Life-Cycle Assessment of the Production of Swiss Road Materials

Florian Gschösser[1]; Holger Wallbaum, Ph.D.[2]; and Michael E. Boesch, Ph.D.[3]

Abstract: Sustainable development demands contributions across all economic sectors. Thus, the infrastructure field, in this case road infrastructure, also has to contribute its part by generating road materials and road construction with lower environmental impacts. This paper analyzes the environmental potentials hidden in road materials used in Swiss road pavements. For several materials used in road construction, cradle-to-gate life-cycle assessments (LCA) were performed, taking into account all environmental impacts from raw material extraction to the finished product at the production plant. Environmental improvement potentials were analyzed for the production of asphalt mixtures, concrete mixtures, and subbase mixtures, using eight different environmental impact indicators. The results show differences in the environmental impact between best case and current status production setup of up to 54% for asphalt mixtures, 38% for concrete mixtures, and 93% for subbase mixtures. **DOI: 10.1061/(ASCE)MT.1943-5533.0000375.** *© 2012 American Society of Civil Engineers.*

CE Database subject headings: Life cycles; Pavements; Sustainable development; Switzerland; Construction materials.

Author keywords: Life cycles; Pavements; Sustainable development; Switzerland.

Introduction

Life-cycle assessment (LCA) is a methodology to determine or compare ecological impacts of different products over the whole life cycle (ISO et al. 2006). This study applies cradle-to-gate LCA to compare alternative production setups for several road materials. In a cradle-to-gate study, all impacts from raw material extraction to the finished product are taken into account, whereas the use and disposal phase are neglected. The functional unit in this study is 1 m^3 of road construction material. The life cycle of a road construction contains four different phases: material production, construction, use, and maintenance. The temporal system boundary of an LCA study defines the observation period, within which environmental impacts are taken into account. Depending on the length of this period and the maintenance strategy, the four different life-cycle phases occur with a different frequency during the analyzed time period.

Several previously conducted LCA studies demonstrate the ecological properties of materials used within road constructions (Mroueh et al. 2000; Stripple 2001; Birgisdóttir 2005; Gambatese and Rajendran 2005; Zapata and Gambatese 2005; Rajendran and Gambatese 2007; Boesch et al. 2009; Zhang et al. 2009; Cass and Mukherjee 2010; Muench 2010; Zhang et al. 2010). These studies either determine or compare ecological impacts of different road construction types or road materials over the whole life cycle or for specific life-cycle phases.

This paper analyzes the production processes for materials used in Swiss road pavements by applying a from-cradle-to-gate approach, which comprises all resource consumptions and emissions from the primary resource extraction to the finished product at the plant. Construction, use, and maintenance are not taken into account. This is justified by the assumption that different production setups for each of the road construction materials do not influence the use and maintenance of the road. The differences in lifetime of different road material types (e.g., concrete roads, asphalt roads) do not affect the result, as the study does not compare these materials against each other, but focuses on different production options for each of the material types.

The impact categories considered in the LCA studies are climate change (global warming potential, GWP 100), cumulative energy demand (primary energy consumption from nonrenewable resources), and the method of ecological scarcity 2006.

[1]Ph.D. Candidate, Chair of Sustainable Construction, Institute of Construction and Infrastructure Management, Dept. of Civil, Environmental and Geomatic Engineering, ETH Zurich, Zurich 8093, Switzerland (corresponding author). E-mail: gschoesser@ibi.baug.ethz.ch

[2]Assistant Professor, Chair of Sustainable Construction, Institute of Construction and Infrastructure Management, Dept. of Civil, Environmental and Geomatic Engineering, ETH Zurich, Zurich 8093, Switzerland. E-mail: wallbaum@ibi.baug.ethz.ch

[3]Research Associate, Chair of Ecological Systems Design, Institute of Environmental Engineering, Dept. of Civil, Environmental and Geomatic Engineering, ETH Zurich, Zurich 8093, Switzerland. E-mail: boesch@ifu.baug.ethz.ch

Note. This manuscript was submitted on October 28, 2010; approved on August 4, 2011; published online on August 4, 2011. Discussion period open until July 1, 2012; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Materials in Civil Engineering***, Vol. 24, No. 2, February 1, 2012. ©ASCE, ISSN 0899-1561/2012/2-168–176/$25.00.

Material Production

Standard asphalt pavements consist of an asphalt concrete (AC) wearing course, base course, and road base placed on a subbase (SB) layer (VSS 2008b). Concrete pavements contain an exposed aggregate (EAC) on top and a bottom concrete (BOC) layer also set on a SB layer. This study analyzes production options for road materials used within Swiss asphalt and concrete road pavements (Table 1).

Asphalt

Data on asphalt production was collected with a survey, covering 25% of all Swiss asphalt production companies producing 22% of the total Swiss asphalt sales. A questionnaire was compiled

Table 1. Materials and Production Options Analyzed (ASTRA 2007; Canton Aargau 2008; Canton Zurich 2008)

	Material options					Recycling scenarios
Asphalt mixtures	Wearing course (WC)	Base course (BC)	Road base (RB)	Asphalt subbase (SB)	Production options	No recycling (NR)
	(WC 1) AC 8 S	(BC 1) AC B 16 S	(RB 1) AC T 22 N	(ASB 1) AC F 22	Standard production (ASP)	Average recycling (AR)
	(WC 2) AC 8 H	(BC 2) AC B 22 H	(RB 2) AC T 22 S	(ASB 2) AC F 32	Optimized production (AOP)	Production share of recycling asphalt (PSR)
	(WC 3) AC MR 8		(RB 3) AC T 22 H			Maximum recycling (MR)
	(WC 4) AC MR 8 ASTRA		(RB 4) AC EME 22 C1			
			(RB 5) AC EME 22 C2			
	Material options					
Concrete mixtures	Exposed aggregate concrete (EAC)	Bottom concrete (BOC)			Production options	Recycling scenarios
	(C1) CEM I	(C1) CEM I			Standard production (SP)	0% (R0)
	(C2) CEM II/A-S	(C2) CEM II/A-S				25% (R25)
	(C3) CEM II/A-LL	(C3) CEM II/A-LL				50% (R50)
	(C4) CEM II/B-T	(C4) CEM II/B-T				75% (R75)
						100% (R100)
					Production options	Recycling scenarios
Subbase mixtures	Material options				For HSB and BSB	For HSB and BSB
	Unbound (USB)				Central mixing at plant (CP)	Primary material (PM)
	Hydraulically bound (HSB)				Central mixing at site (CS)	Secondary material (SM)
	Bituminous bound (BSB)				In-situ mixing (IS)	

in cooperation with the Swiss Bituminous Mixture Industry to gather data about production volumes, mixture compositions, the used energy for the production, internal transport processes, transport distances of the sub-suppliers, emissions, auxiliary materials, and existing ecological potentials of the asphalt production.

Asphalt Production

In Switzerland, asphalt production generally takes place in batch mixing plants. The survey showed an average heat requirement for the production of 1 t of asphalt is 305.4 MJ and the average moisture of the mineral aggregates is 4%. A furnace heated by light fuel oil or gas provides the needed energy to dry and heat up the mineral aggregates and the reclaimed asphalt pavement (RAP). In this study, it is assumed that the fuel types used are 50% gas and 50% oil, according to the recommendations of the Swiss Bituminous Mixture Industry. At the moment, 35% of the required heat is used for drying the aggregates and 51% is used for heating it up to 180°C. Four percent of the heat is lost through insulation and 10% is lost by emissions.

Jenny (2009) states that optimized storage (i.e., covered storages or silos) would reduce the initial moisture of the aggregates to 2%, and with the use of low-viscosity bitumen, the mixing temperature could be reduced from 180 to 115°C. This production optimization (OP) lowers the required drying and heating energy as well as the losses throughout the insulation and the emissions.

The Swiss standard for requirements to asphalt mixtures (VSS 2008a) mentions that for the production of the different asphalt mixtures specific amounts of primary material can be replaced with RAP (Table 2).

RAP can be used in asphalt production either by warm or cold recycling. Warm recycling means that RAP is heated up in a parallel process to the heating of the mineral aggregates. Cold recycling is when RAP is added to the already-heated mineral aggregates before the mixing process. The heat requirement for asphalt production is not affected by warm or cold recycling (Jenny 2009). Table 3 shows energy resources and operating materials taken into account for the modeling of asphalt production.

Table 2. Maximum Share of Reclaimed Asphalt Pavement (reprinted from VSS 2008a, with permission from Swiss Association of Road and Transportation Experts VSS)

Maximum share of RAP	Cold recycling	Warm recycling
Wearing courses		
AC S, AC H, AC MR	0	0
Base courses and high modulus asphalt		
AC B, AC EME	≤ 15	≤ 30
Road bases		
AC T	≤ 25	≤ 60
Subbases		
AC F	≤ 30	≤ 70

Table 3. Energy Resources and Operating Materials of Asphalt Production

Energy and operating material		
Electricity, medium voltage	8.6	kWh/t
Heat, natural gas	152.7 (SP), 87.9 (OP)	MJ/t
Heat, light fuel oil	152.7 (SP), 87.9 (OP)	MJ/t
Diesel, burned in wheel loader	11.1	MJ/t
Transport, lorry 20–28 t	57.1	tkm/t
Lubricating oil	3.01E-06	kg
Tap water	0.009	kg
Mixing plant	2.51E-10	p

Asphalt Mixture Compositions

Asphalt mixtures generally consist of mineral aggregates, asphalt binder (i.e., bitumen), and optional additives. The mixtures have a density between 2,280 and 2,410 kg/m^3 and a bitumen content of 3.4 to 5.8%. The analyzed asphalt concrete mixtures in this study are listed in Table 1. In the study, four different compositions are analyzed for each mixture, except for the wearing course mixtures. The first composition scenario is the one without recycling material (NR), the second one uses the average share of warm and cold asphalt recycling (AR) (0.4 to 9.3%—cold; 8.3 to 58.2%—warm), the third takes the production share of recycling asphalt of each producer into account (PSR) (0.4 to 9.2%—cold; 7.8 to 50.8%—warm), and the fourth applies the maximum amount of RAP (MR).

The utilized mineral aggregates for the asphalt mixtures contain 95% crushed gravel and 5% round gravel. The applied filler consists of 50% internally generated filler and 50% limestone filler. The several mixtures can use different bitumen types (VSS 2008a). In this study, production data for average Swiss bitumen is applied, as no specific data for different bitumen types was available (Ecoinvent Center 2010).

Concrete

Concrete Production

The study applies data representing average Swiss production data for the production of clinker, the main ingredient of cement (heat requirement, 3450 MJ/t clinker; thermal substitution rate of waste, 46.5%) (Cemsuisse 2008). Improvement potentials in clinker production (e.g., by changing the resource mix or upgrading production technology to achieve lower heat requirement) are not assessed. Electricity requirement per ton of cement is assumed to be 99.7 kWh/t for all cement types according to the German Cement Works Association (2007).

Table 4 shows energy resources and operating materials taken into account for modeling the asphalt production.

Table 4. Energy Resources and Operating Materials of Concrete Production (Data from Cemsuisse 2008; Ecoinvent Center 2010)

Energy and operating material		
Electricity, medium voltage	4.5	kWh/m^3
Heavy fuel oil, in industrial furnace	3.2	MJ/m^3
Light fuel oil, in industrial furnace	13.7	MJ/m^3
Natural gas, in industrial furnace	1.4	MJ/m^3
Diesel, burned in wheel loader	23.3	MJ/m^3
Transport, barge	50.7	tkm/m^3
Transport, freight, rail	7.0	tkm/m^3
Transport, lorry 3.5–20 t	1.0	tkm/m^3
Transport, lorry 20–28 t	9.7	tkm/m^3
Lubricating oil	0.012	kg/m^3
Steel, low-alloyed	0.025	kg/m^3
Mixing plant	4.70E-07	p/m^3

Table 5. Concrete Compositions in This Study (Data from Wilk et al. 1994; Holcim Schweiz AG 2008)

	Bottom concrete					EAC
Recycling (%)	0 (R0)	25 (R25)	50 (R50)	75 (R75)	100 (R100)	0 (R0)
Material	kg/m^3					
Recycling sand	0	149	299	448	597	0
Recycling gravel	0	289	580	869	1,159	0
Sand	650	488	325	163	0	420
Gravel, unspecified	1,262	947	631	316	0	0
Gravel, crushed	0	0	0	0	0	1,325
Cement	343	375	375	375	375	420
Water	144	183	187	190	194	170
Plasticizer	3.5	2.5	2.5	2.5	2.5	3.5
Air entering agent	2.5	2.5	2.5	2.5	2.5	2.5
Total	2,405	2,436	2,402	2,366	2,330	2,341

Table 6. Cement Compositions (Reprinted from EN 2000, with Permission from Swiss Association of Engineers and Architects SIA)

	Composition in mass percent			
	Clinker	Other main component		Minor
Cement name	%	%	Type	Components
CEM I (C1)	95–100	0		0–5
CEM II/A-S (C2)	80–94	6–20	Slag Sand	0–5
CEM II/A-LL (C3)	80–94	6–20	Limestone	0–5
CEM II/B-T (C4)	65–79	21–35	Oil Shale	0–5

Concrete Compositions

Concrete generally consists of cement, mineral aggregates, water, and optional additives. The Swiss standard for recycling materials within road constructions (VSS 1998) allows a percentage of up to 100% recycled concrete aggregates in bottom concretes. Because exposed aggregate concrete must fulfill further requirements compared to BOC, such as reducing noise generation and increasing traction, it is comprised of no recycled aggregates, only crushed gravel and a higher portion of cement paste. Table 5 shows all analyzed concrete compositions.

Either portland cement or blended cements (i.e., cements with reduced clinker contents) can be used as a binding agent in the concrete (Bilgeri et al. 2007). In this study, four different cement types are assessed (Table 6).

Subbases

Unbound Subbases

Unbound SB layers analyzed in this LCA study consist of round or crushed gravel.

Hydraulically Bound Subbases

A survey concerning production variants, mixture compositions, energy consumption, transport processes, emissions, auxiliary materials, and existing ecological potentials of the production of both hydraulically and bituminous stabilized mixtures was the base for the LCAs of these SB mixtures. Three Swiss construction companies covering a bigger part of the Swiss road construction market gave their feedback and input to this poll.

Production

Hydraulically bound mixtures can be centrally mixed or mixed in place. The central mixing method either takes place in a stationary concrete mixing plant or a mobile mixing plant at the building site. The mixing energy consumption for the production in concrete plants is about 90% of the energy needed for the production of pavement concrete i.e., 4.04 kWh/m^3. The data used to model the central mixing method on-site refers to a mobile mixing plant with a diesel-electric generating set (KAMPAG 2010). For the central mixing methods, either the soil or aggregates present on-site are used as mineral aggregates, or, for a maintenance process, the existing unbound SB is used. The in situ mixing method combines the production process with the construction process of the subbase layer. The soil or the former unbound subbase given on-site is mixed with water and the hydraulic binder by a special stabilizer (Wirtgen Group 2009).

Table 7 shows energy resources and operating materials taken into account for modeling the asphalt production.

Table 7. Energy Resources and Operating Materials of Hydraulically Bound Mixture Production (Data from Wirtgen Group 2009; Ecoinvent Center 2010; KAMPAG 2010)

	Central mixing method		In-situ mixing	
	At plant (CP)	At site (CS)	Method (IS)	
Electricity, medium voltage	4.0			kWh
Heavy fuel oil	3.1			MJ
Light fuel oil	13.3			MJ
Natural gas	1.2			MJ
Diesel, in wheel loader	22.7	22.7		MJ
Diesel, in mixing plant		11.1		MJ
Diesel, in stabilizer			2.9	MJ
Transport, barge	49.2	2.09		tkm
Transport, freight, rail	6.8	0.29		tkm
Transport, lorry 3.5–20 t	1.0	0.998		tkm
Transport, lorry 20–28 t	9.4	0.4		tkm
Transport, lorry > 32 t		0.08	0.08	tkm
Lubricating oil	0.012	0.012	0.003	kg
Steel, low-alloyed	0.023	0.024		kg
Mixing plant	4.57E-07			p
Mobile mixing plant		2.88E-07		p
Stabilizer			6.94E-08O_2^-	p

Table 8. Analyzed Compositions for Hydraulically Stabilized Subbases

Primary material	kg/m^3	Secondary material	kg/m^3
Sand	104	Recycling sand	106
Gravel, unspecified	1,746	Recycled granulates	1,794
Cem II/A-LL	78	CEM II/A-LL	78
Water	145	Water	148
Total	2,073	Total	2,126

Compositions

Hydraulically bound mixtures generally consist of mineral or recycled aggregates, cement, water, and possible other additives. The specific composition depends on the grading of the used aggregates. Possible aggregate sources are the soil present on-site, external mined aggregates, or different types of recycled granulates. The cement type used is CEM II/A-LL. A preanalysis of the hydraulically bound SB production showed that the usage of alternative hydraulic binders such as hydraulic road binder (HRB) has the same influence on the results as CEM II/A-LL. Therefore, the production of hydraulically bound subbases was analyzed with the CEM II/A-LL. This study analyzes two compositions using either primary gravel or recycled granulates (Table 8). The composition using primary material (PM) contains primary sand and the composition using secondary material (SM) applies recycling sand.

Bituminous Bound Subbases

Production

Cold bituminous bound mixtures can also be mixed centrally or in situ. The stationary central mixing method takes place in an asphalt mixing plant. The mobile central and the in situ mixing method use the same equipment as for hydraulically bound mixtures (Table 9).

Compositions

Bituminous bound mixtures consist of mineral or recycled aggregates, a cold bituminous binder, water, and a small share of cement.

Table 9. Energy Resources and Operating Materials of Bituminous Bound Mixture Production (Wirtgen Group 2009; Ecoinvent Center 2010; KAMPAG 2010)

	Central mixing method		In-situ mixing method	
	At plant (CP)	At site (CS)	(IS)	
Electricity, medium voltage	19.4			kWh
Diesel, in wheel loader	25.0	25.0		MJ
Diesel, in mixing plant		11.1		MJ
Diesel, in stabilizer			2.9	MJ
Transport, lorry 20–28t	113.3	45.5		tkm
Transport, lorry> 32t		0.1	0.1	tkm
Lubricating oil	0.007	0.012		kg
Steel, low-alloyed		0.024	0.003	kg
Mixing plant	5.65E-07			p
Mobile mixing plant		2.88E-07		p
Stabilizer			6.49E-08	p

Table 10. Analyzed Compositions for Bituminous Stabilized Subbases

Primary material	kg/m^3	Secondary material	kg/m^3
Primary sand	338	Primary sand	338
Primary gravel	1,788	Asphalt granulates	1,788
Cement	23	Cement	23
Bituminous emulsion/ Foamed bitumen	79	Bituminous emulsion/ Foamed bitumen	79
Water	22	Water	22
Total	2,250	Total	2,250

The specific composition depends on the grading of the used aggregates. The mixture uses either a bitumen emulsion or foamed bitumen as a binder. Possible aggregate sources are the soil present on-site, external mined aggregates, or different types of recycled granulates. This study analyzes two compositions using either primary gravel or asphalt granulates (Table 10).

Life-Cycle Assessment

This cradle-to-gate LCA study applies the cut-off rule concerning the allocation of recycled materials. Recycling materials enter the system burden free i.e., for the analysis of the production processes it is assumed that the upgrading to usable recycling materials is part of the previous life-cycle system. Hence, the first process included in the analyzed system is the transport from the recycling pool to the place of production.

All inputs and outputs analyzed for the evaluation of environmental impacts relate to a functional unit. Fig. 1 shows all possible processes needed for the production of 1 m^3 of road material.

Impact Categories

The impact categories to evaluate the environmental impact of the production of the road construction materials are global warming potential 2007, cumulative energy demand (CED), and the method of ecological scarcity 2006. These categories are briefly described in this section.

Global Warming Potential 2007

The global warming potential (GWP) indicator, according to Intergovernmental Panel on Climate Change (IPCC), includes all

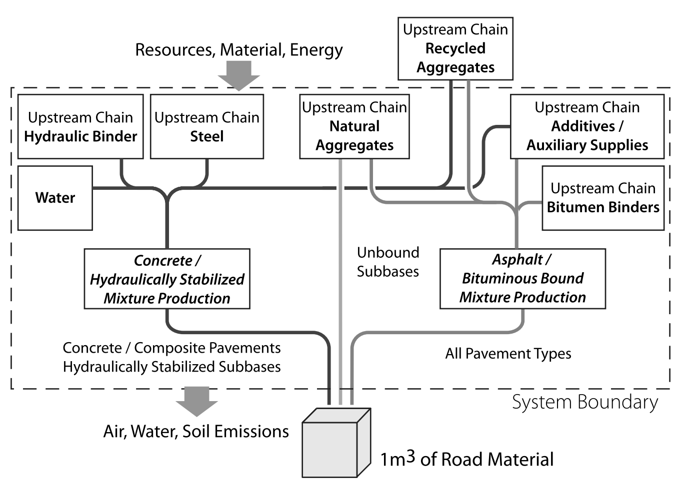

Fig. 1. Process model for production of road materials

substances that contribute to climate change (Forster et al. 2007). The atmospheric lifetime of a substance and the efficiency of the substance as a greenhouse gas are considered to determine the GWP. The GWP of a greenhouse gas is measured relative to the same mass of CO_2, yielding kg CO_2 equivalents. According to the Kyoto protocol, this study evaluates the GWP for a time horizon of 100 years.

Cumulative Energy Demand

CED describes the consumption of fossil, nuclear, and renewable energy sources along the life cycle of a product or service. This includes the direct use, as well as the indirect or gray consumption of energy use of materials (e.g., gravel or concrete) as construction or raw materials (Boustead and Hancock 1979). The CED indicator calculated is CED, nonrenewable [MJ-eq], which consists of fossil, nuclear, and biomass from primary forests.

Ecological Scarcity

The Swiss ecological scarcity method allows the assessment of the impacts generated by release of pollutants and extraction of resources. Eco-points (UBP) per unit are the key parameter used by the method (Frischknecht et al. 2009).

Results

Table 11 shows all results that will be discussed in this chapter. The LCAs of all 13 asphalt mixtures with their two production options and four recycling scenarios brought in total 320 result values for the four different indicators. The evaluation of all asphalt results showed that there is hardly any difference for the results of the average recycling mixtures (AR) and the mixtures taking the production share of recycling asphalt into account (PSR). Therefore, Table 11 shows averaged results for AR and PSR mixtures. Furthermore, the results for the two high-modulus road base mixtures (RB5, RB5) as well as for the AC T 22 H, N, and S mixtures (RB1, 2, 3) are almost identical. Thus, for Table 11 these mixtures were combined to AC EME (RBI) and AC T (RBII). Results for concrete mixtures using CEM II/A-LL (C2) and CEM II/A-S (C3) were combined to C2-3. For some indicators the impact does not change with the share of recycling aggregates and for other indicators the impact decreases linearly with the rise of the recycling percentage. Therefore, Table 11 shows results for the recycling shares R0, R50, and R100.

Results: Asphalt

Table 11 demonstrates that for wearing course (WC) layers the material options have the biggest influence on the results of the nonrenewable cumulative energy demand with a 4% lower impact for the WC4-SP than for the WC1-SP mixture. The optimized production (OP) lowers the global warming potential by 17% for all four analyzed material options (WC1-4).

Concerning mixtures for base course (BC) layers, Table 11 shows the high reuse rate of RAP for base course mixtures in Switzerland because of the small difference between the impacts of the PSR mixture and the MR mixture. The application of the PSR and the MR mixture has the biggest influence concerning the CED nonrenewable indicator with impacts lowered by up to 28% for the BC1-SP-PSR and 40% for the BC1-SP-MR mixture in comparison to the BC1-SP-NR mixture. The production of BC2 mixture causes lower impacts (in a range of 3 to 15% less) regarding all analyzed indicators, recycling, and production scenarios than the production of BC1 because of its lower bitumen and sand content. OP conditions reduce the GWP of the BC2-OP-MR mixture by 23% in comparison to the BC2-SP-MR. The comparison of the current status production (SP-NR) with the best case production (OP-MR) shows for the RB2 mixture a reduction of 37% for the GWP indicator, 42% for CED nonrenewable indicator and 37% for ecological scarcity method.

Table 11 demonstrates the small difference of the PSR mixtures and the NR mixture for road base (RB) layers, which shows the low reuse rate of RAP for these mixture types. The PSR and the MR mixtures reduce the impact concerning the CED nonrenewable indicator by 21% for the RBII-SP-PSR and 64% for the RBII-SP-MR mixture in comparison to the RBII-SP-NR mixture. The production of RBII mixtures generally causes lower impacts on all analyzed indicators than the production of RBI mixtures (i.e., between 3 and 54% less) because of higher bitumen content of the RBI mixtures. OP conditions have a high influence on the GWP of both material options because of the lower energy consumption. For example, the global warming potential of the RBII-OP-MR mixture is reduced by 29% in comparison to the RBII-SP-MR mixture. The evaluation of the current status production (SP-NR) and the best case production (OP-MR) demonstrates for the RBII mixture a reduction of 52% for the GWP indicator, 72% for CED nonrenewable indicator and 62% for ecological scarcity method.

The results in Table 11 show that the impacts of the ASB1 mixtures are lower than those of the ASB2 mixtures, which is because of a higher production share of recycling in ASB1-PSR mixtures. The application of the PSR and the MR mixture has the biggest influence concerning the CED nonrenewable indicator with impacts lowered by up to 38% for the ASB1-SP-PSR and 74% for the ASB1-SP-MR mixture in comparison to the ASB1-SP-NR mixture. Except for the PSR mixtures, there is hardly any difference between the impacts of the similar production and recycling scenarios for the ASB1 and the ASB2 mixtures. The alternative production has high effects on the global warming potential. The GWP of the ASB2-OP-MR mixture is reduced by 32% in comparison to the ASB2-SP-MR mixture. The comparison of the current status production (SP-NR) with the best case production (OP-MR) shows for the ASB2 mixture a reduction of 56% for the GWP indicator, 81% for CED nonrenewable indicator and 71% for ecological scarcity method.

Results: Concrete

Table 11 demonstrates that use of the alternative cement types lowers the impact concerning all analyzed indicators for all mixture types. The use of CEM II/B-T (C4) decreases the impacts of all mixtures for all indicators within a range of 15 and 25%. Table 11 also shows that the two recycling bottom concrete mixtures (R50 and R100) have higher or equal impacts, except for the ecological scarcity indicator, in comparison to the primary bottom concrete mixtures (R0). The higher cement content of the recycling mixtures causes this increased impact. For example, the GWP rises by 8% for the R50 mixture and 7% for the R100 mixture using C1. The impact concerning the CED nonrenewable indicator increases by 4% for the C1-R50 mixture and by 1% for the C1-R100 mixture. Exposed aggregate concretes EAC-R0 cause higher impacts concerning all analyzed indicators in comparison to BC-R0 mixtures, in the range of 13 to 23% because of their higher cement content. The comparison of the current status production (C1-R0) with the best practice production (C4-R100) shows for the BC mixture a reduction of 19% for the GWP indicator, 15% for CED nonrenewable indicator, and 38% for ecological scarcity method. Regarding EAC mixtures, the impact is lowered by 25% for the global warming potential indicator, by 15% for the nonrenewable cumulative energy demand, and by 17% for the ecological scarcity method, if best case production (C4-R0) is applied instead of current status production.

Table 11. Results

Asphalt mixtures

Layer	Wearing courses (WC)							
Material option	AC 8 S (WC1)		AC 8 H (WC2)		AC MR 8 (WC3)		AC MR8 ASTRA (WC4)	
Production option	SP	OP	SP	OP	SP	OP	SP	OP
Recycling scenario	NR	NR	NR	NR	NR	NR	NR	NR
Ipcc gwp 100a kg (kg CO_2-eq/m^3)	201	167	201	167	199	165	195	162
Ced nonrenewable (MJ-eq/m^3)	9,363	8,831	9,329	8,793	9,156	8,626	8,955	8,435
Ecological scarcity (1,000 Pt/m^3)	253	236	254	236	252	234	246	229

Layer	Base courses (BC)											
Material option	AC B 16 S (BC1)						AC B 22 H (BC2)					
Production option	SP			OP			SP			OP		
Recycling scenario	NR	PSR	MR	NR	PSR	MR	NR	PSR	MR	NR	PSR	MR
Ipcc gwp 100a kg (kg CO_2-eq/m^3)	197	167	153	162	133	119	180	160	148	146	125	114
Ced nonrenewable (MJ-eq/m^3)	8,840	6,372	5,271	8,294	5,826	4,725	7,481	5,782	4,863	6,934	5,235	4,316
Ecological scarcity (1,000 Pt/m^3)	251	194	171	233	176	153	234	189	166	216	171	148

Layer	Road bases (RB)											
Material option	AC EME (RBI)						AC T (RBII)					
Production option	SP			OP			SP			OP		
Recycling scenario	NR	PSR	MR	NR	PSR	MR	NR	PSR	MR	NR	PSR	MR
Ipcc gwp 100a kg (kg CO_2-eq/m^3)	189	181	151	155	147	117	181	162	122	147	127	87
Ced nonrenewable (MJ-eq/m^3)	8,235	7,576	5,130	7,693	7,034	4,589	7,491	5,905	2,666	6,942	5,355	2,116
Ecological scarcity (1,000 Pt/m^3)	243	227	169	225	209	151	235	193	107	217	175	89

Layer	Asphalt subbases (ASB)											
Material option	AC F 22 (ASB1)						AC F 32 (ASB2)					
Production option	SP			OP			SP			OP		
Recycling scenario	NR	PSR	MR	NR	PSR	MR	NR	PSR	MR	NR	PSR	MR
Ipcc gwp 100a kg (kg CO_2-eq/m^3)	174	141	110	139	107	76	171	154	110	137	120	75
Ced nonrenewable (MJ-eq/m^3)	6,937	4,291	1,805	6,393	3,747	1,261	6,739	5,380	1,801	6,195	4,836	1,256
Ecological scarcity (1,000 Pt/m^3)	227	153	84	209	135	66	224	184	83	206	166	65

Concrete mixtures

Layer	Bottom concrete (BOC)									EAC		
Recycling scenario	R0			R50			R100			R0		
Cement type	C1	C2-3	C4	C1	C2-3	C4	C1	C2-3	C4	C1	C2-3	C4
Ipcc gwp 100a kg (kg CO_2-eq/m^3)	308	274	233	333	295	250	330	293	248	375	333	283
Ced nonrenewable (MJ-eq/m^3)	1,734	1,614	1,479	1,800	1,669	1,522	1,749	1,618	1,471	2,124	1,977	1,812
Ecological scarcity (1,000 Pt/m^3)	252	234	212	234	214	190	201	181	157	289	266	239

Other subbase mixtures

Material option	Bituminous bound subbase (BSB)						Hydraulically bound subbase (HSB)						Gravel (USB)	
Production option	at plant (CP)		at site (CS)		In-situ (IS)		at plant (CP)		at site (CS)		In-situ (IS)		at mine	
Recycling scenario	PM	SM	PM	SM	PM	SM	PM	SM	PM	SM	PM	SM	Crushed	Round
IPCC gwp 100a kg (kg CO_2-eq/m^3)	106	101	82	77	70	65	75	70	67	62	64	58	8	4
CED nonrenewable (MJ-eq/m^3)	5,064	4,944	4,641	4,511	4,448	4,328	599	476	474	352	420	298	216	96
Ecological scarcity (1,000 Pt/m^3)	179	116	152	88	138	75	114	49	105	39	100	35	68	62

Results: Other Subbases

The use of recycling materials lowers the impacts of all bound mixtures for all analyzed indicators within a range of 2 to 63% in comparison to mixtures using primary aggregates. For example, the GWP of the hydraulic mixture produced at the plant is reduced by 7% and the impact concerning CED nonrenewable is reduced by 21%. Table 11 shows that hydraulically stabilized mixtures generally have lower impacts concerning all analyzed indicators than bituminous stabilized mixtures i.e., between 9 and 93%. The fact that the bituminous mixtures contain a bituminous binder and cement causes its high impacts. The nonrenewable cumulative energy demand for a hydraulic mixture produced in a mobile mixing plant on-site containing primary material is 92% lower than for a bituminous mixture produced under the same conditions. The production scenarios on-site (CS) and in situ generally cause lower impacts than the central production at plant within the range of 8 and 64%. Unbound subbases containing round or crushed gravel have the lowest impacts per cubic meter.

Sensitivity Analysis

With the objective to reduce the amount of different material and production variants, a sensitivity analysis was carried out for representative road materials before the overall analysis. For example, concerning the asphalt production, the influence of the amount of limestone filler was determined as insignificant, so the 50-50 approach (i.e., 50% limestone and 50% self-generated filler) was applied. This analysis also showed the high recycling production share of Swiss asphalt producers because of the impacts of the AR asphalt mixtures and the PSR asphalt mixtures are nearly equal. The survey of the concrete results demonstrated that, for some indicators, the impact does not change with the share of recycling aggregates, and that for other indicators, the impact decreases linearly with the rise of the recycling percentage. Therefore, the mixtures using a share of 25 and 75% of recycled aggregates were excluded. Thus, finally the study focused on mixture and production variants with significant deviations.

Monte Carlo Simulation

In order to verify the reliability of the results in Table 11, Monte Carlo simulations for best case and current status production setups for asphalt, concrete, and SB mixtures have been performed. A Monte Carlo simulation takes a random value within the uncertainty range specified for every inventory entry. For each mixture comparison 1,000 Monte Carlo runs are calculated to form an adequate uncertainty distribution. Fig. 2 shows the probability that the environmental impacts of the best practice production setup is higher or lower compared to the current status production setup for the GWP, the CED nonrenewable, and the ecological scarcity indicator. For all material types except for the asphalt WC mixtures, the results regarding all three demonstrated indicators are stable, as shown by the fact that the highest possibility that the impact of the current status production is lower at 18.5% for the CED nonrenewable indicator of the asphalt BC mixtures. The fact that there is no recycling applied for the production of asphalt WC causes only small differences between the best practice and current status production for wearing courses and therefore causes a high instability in between those two mixtures. The possibility that the impact regarding the ecological scarcity indicator of the best practice asphalt WC production is lower than the impacts of the current status production is 44%.

Discussion and Conclusions

The study analyzed different production scenarios for the production of asphalt, concrete, and SB from an environmental perspective. The results showed that the application of recovered materials instead of primary resources mostly lowered the environmental impacts in the production of all three kinds of road construction materials. The analysis also clearly identified that this is not the case when recycling bottom concretes substitute primary resources, as an increased recycling material content also increases the cement requirement in the concrete pavement. For bottom concretes, a higher recycling share leads to a lower ecological scarcity score, but an increased global warming potential and a higher nonrenewable energy use.

The data used for this paper are representative for the situation in Switzerland due to the fact that the study is based on ecoinvent data for Switzerland, representative surveys concerning the asphalt and stabilized mixture production in Switzerland, recent data from the Association of the Swiss Cement Industry, and current Swiss as well as European standards. However, more detailed information would be preferable for bitumen production, as the available data only allowed for the modeling of one type, while in reality different types of bitumen are used.

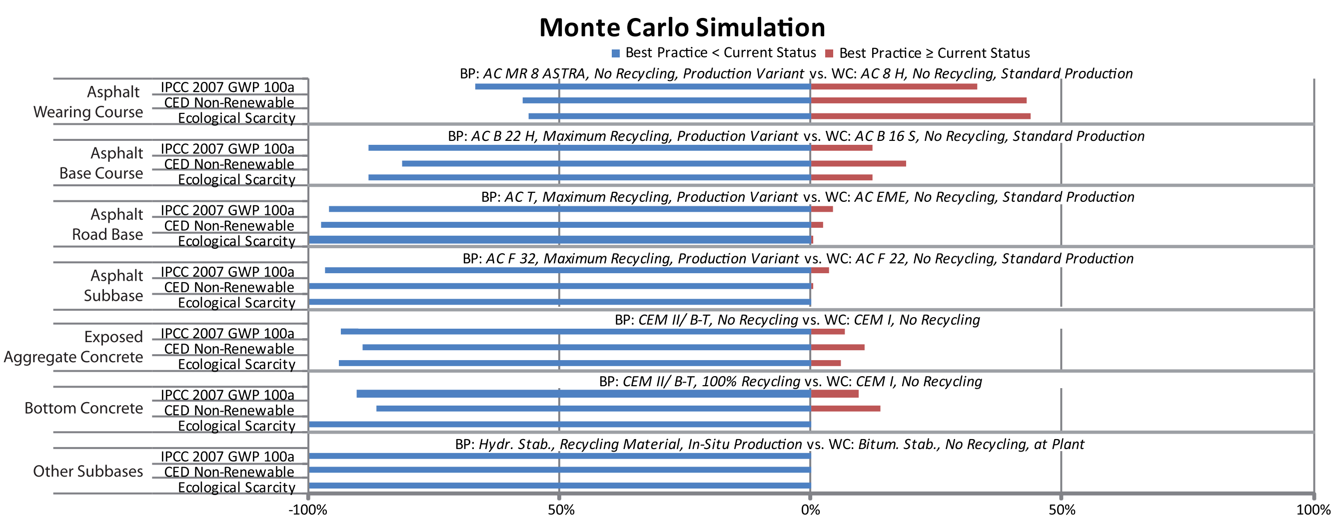

Fig. 2. Results of Monte Carlo simulation

This study assesses and compares different production options for asphalt, concrete, and SBs, but does not compare these material types to each other. A full comparison of different road construction materials needs to take into account the whole life cycle of the road, including road construction and maintenance, as the materials may substantially influence the construction process and the lifetime of a road (i.e., the time span until maintenance is required). For such comparative studies, further research on the influence of construction materials on the construction and maintenance phases of roads is required.

Because of the fact that the study does not compare asphalt with concrete, it is evident that in the next steps, the analyzed production processes are combined concerning the amount of road materials needed for representative Swiss road pavements in order to identify the differences between pavements using concrete or asphalt as a paving material (Gschösser et al. 2011).

Acknowledgment

This work was supported by the Swiss Bituminous Mixture Industry and Association of the Swiss Cement Industry. We would like to thank all 15 members of the expert group guiding this research project for their support and their inputs. Furthermore, we would like to thank Prof. Dr. Stefanie Hellweg and her team from the Institute of Environmental Engineering at ETH Zurich for the very valuable discussions.

References

ASTRA. (2007). *Merkblatt Oberbau*, Swiss Federal Road Office ASTRA Ed., Swiss Confederation, Bern, Switzerland.

Bilgeri, P., Eickschen, E., Felsch, K., Klau, S., Vogel, P., and Rendchen, K. (2007). "Verwendung von CEM II- und CEM III-Zementen in Fahrbahnbetondecken: Erfahrungsbericht [Use of CEM II and CEM III cements in concrete road pavements: Experience report]." *Strasse und Autobahn*, 58(2), 61–68 (in German).

Birgisdóttir, H. (2005). "Life cycle assessment model for road construction and use of residues from waste incineration." Ph.D. dissertation, Technical Univ. of Denmark, Lyngby, Denmark.

Boesch, M., Koehler, A., and Hellweg, S. (2009). "Model for cradle-to-gate life cycle assessment of clinker production." *Environ. Sci. Technol.*, 43(19), 7578–7583.

Boustead, I., and Hancock, G. F. (1979). *Handbook of industrial energy analysis*, Ellis Horwood Ltd., Chichester, England.

Canton Aargau. (2008). *Belagsaufbau auf Fundationsschicht—Ungebundene Gemische*, Civil Engineering Office—Canton Aargau Ed., Canton Aargau, Aarau, Switzerland.

Canton Zurich. (2008). *Dimensionierung Strassenoberbau*, Civil Engineering Office—Canton Zurich Ed., Canton Zurich, Zurich, Switzerland.

Cass, D., and Mukherjee, A. (2010). "Calculation of greenhouse gas emissions associated with highway construction projects using an integrated life cycle assessment approach." *Proc., Construction Research Congress 2010: Innovation for Reshaping Construction Practice*, ASCE, Reston, VA.

Cemsuisse. (2008). *Kennzahlen 2008*, Bern, Switzerland.

Ecoinvent Center. (2010). *Ecoinvent database v2.2*, Swiss Center for life cycle assessment, Dübendorf, Switzerland. ⟨www.ecoinvent.com⟩ (July 10, 2010).

EN. (2000). "Cement: Part 1—Compositions, specifications and conformity criteria for common cements." *European Committee for Standardization (EN), Schweizerischer Ingenieur- und Architektenverein (SIA)*, Schweizer Norm (SN), Zurich, Switzerland.

Forster, P., et al. (2007). *Changes in atmospheric constituents and in radiative forcing*, Cambridge University Press, Cambridge, U.K.

Frischknecht, R., Steiner, R., and Jungbluth, N. (2009). *The ecological scarcity method—Eco-factors 2006*, Federal Office for the Environment—Environmental Studies Ed., Bern, Switzerland.

Gambatese, J. A., and Rajendran, S. (2005). "Sustainable roadway construction: Energy consumption and material waste generation of roadways." *Proc., Construction Research Congress 2005*, ASCE, Reston, VA.

German Cement Works Association. (2007). "Verminderung der CO2-Emissionen: Beitrag der deutschen Zementindustrie." VdZ, Düsseldorf, Germany.

Gschösser, F., Wallbaum, H., and Boesch, M. E. (2011). "Hidden ecological potentials in the production of materials for swiss road pavements." *J. Manage. Eng.*, 10.1061/(ASCE)ME.1943-5479.0000077 (June 10, 2011).

Holcim Schweiz AG. (2008). *Betonstrassenpraxis: Der Leitfaden für den Betondeckenbau*, Holcim Schweiz AG, Zurich (in German).

ISO, EN, and DIN. (2006). "DIN EN ISO 14040:2006—Environmental management—Life cycle assessment—Principles and framework." *International Standard Office*, Berlin.

Jenny, R. (2009). "CO2-Reduktion bei der asphalt-Produktion [CO2 reduction within asphalt production]." *GESTRATA Journal—Das Asphaltmagatin*, 2009(126), 10–18 (in German).

KAMPAG. (2010). "Baustoffgerechtes Recycling von Ausbauasphalt [Suitable recycling of reclaimed asphalt." KAMPAG, Müllingen, Germany (in German).

Mroueh, U.-M., Eskola, P., Laine-Ylijoki, J., and Wellman, K. (2000). "Life cycle assessment of road construction." Finnish National Road Administration, Helsinki, Finland.

Muench, S. T. (2010). "Roadway construction sustainability impacts—Review of life-cycle assessments." *J. Transp. Res. Board*, 2151(05), 36–45.

Rajendran, S., and Gambatese, J. A. (2007). "Solid waste generation in asphalt and reinforced concrete roadway life cycles." *J. Infrastruct. Syst.*, 13(2), 88–96.

Stripple, H. (2001). "Life cyle assessment of road." Swedish Environmental Research Institute, Gothenburg, Sweden.

VSS. (1998). "Recycling; Allgemeines [Recycling; General]." *Schweizerischer Verband der Strassen- und Verkehrsfachleute—Schweizer Norm (SN)*, Zürich.

VSS. (2008a). "Asphaltmischgut: Mischgutanforderungen—Teil 1: Asphaltbeton [Bituminous mixtures: Material specifications—Part 1: Asphalt concrete]." *Schweizerischer Verband der Strassen- und Verkehrsfachleute—Schweizer Norm (SN)*, Zürich, Switzerland (in German).

VSS. (2008b). "Walzasphalt [Rolled asphalt]." *Schweizerischer Verband der Strassen- und Verkehrsfachleute—Schweizer Norm (SN)*, Zürich, Switzerland.

Wilk, W., Tsohos, G., and Werner, R. (1994). "Neue Betondecken uas Betonrecyclingmaterial [New concrete pavements applying recycled concrete material]." *Eidgenössisches Verkehrs- und Energiewirtschaftsdepartement*, Bundesamt für Strassen, Zürich, Switzerland (in German).

Wirtgen Group. (2009). "Technical specification—Recycler WR 2500S." Winghagen, Germany.

Zapata, P., and Gambatese, J. A. (2005). "Energy consumption of asphalt and reinforced concrete pavement materials and construction." *J. Infrastruct. Syst.*, 11(1), 9–20.

Zhang, H., Keoleian, G. A., Lepech, M. D., and Kendall, A. (2010). "Life cycle optimization of pavement overlay systems." *J. Infrastruct. Syst.*, 16(4), 310–322.

Zhang, H., Lepech, M. D., Keoleian, G. A., Qian, S., and Li, V. C. (2009). "Dynamic life cycle modeling of pavement overlay systems: Capturing the impacts of users, construction, and roadway deterioration." *J. Infrastruct. Syst.*, 16(4), 299–309.