further modification of asphalt structure – with the use of polymers, recycled plastic, or rubber – and the development of recycling rate are also effective way for developing environmental protection. In my opinion the greatest and most effective steps could be made if only the road building companies take responsibility for further development of their products – with investment on research programs, redesign of their production chain and do marketing for green products - which efforts must be financially and legally supported from national and international organisations. In general, the long-term impacts of green innovations must be grounded with legal and economic decisions in the near future. The European Union had made the steps to the integrated control of road building processes with the EN standard, but for real global impacts this guidance must be agreed and complied by all countries on a higher level of observing. The political steps from the EU are promising start for a green mentality shift, but until this point most of the successes were staying on the level of concept. The bureaucratic approach of the question also can be seen as an obstacle to the waited progress from concept to reality. The Forever Open Road concept aims at a grandiose goal of the future, which must be bear in mind, but at this point of struggling progresses to achieve at least minor success at reduction of energy, the energy-producing European road-network for electric cars looks more like an utopian view. The dependency from the economic progress of electric cars, the major rebuilding of thousands of kilometres of road network and the uncertain suitability of solar pavements are all obstacles, which could be defeated only in decades from now. Bearing these long-term concepts in mind too, it is important to support those steps which are offering immediate impacts and fast solutions, even if first only in smaller cases. It is the responsibility of the states and international organisations to support green innovations and provide legal and economic framework for the fruition of the suitable concepts. The mentioned Green Public Procurement is a promising concept, but further progresses need to be taken. Management tools, like Life Cycle Analysis could help not only compare different technologies but also highlight economic and environmental connections for the decision makers. Even with the support of green innovations it is important to hold strict rules for the technical examination and test methods of new innovations to detect concepts not suitable for road pavements.

The progress of solar panel systems in the last decades brings back hope in green energy production, and there are encouraging signs from the economic aspect of solar energy production too, but I would not support the use of photovoltaic cells as road surfaces. Revealing more details of this good sounding idea too much technical obstacle came into the picture from bearing capacity problems, limited efficiency to expensive and waste producing maintenance, that I would recommend the reshaping of the concept. The lack of practical success with solar panels – thinking about the obstacles for SolaRoad and Solar Roadways test projects – shows that our current technological development level is not prepared yet for sufficient solar pavements. Still I would not reject the idea of combing road structures and photovoltaic panels, and support the idea to use them as traffic technology devices ensure electricity for the traffic lightings and control devices, or in higher level of production even for gas stations and other road service buildings. My idea about the combination of noise barriers and solar trackers is only at the stage of concept, but with further physical simulations and tests – especially on the effects of noise on photovoltaic surface – would reveal it is potential. Similar to solar pavements the brand-new alternatives like plastic pavements also showing questionable properties not only from the point of physical strength – which could be too brittle to bear even small traffic loads – but also from the view of recycling, which is claimed as its major advantage. Proper waste management still has a major role in road building, and a lot of unused potential, which turns to recycling as the last solution and tries to optimize the material and energy use for all phases of the life cycle. Using recycled plastic as additive in asphalt, raise the amount of reclaimed asphalt pavement in new products or multiplying the allowed cycles of recycling without loss of physical properties are all possible but need further researches to achieve such goals.

As my thesis summarized, there are many innovative ideas especially in the field of the development of conventional materials with unused potential, and there are concepts might lead to deadlock, or their benefits not revealed themselves yet. There could be a brand new innovation with the possibility to rewrite the whole area of road building, but until then, we need to make the most of road building sector to start its way to a greener – and hopefully near – future.

Outlook to the near future

This master thesis had been written in the first half year of 2020. The preparation for the research and data collection had begun in the late 2019 after an area that could be seen as a promising start for global mentality shift in the field of environmental protection. Even with unfortunate political decisions and long-term failures of former promising climate saving processes the mentality had changed and energy saving more sustainable lifestyle has moved to the forefront. The social mentality changed in a way like the undeniably presence of climate change was finally adopted not only by the scientific community but public and in some cases even by the political view. Despite the fact that this mentality shift had not been reflected in the global statistical data - like GHG-emission, energy consumption, rate of non-renewable fossil resources, material sparing or green investments - the positive change of mentality was the first and long awaited change to the good direction promising real, technical changes and results.

After years of continuous economical increasing in most of the developed countries, the events of 2020 would possibly stop this trend with long-term effects. The consequences of the global pandemic and the lockdown on the economy and on the nature are unpredictable at this point. The short-term positive effects on the nature are visible after only a few weeks – clearer air in cities, cleaner natural waters, beginning of the regeneration of some landscapes, returning of wildlife – which could make us hopeful for the healing property of our world, but should not lead to the erroneous conclusion that our impact on the world is negligible and it is easy to tackle all the problems we caused. The manmade climate change would not stop because of a short and minor setback in the economical processes, even an immediate stop of all GHG-emissions would not be enough to stop the run-away warming. To hold the warming below a still liveable value – which claimed to be the 2 °C of warming compared to the global average temperature before the industrial revolution – need enormous effort and quick, long-term changes in quite every aspect of our life, society and economy.

The economic consequences are even harder to foreseen at this point, and only the magnitude and not the inevitable presence of the economic crisis could be questioned at that point. As my thesis highlighting the interdisciplinarity between the technical, political, and economic aspects, the near future of the global economy influences every part of the road construction and the building sector as whole. Most of the presented statistics are showing an exponential rise in production, construction, and emission, whether speaking about global asphalt or cement production, fossil fuel consumption, renewable energy consumption or emissions. I referred many times to the economic crisis in 2008 as a major setback in the economic indicators which might stopped the former trends for a couple of years but has not shown long-term effects on the potential change of these trends. The economic downturn is unavoidable for the next years, but the consequences can be proceeded with different outcomes. The Figure 7.1 of this thesis shows an evaluation of the three different outcomes, which are interestingly similar to the three possible future of the expendable universe.

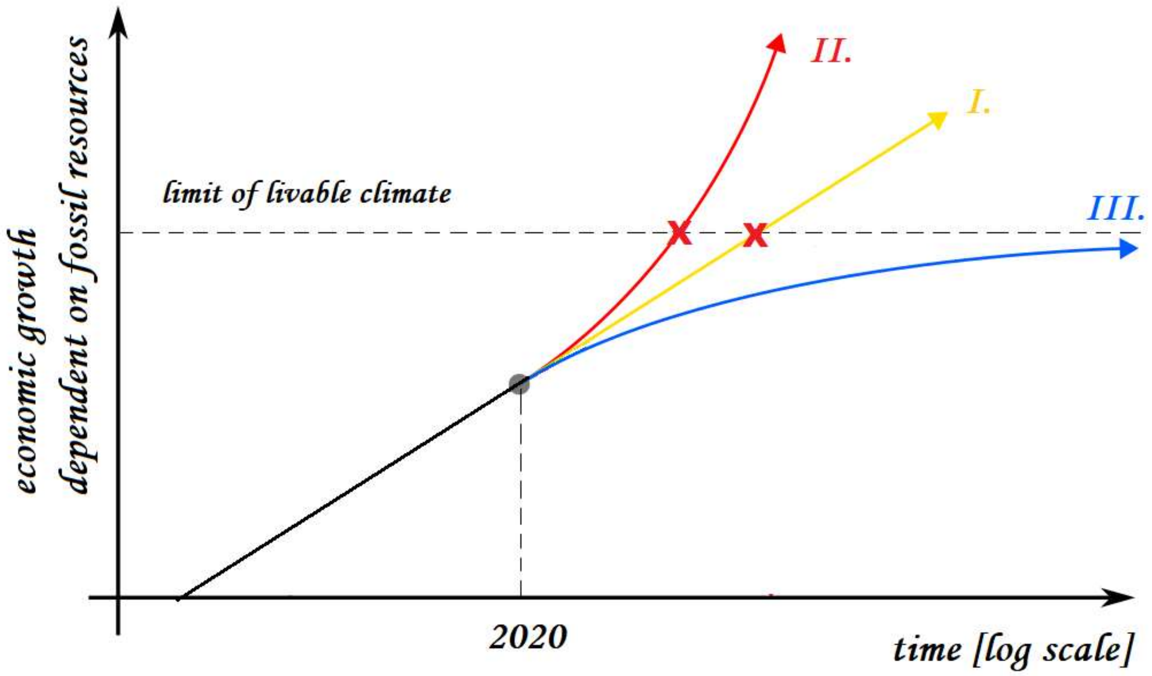

Figure 7.1 - Three outcome of economic development (original picture from wikimedia.org) [120]

The graph shows the development of the economics – dependent on fossil energy sources – on a logarithmic scale of time. With a good estimation – and simplifying the yearly differences like in the years after 2008– this development from the last decades could be seen as a line in the logarithmic scale, presenting the logarithmical growth. Now, at the year of 2020, there are three opportunities to continue the line. After some year of recession, the line could get back to the trend following the former growth as the world changed back to normal – in economic terms. This is equivalent to the continuous expansion of the university from the big bang to the foreseeable future and possible beyond (I. curve) [95]. To help the collapsing economy, further support for the cheap and quickly producible energy might will growing with an even higher scale than at this point. As seen after great economic crises the environmental aspects getting lower priority behind the redemption of economy based on fossil fuels, which would mean for the economy, as well as for the polluting emissions and energy consumption an even higher grade of increasing. This version is equivalent to the accelerating expansion of the universe (II. curve). The third version assumes an actual change in the global economy which based on the high scale replacement of fossil sources to renewables causing a slowing down growth of economy dependent on fossil fuels, meaning slower growth of GHG emission and the possible

[95] With Hubble Constant defined as zero. Ω=0. If $\Omega\geq0$ the expansion will slow down, and reverse if $\Omega>1$.

chance to change the trend. The slowing down of the expansion and reverse process would be similar to this, highly optimistic outcome (III. curve)[96]. The mystery of the universe, the inconceivable concept of infinity makes the scientist insecure about the future of the expanding universe. Could it expand stagnant or accelerate endlessly until the so-called "Big Freeze", as everything cools down? Or would the expansion reverse until the "Big Crunch" to frame its history with the Big Bang? We cannot be sure. The only thing is sure, that endless growth in a limited system – like the Earth – is impossible, which means unknown but sure end of the first two curves. The only outcome that might could be sustainable for the future is the third version. As seen from the thesis the widespread of alternative solutions in road construction are hard even with good economical background, not to talk about crisis, when the price has the priority opposite to environmental benefits. The branching of the three version could happen at any point of the time, does not need a crisis or global pandemic to make a decision between the three options, but the humanity might need global impact to change it attitude towards the world we are live in. Maybe an impact that affects us all, will help humanity to work together and make the right choice for the future before it will be too late.

[96] Avoiding any kind of misunderstanding, this hypothetical graph would not describe the collision and end of the economy but the demolition of carbon-dependent economic growth which would reach the totally sustainable economics at point 0.

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