ACTA TECHNICA JAURINENSIS
Vol. 17, No. 3, pp. 118-129, 2024
10.14513/actatechjaur.00749

Research Article

Reducing Energy Demand in Concrete Pavements by the Use of Blended Cements

Réka Szpotowicz[1] and Csaba Tóth[1,*]

[1] Department of Highway and Railway Engineering, Budapest University of Technology and Economics,
Műegyetem rkp. 3., K épület magasföldszint 98., 1111 Budapest, Hungary
*e-mail: toth.csaba@emk.bme.hu

Submitted: 22/08/2024 *Accepted: 26/08/2024* *Published online: 28/08/2024*

Abstract: This research explores strategies to minimise energy consumption and enhance environmental sustainability in road construction. Focusing on concrete pavement structures, the study evaluates the impact of substituting Portland cement with environmentally friendly alternatives such as fly ash and blast furnace slag. A comprehensive model is employed to analyse the energy demands of different pavement types, considering various cement replacements over their lifetime, from the initial extraction of materials to the conclusion of construction. Results indicate an energy saving potential of 8.63% by substituting 10% of Portland cement with fly ash, while an impressive reduction of 58.63% in cement production energy is achieved by replacing Portland cement with 80% blast furnace slag. The study underscores the significant role of cement variations in mitigating energy consumption, emphasizes the potential of blast furnace slag as a sustainable alternative as well as highlights the significance of alternative cement types in reducing energy consumption in concrete pavement construction, aligning with environmental sustainability goals and offering insights for more eco-friendly infrastructure development.

Keywords: Sustainability;Blended cements; Concrete structures; Energy; Reduction of energy consumption

I. INTRODUCTION

The energy and climate crises call for urgent action by decision-makers, road project investors, and others. The European Parliament and the Council made significant strides toward achieving carbon neutrality in Europe by ratifying the Climate Change Act in 2021, elevating the EU's interim emissions reduction target for 2030 from 40% to a minimum of 55%. "Fit for 55" includes emissions regulations and decarbonisation efforts in various sectors, including road management, targeting the concrete and asphalt industries to reduce emissions and energy consumption.

AzariJafari et al. [1] found that achieving carbon-neutral pavements by 2050 is only feasible with policy and industry interventions. Without decarbonization efforts, US road construction material emissions could increase by 19.5% by 2050. Transitioning to renewable energy sources for road materials is crucial for meeting decarbonization goals.

Understanding the anticipated energy demand throughout each infrastructure layer's production, construction, and operational phases is vital for making informed construction and renewal decisions. Implementing an efficient management system, as proposed by Volkov et al. [2], could further optimize the energy demand in concrete pavement projects by streamlining resource allocation and operational processes. Concrete pavements offer greenhouse gas savings and longevity, reducing maintenance and improving fuel efficiency. They also have a cooling effect and contribute to carbon dioxide removal [3]. A previous study conducted in Hungary investigated the energy consumption of various construction processes [4]. The findings revealed that concrete pavements had, on average, 60% higher energy demand than asphalt structures in the examined pavement types. This notable disparity predominantly stemmed from utilizing high-energy-demand Portland cement (CEM I). In this article, we extend this research by exploring the potential reduction in the modelled energy demand of these Hungarian concrete pavements by adopting environmentally friendly cement types.

II. Strategies to Reduce Energy Demand in Cement Production

According to CEMBRUREU (The European Cement Association), the total cement production for 2020 reached 4.17 billion tonnes.

The breakdown is as follows [5] (Mt means a million tonnes):

- China: 2377 Mt;
- India: 290 Mt;
- EU27: 171.5 Mt;
- USA: 89 Mt.

The carbon dioxide emissions averaged 783 kg CO_2/tonne of cement in 1990. The Association aims to cut CO_2 emissions from cement production to 472 kg CO_2/tonne by 2030 and achieve carbon neutrality by 2050, which aligns with the Paris Agreement. The report outlines the potential for reducing CO_2 emissions during clinker, cement, concrete production, construction, and (re)carbonation. Implementing the following measures plays a significant role in achieving emission reductions: technological investments, policy adjustments, and production changes throughout the life cycle, spanning from production and clinker production to concrete recarbonation and recycling [6-11]. For instance:

- incorporating alternative fuels like non-recyclable waste and biomass-derived sources to substitute fossil fuels;
- implementing more energy-efficient furnaces;
- advancing the utilization of innovative, low-clinker concrete;
- introducing and enhancing carbon capture and storage/utilization technologies (CCUS);
- Optimization of concrete blends and construction methodologies leveraging concrete's potential to capture carbon and reduce production emissions by up to 23%.

Highlighting the potential to decrease energy demand through mechanical engineering solutions and adopting alternative energy sources, coupled with the considerable capacity of concrete surfaces for CO_2 absorption, it is worthwhile to concentrate on optimizing the clinker-cement ratio for road concretes.

In Europe, 44% of cement production comprises Portland cement composite, with blast furnace and pozzolanic cement contributing 12%. The estimated thermal energy savings and emission reductions achieved through blended cement range from 0.009 to 1.4 GJ per ton and 0.3 to 213.54 kg CO_2 per ton, respectively [6].

In the publication [12], a study was carried out on the lifecycle greenhouse gas emissions associated with different cement mixes, considering factors such as carbonation and durability. Their analysis involved the addition of blast furnace slag and fly ash to clinker, revealing that more substantial reductions in emissions were attainable with blast furnace slag. This is primarily because the proportion of Portland cement replaceable by fly ash is lower than that of blast furnace slag replaceable by fly ash. The most significant impact was observed with an 80% substitution of blast furnace slag, resulting in a remarkable 70% reduction in production stage emissions. Meanwhile, fly ash mixtures achieved a 36% reduction compared to Portland cement when replacing 35% of the clinker. Comparing cement with equal substitution amounts for both blast furnace slag and fly ash indicated that fly ash usage is more environmentally favourable. Fly ash involves fewer downstream processes (e.g., grinding) compared to blast furnace slag, resulting in lower emissions. However, it is essential to note that the article calculated considerably longer transport distances for blast furnace slag (1640 km) in contrast to fly ash (180 km).

Karadumpa and Pancharathi [13] present the energy consumption of different types of cement in five different manufacturing plants in India. It is shown that the 15% fly ash (FA) content in the Portland cement leads to an average 14,69% lower energy consumption than the reference Portland cement (OPC). In the case of the highest examined granulated blast furnace slag (GBFS) content studied (45%), the average energy reduction was 35,29%. The study also examines the composite cements' energy reduction, combining 20% or 25% FA with 20%, 30%, or 35% GBFS content. The highest energy reduction was obtained with 45% OPC+20%FA+35%GBFS with an average of 47%.

Anastasiou et al. [14] investigated the environmental impact of concrete pavements in Greece, incorporating fly ash and slag across six variants. The energy input per kg to produce the clinker, cement, limestone, fly ash, steel slag, and concrete was presented in the paper, where the data was collected from the relevant industries in the region of Northern Greece. Results show significant CO_2 emission reduction compared to standard concrete pavements, with fly ash substitution remaining beneficial even over long distances.

The study by [15] analyses 20 papers (2017-2022) on blast furnace slag as cement replacement in pavements. The article provides a useful overview of the values of the physical properties of OPC, GBFS, and BFS, such as specific gravity, surface area and loss on ignition, and the chemical composition of the materials. It gives a summary of the results of the different replacement methods based on the papers analysed. They found that 50-70% substitution was satisfactory, with 60% being the most common. Only 7 papers addressed cost and eco-efficiency, suggesting that 60% GGBFS replacement could reduce embodied energy by 37% and CO_2 emissions by 48% compared to control measures.

In Germany, the average clinker-cement ratio was approximately 71% in 2017, indicating that, on average, cement production comprised 71% clinker. Substituting clinker with alternative primary components like granulated blast furnace slag (from the steel industry) or fly ash (from energy/conversion sources) within the clinker rotary kiln process leads to fuel conservation required for clinker production [16]. This results in an environmentally and energy resource-conscious solution, aiding the concrete industry in striving toward its objectives of achieving carbon neutrality, energy efficiency, and cost-effectiveness. (Kurhan [17] demonstrated that entropy-based simulation techniques could effectively model the stability of railway ballast, and similar methodologies could be explored to assess the energy dynamics within concrete pavement layers.)

The German Cement Works Association demonstrates in its publication [18] the impact of increasing blast furnace slag content on CO_2 emissions in cement production. **Fig. 1.** illustrates this impact, indicating that while emissions for CEM I (Portland cement) are estimated to be around 0.9 CO_2/t of cement, emissions for CEMIII/B (blast furnace slag cement), the emissions of CEMIII/B (blast furnace slag cement), which contains 80% blast furnace slag and is the maximum permissible level according to the Hungarian standard e-UT 06.03.37 [19], are below 0.3 CO_2/t of cement. The figure also depicts that the electrical energy demand remains relatively constant with increased blast furnace slag content, attributed to the 'savings' from reducing clinker burning and substituting primary raw materials.

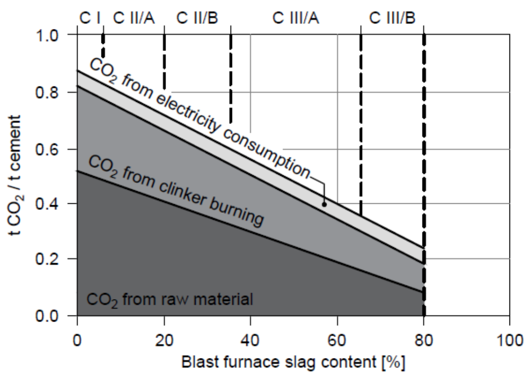

Figure 1. *Comparison of CO_2 emissions from the production of blast furnace slag cement and Portland cement, VDZ [17]*

Both fly ash and blast furnace slag additive cements are accessible in Hungary, and their impact on concrete is widely recognized. The types of cement admixtures utilized in Hungarian cement production include:

- fly ash – Nyitranovák (SK), Visonta, Oroszlány;
- blast furnace slag – Kassa (SK), Dunaújváros.

The upcoming paragraph III.1 outlines the alternative cement variations approved by the Hungarian Standards for constructing concrete road structures.

III. Varieties of cement for concrete pavements in Hungary

Clause 8.2.1 of the relevant Hungarian specification 'Design and Construction of Concrete and Composite Pavements' (e-UT 06.03.37:2021, [19]), stipulates the selection of cement type aligned with Hungarian Standard MSZ 4798 [20] and corresponding to the specified concrete types. According to the specification and MSZ EN 197-1 [21], the permitted cements applicable for concrete pavements include:

- portland cement: CEM I 42.5; CEM I 32.5 and CEM I 32.5N LH;
- blast furnace slag - Portland cement: CEM II/A-S 42.5; CEM II/A-S 32.5; CEM II/B-S 42.5 and CEM/II B-S;
- fly ash - Portland cement: CEM II/A-V 42.5 and CEM II/A-V 32.5;
- blast furnace slag cement: CEM III/A 32.5 N-M-SR, CEM III/A 32.5 R-M-SR and CEM III/B 32.5 N-SR.

The third element within these symbols (A, B) denotes the proportions of the mixture's components, which include:

- CEM II "A" 6-20%;
- CEM II "B" 21-35%;
- CEM III "A" 36-65%;
- CEM III "B" 66-80%.

Nevertheless, the regulation also specifies that the blending material content in fly ash Portland cement (CEM II/A-V) should not surpass 10 percent of the cement mass. While there are no further specifications in the standard, blast furnace slag Portland cement (composite Portland cement) permits up to a 35% replacement. In the case of blast furnace slag cement (CEM III/B), this replacement rate can reach up to 80%. Typically, manufacturers anticipate a blast furnace slag content of around 75% for CEM III/B, utilizing the standard's allowance of 5%t for other materials in the mixture.

However, it is essential to note that within exposure class XF4 (characterized by high water saturation and the requirement for ice melting agents or seawater), only blast furnace slag cement of type CEM III/A 42.5 N or CEM III/A 32.5 R, containing a blast furnace slag major constituent of less than 50% by weight, is permissible for use [22].

According to the German General Circular for Road Construction (Allgemeine Rundschreiben Strassenbau Deutschland, ARS 04 2022), the following cement types can be utilized, from those available as per DIN EN 197-1, for road paving, with the contractor's consent: CEM II/B-S, CEM II/A-T, CEM II/B-T, CEM II/A-LL, CEM III/A (with a maximum blast furnace slag content of 50% and a minimum strength class of 42.5 N) [3,23]. Considering the more advantageous availability of limestone in Hungary, it would be advisable to explore its potential use (CEM II/A-LL) in cement mixtures for concrete road pavement structures in Hungary.

IV. Energy demand of concrete pavements for complex Portland cement and blast furnace slag cement

Concrete production is a complex, energy-intensive process. **Fig. 2**. illustrates key aspects of the concrete life cycle. A comprehensive understanding of these processes can be found in the article titled 'Energy demand assessment of domestic pavement structures' [4]. The article gathered pertinent energy data from literature sources, such as [24-32], concerning raw material extraction, cement production, concrete mixing, and various raw material production. The average energy values derived from this data collection include:

- production of Portland cement: 6.04×10^9 [J/t];
- mining of additives: 41.67×10^6 [J/t];
- concrete plant and the mixing: 7.67×10^6 [J/t].

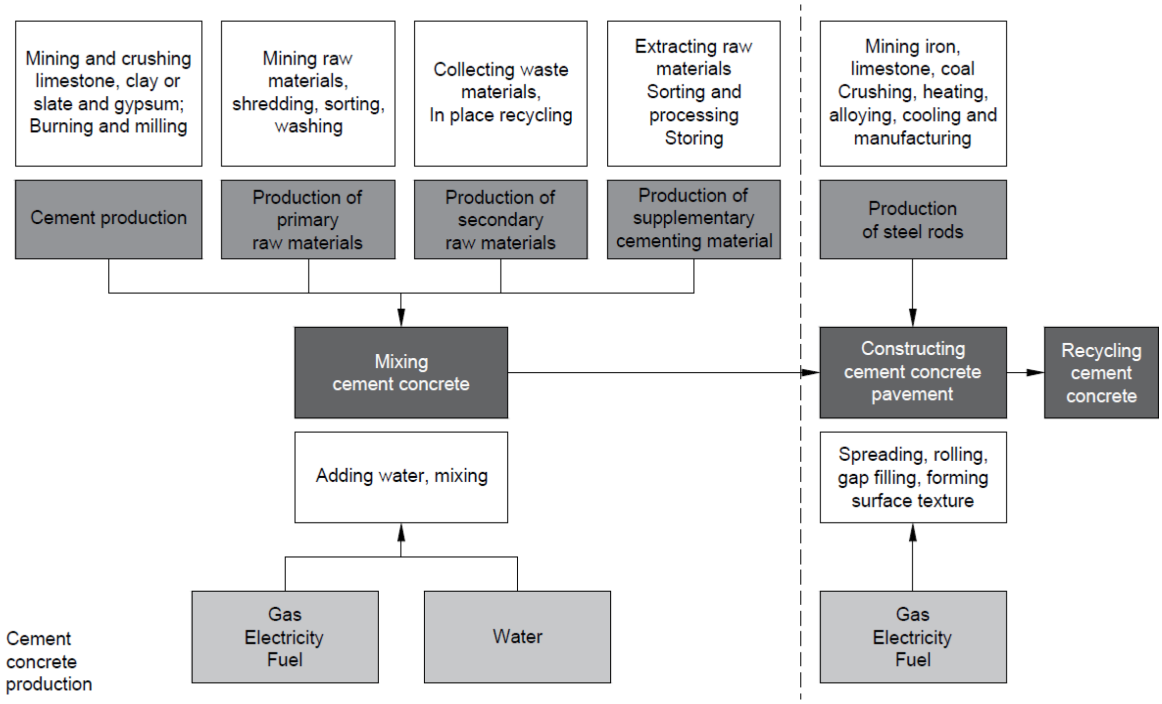

Figure 2. *Production of Concrete Mix and Life Cycle Components*

On the basis of the values provided, it is clear that the production of Portland cement requires the highest energy input (6.04×10^9 [J/t], which is significantly higher than the energy required for the production, i.e., the mixing of the concrete mixture (7.67×10^6 [J/t]).

Furthermore, the paper [4] compared the energy requirements between concrete pavements and asphalt pavements designed for the same traffic category. The findings reveal that, on average, concrete pavements exhibit a 60% higher energy demand, primarily attributed to cement production. However, it is essential to note that these results represent the specific energy demands observed in the case study, and variations in pavement structure combinations might yield slightly different outcomes.

The aim of the present paper is to recompute the calculations for fly ash Portland cement and blast furnace slag cement. The model assumes the maximum permissible content of blended material outlined in the standard [19]. The calculation does not account for the potential addition by the manufacturer of other materials up to 5% in addition to clinker, gypsum, and the specific additive being studied (blast furnace slag or fly ash). **Fig. 3**. illustrates a simplified depiction of the production process chain.

To ensure comparability of the obtained results, this article also adopts the energy demand of 6.04×10^9 [J/t] for Portland cement production. Based on the article by Huntzinger and Eatmon [33], the estimated energy demand for Portland cement production can be broken down as follows:

- raw material extraction: 5%;
- thermal energy demand: 70%;
- electric power: 25%.

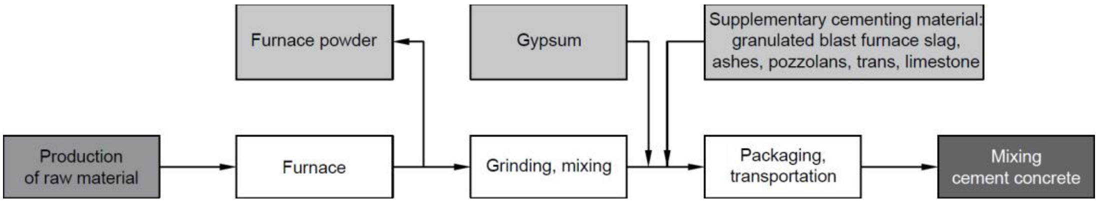

Figure 3. *Illustration of Cement Production Processes with blending material*

As the preceding literature cited in this article – i.e. [6,10,12,18] – has presented a range of electricity demand from 12% to 38% and thermal energy demand from 62% to 88%, this study adopts averages that align with the findings of Huntzinger and Eatmon [31]. Consequently, the estimated energy demand for cement production is applied as follows:

- Raw material extraction: 0.302×10^9 [J/t]
- Thermal energy demand: 4.228×10^9 [J/t]
- Electric power: 1.510×10^9 [J/t]

The incorporation of additives, such as fly ash and granulated blast furnace slag into clinker is evaluated based on these energy distributions.

1. Procedure for calculation and model's dimensions

The modelled 1 km hypothetical road segment near Budapest in this study adheres to Hungarian standards. It was specifically designed for the "extremely heavy" traffic load class, where the design traffic (TF) F100 surpasses 30,000,000 axle units. Considering the road class and environmental conditions, the designated speed was set at 110 km/h. The analysed cross-section involved a single traffic lane. As the primary focus of this article is to compare the energy demand of various concrete pavement structures, aspects unrelated to the different pavement designs, such as earthworks or road components like signs, pavement markings, safety elements, and barriers, were excluded from the calculations.

Dimension of the calculated section:

- traffic lane width: 3,75 m;
- number of traffic lanes: 1;
- section length: 1000 m.

The pavement structures have been designed in accordance with the Hungarian regulations of the Technical Specification for Hungarian Roads listed in this Section.

Based on the specified traffic category (extremely heavy), five distinct design alternatives for concrete pavement were examined. This is visually represented in **Fig.4**.

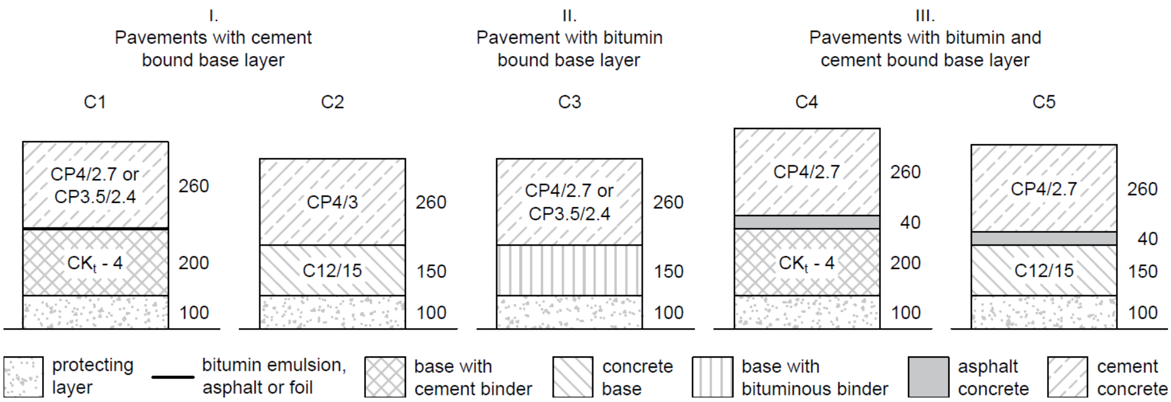

Figure 4. *Analysed variations of concrete pavement structures, where CP stands for pavement concrete, C for normal concrete and CKt-4 represents hydraulically bound concrete base layer in C4 quality class*

The transportation distance from the mixing plant to the construction site has been established at 50 km, employing heavy goods vehicles with a 32-tonne capacity. These vehicles will traverse the distance twice, once when fully loaded and once while empty.

According to Stripple's study [28], the diesel consumption of these vehicles is recorded at 0.47 l/km (full) and 0.29 l/km (empty), resulting in energy consumption under these conditions (full and empty) equating to 13.3 MJ/km.

The quantity of load-bearing reinforcement for the concrete pavement remains consistent with the previous article [4], determined in accordance with the applied Hungarian standard specification [19]. Considering the surface area of the section, which measures 3750 m², the calculation indicates that this section necessitates 29,250 kg of reinforcing steel.

Based on the cross-sectional and thickness data, it can also be determined that the section under investigation contains 154 transverse joints. To fill these voids, the article considers employing bitumen-based filling material complying with relevant Hungarian specification e-UT 05.02.42 for Joint Filling Materials of Road Pavements [34].

The mixture design employed for the computation aligns with e-UT 06.03.37:2021 Construction of Concrete Pavements: Specifications, Requirements [19]. Furthermore, the design of the base course aligns with specifications outlined in e-UT 06.03.32 "Concrete Subbases for Road Building: Requirements" [35], e-UT 06.03.33 "Concrete Base Course of Pavement Design Requirements" [36], and e-UT 06.03.53:2018 "Requirements of non-bonded and hydraulic bonded concrete base layers" [37].

2. Energy demand of concrete pavement structures utilizing 10% fly ash-Portland cement

According to Clause *8.2.1 Cement* of the specification [19], the article calculates with a maximum permissible fly ash content of 10% of CEM II/A-V fly ash Portland cement. This implies that 10% of the Portland cement clinker is substituted with fly ash. The benefit lies in regarding the production of fly ash as a secondary by-product, which is considered CO_2 emission neutral. Its utilization not only diminishes waste production but also conserves 10% of the substantial thermal energy demand incurred during clinker production. Nevertheless, it is vital to consider the energy demand associated with transporting the fly ash additive.

In the model, the estimated energy demand for cement production was calculated as follows:

- raw material extraction:
  0.302×10^9 [J/t] (PC) → 0.355×10^9 [J/t] (VPC);
- thermal energy demand:
  4.228×10^9 [J/t] (PC) → 3.805×10^9 [J/t] (VPC);
- electric power:
  1.510×10^9 [J/t] (PC) → 1.359×10^9 [J/t] (VPC).

Since the Hungarian fly ash sites (Oroszlány, Visonta, Nyitranovák) are situated at varying distances from Budapest (approximately 75 km, 90 km, 215 km), the article approximates an average distance of 100 km. The energy required for transportation is calculated at 13.3 MJ/km for 32-ton trucks, considering one full and one empty run, as per Stripple's research. Consequently, it results in an energy requirement of 2660 MJ for 32 tonnes, roughly equating to 0.083 [J/t]. It has been considered in the energy demand for raw material extraction. The quantity required for producing Portland cement has been adjusted by a 10% reduction to determine thermal and electrical energy demands. Optimization of logistics, such as early garbage collection schedules in urban environments, as studied by Saukenova et al. [38], could similarly be applied to transporting raw materials in road construction, reducing overall energy consumption. The multi-body simulation approach used by Benmeddah et al. [39] for modeling vehicle dynamics could also be adapted to simulate the energy demands of different pavement types, offering more precise predictions and optimizations. As comprehensive data regarding the distribution of grinding and mixing energies in the literature is scarce, further refinement of the model in this aspect may be beneficial.

The calculated energy demand for 10% fly ash Portland cement is roughly equal to **5.519×10^9 [J/t],** reflecting an energy saving of 8.63% in comparison to Portland cement (6.04×10^9 [J/t]).

When transitioning from Portland cement to fly ash Portland cement for C1-C5 pavement types, the energy demands presented in **Table 1.** can be attained.

Table 1. *Energy savings in cement production for C1-C5 pavement types using 10% fly asphalt-Portland cement (PC: Portland cement, VPC: fly ash Portland cement)*

Pavement structure	Cement quantity [kg]	Energy PC [MJ]	Energy VPC [MJ]	Energy savings [MJ]
C1	675 000.00	4 077 000.00	3 725 325.00	351 675.00
C2	615 937.50	3 720 262.50	3 399 359.06	320 903.44
C3	438 750.00	2 650 050.00	2 421 681.25	228 588.75
C4	675 000.00	4 077 000.00	3 725 325.00	351 675.00
C5	639 562.50	3 862 957.50	3 529 745.44	333 212.06

The values in **Table 1.** represent the life cycle stage of the investigated pavement types until cement production, where Portland cement was substituted by 10% fly ash in the model under investigation. The most substantial savings are notably observed in the C1 and C4 pavement types, which contain the highest cement content. In these cases, energy savings of up to 3.51×10^4 MJ can be attained.

Table 2 shows the change in energy demand for the entire model, from extraction of raw materials to construction of the road section, for a 10% fly ash substitution.

Table 2. *Total energy savings [%] for C1-C5 track structure types*

Pavement structure	**Energy PC [MJ]**	**Energy VPC [MJ]**	**%**
C1	4 915 169.99	4 563 494.99	**7.15**
C2	4 428 883.27	4 107 979.83	**7.25**
C3	3 802 448.60	3 573 858.85	**6.01**
C4	5 064 576.62	4 712 901.62	**6.94**
C5	4 741 580.90	4 408 363.83	**7.03**

The most significant energy savings are observed for the C2 pavement types (32.09×10^4[MJ]; 7.25%, followed by C1 and C5. This outcome aligns with expectations, as the C2 pavement types do not contain an asphalt layer. Thus, substituting cement clinker with fly ash can have a greater impact on the total energy demand than the other solutions.

3. Energy demand of concrete track structure with 80% granulated blast furnace slag cement

The literature indicates that while fly ash is considered more environmentally friendly than blast furnace slag due to requiring less additional processing (like grinding), resulting in lower emissions, granulated blast furnace slag can replace a higher percentage of clinker, as per regulations. This is attributed to its latent hydraulic properties, which enhance concrete's resistance to sulphate groundwater.

The paper employs the maximum permissible ratio of 80% slag to clinker for calculation purposes, which determines the estimated energy demand for cement production as follows:

- raw material extraction:
  0.302×10^9 [J/t] (PC) → 1.351×10^9 [J/t] (SC);
- thermal energy demand:
  4.228×10^9 [J/t] (PC) → 0.846×10^9 [J/t] (SC);
- electric power:
  1.510×10^9 [J/t] (PC) → 0.302×10^9 [J/t] (SC).

The article also assumes 100 km for transportation distance, accounting for the varying locations of Hungarian and nearby sites (Kassa, Dunaújváros) from Budapest (approximately 80 km, 265 km). Consequently, an energy value of 0.083×10^9 [J/t] has been considered in the model's energy demand calculation for raw material extraction.

Little information about the energy requirements for grinding granulated blast furnace slag is available. The distribution of energy requirements has been approximated based on the VDI publication (see **Fig. 1**). In the model, it is assumed that the grinding energy of blast furnace slag is equal to the grinding energy of clinker. Accordingly, the estimated value for blast furnace slag's energy demand during raw material extraction is 1.291 J/t. Adding this to the energy requirement for clinker raw material extraction results in a total of 1.351×10^9 J/t. To determine the thermal and electricity energy demand, the quantity required for the production of Portland cement has been considered and reduced by 80%. Given the scarcity of precise data on grinding and mixing energy distributions in the available literature, further refinement of the model regarding this aspect might also be beneficial.

The resulting energy demand for the 80% granulated blast furnace cement is 2.499×10^9 [J/t], which resulted in an energy saving of 58.63% compared to Portland cement (6.04×10^9 [J/t]).

By shifting from Portland cement to blast furnace cement for C1-C5 pavement types, the resulting energy savings are shown in **Table 3**.

Table 3. *Energy savings in cement production for C1-C5 pavement types by replacing 80% of Portland cement with granulated blast furnace slag (PC: Portland cement, SC: Blast furnace slag cement))*

Pavement structure	Cement quantity [kg]	Energy PC [MJ]	Energy SC [MJ]	Energy savings [MJ]
C1	675 000.00	4 077 000.00	3 725 325.00	351 675.00
C2	615 937.50	3 720 262.50	3 399 359.06	320 903.44
C3	438 750.00	2 650 050.00	2 421 681.25	228 588.75
C4	675 000.00	4 077 000.00	3 725 325.00	351 675.00
C5	639 562.50	3 862 957.50	3 529 745.44	333 212.06

The values in **Table 3** represent the life cycle stage of the studied road structure types up to cement production. Substituting Portland cement with 80% blast furnace slag, the most significant savings are noted in C1 and C4 pavement types, with higher cement content, yielding up to 23.90×10^4 MJ. Meanwhile, the highest energy requirement persists in the C4 pavement structure type.

Table 4 shows the change in energy demand for the whole model, from extracting raw materials to constructing the road section. The most significant energy savings are observed for the C2 pavement types (218.10×10^4[MJ]; 49.25%), followed by C1 and C5. This outcome aligns with expectations again since the C2 pavement structure type does not contain an asphalt layer. Therefore, substituting cement clinker with fly ash can have a greater impact on the total energy demand than the other solutions. Meanwhile, the highest energy requirement persists in the C4 pavement structure type.

Table 4. *Total energy savings [%] for C1-C5 track structure types*

Pavement structure	Energy-need PC [MJ]	Energy-need SC [MJ]	%
C1	4 915 169.99	2 524 994.99	**48.63**
C2	4 428 883.27	2 247 848.58	**49.25**
C3	3 802 448.60	2 248 833.85	**40.86**
C4	5 064 576.62	2 674 401.62	**47.19**
C5	4 741 580.90	2 476 890.08	**47.76**

V. Comparison of Energy Requirements of Asphalt and Concrete Pavements and Possibilities for Further Development of the Model

The comparison between concrete and asphalt pavements in terms of energy requirements is crucial for evaluating their sustainability and environmental impact. The paper aims to reassess the energy demand of concrete pavement structures on road section R classified under the "extremely heavy" traffic category, using CEM II/A-V and CEM III/B type cement [4]. Asphalt pavement structures used for comparison are shown in **Fig. 5**.

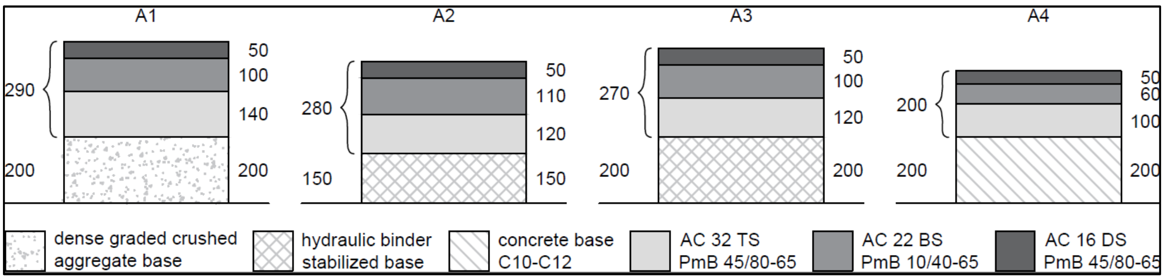

Figure 5. *Analysed variations of concrete pavement structures, where PmB means polymer-modified bitumen*

While the previous findings [4] suggest that concrete pavements using Portland cement (OPC) require approximately 60% more energy than asphalt pavements, the results presented in this article for concrete pavement structures are comparable to the energy requirements of asphalt pavements, as demonstrated in **Table 5.**

Table 5. *Load class R comparison of concrete and asphalt pavement structures applying blast furnace slag cement (SC, 80%)*

Pavement structure	**Energy-need SC Concrete [MJ]**	***Pavement structure***	**Energy-need HMA Asphalt [MJ]**
C1	2 524 995	A1	1 430 375
C2	2 247 849	A2	2 335 698
C3	2 248 834	A3	2 766 590
C4	2 674 402	A4	2 465 943
C5	2 476 890	-	

Looking at **Table 5**, several observations can be made. If we compare these values, we can see that the energy values of the concrete pavements (C1-C5) are similar to those of the asphalt pavements A2-A4, so the concrete pavements with 80% blast furnace slag cement are real competitors of the asphalt pavements in terms of lower energy consumption. Moreover, the results for concrete pavement types C2 and C3 are notably lower than asphalt pavement types A3 and A4. Despite this, it is crucial to note that asphalt pavement type A1 demands significantly (about 63%) less energy.

This finding underlines the importance of pavement design and the potential for optimising energy consumption in the construction of both concrete and asphalt pavements, as well as demonstrates that the negative climate impact of concrete pavements can be reduced using alternative cementitious by-product materials such as fly ash or slag. (As explored by Barać et al. [40], innovative educational platforms for clean production emphasize the importance of incorporating sustainability into engineering curricula, which could lead to more energy-efficient practices in concrete pavement construction.)

The differences presented in **Table 5** can be further nuanced by considering the whole life cycle, where the energy requirements for maintenance and renovation works are included in the model. Furthermore, expanding the model by introducing a cement variation that aligns with environmental class XF4 could be valuable. Additionally, considering the favourable availability of limestone in Hungary, exploring the domestic use of CEM II/A-LL in concrete pavement structures might prove worthwhile. The performance and mechanical properties of concrete pavements with such high levels of blended cements also will require investigation for long-term life cycle objectives.

To compare asphalt and concrete structures, it is also advised to extend the research to the whole life cycle, including the use phase and the end-of-life processes.

VI. Conclusions

The construction sector, known for its high energy demands and significant CO_2 emissions, notably contributes through cement production [41]. The Paris Agreement aims to limit global warming to 1.5-2.0 °C and achieve carbon neutrality by 2050. In order to achieve this, it is essential to reduce emissions and modernise industries such as construction. Blended cements such as fly ash and blast-furnace slag are used worldwide to replace cement in concrete mixes partially.

In Hungary, fly ash in Portland cement is limited to 10%, while blast-furnace slag cement allows up to 80% replacement of clinker. Calculated with these values, replacing 10% of Portland cement with fly ash in the model shows an energy saving of 8.63% in cement production. This substitution could potentially result in energy savings of up to 7.25% for the pavement structures studied from material extraction to the end of construction. Replacing Portland cement with 80% blast-furnace slag can reduce the energy required for cement production by 58.63%. This change could result in up to 49.25% energy savings for the road structures studied. The result is consistent with the existing literature presented in Section 2. Considering the study examines the highest possible fly ash and blast furnace content, a lower Portland cement replacement to maintain concrete performance in the design situation could still result in relevant costs, waste, natural resources, CO2 emissions, and energy savings.

Both fly ash and granulated blast furnace slag have been widely used in concrete production, but their use in pavements is limited [42,43]. However, even though their mechanical properties and performance have been successfully investigated in numerous publications, such as [44-51], there seems to be some doubt among designers and decision-makers about the use of this technology. After reviewing the literature, it also became clear that relatively few articles investigated the energy saving of blended cement concrete for pavements. One of the aims of this publication is to demonstrate the environmental benefits of using fly ash and blast furnace slag to promote their use in road construction. The results show that concrete can become an excellent alternative to asphalt pavements in environmental design decisions. As there are environmental, geographical, and regulatory (EU directives and regulations) similarities between Hungary and many European countries (such as Poland, Czech Republic, Slovakia, Germany etc.), the results of this study may be helpful for policymakers in many countries.

Author Contribution

R. Szpotowicz: Conceptualization, Modelling, Calculation, Writing and editing.

C. Tóth: Conceptualization, Supervision, Review.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

OrcID

Réka Szpotowicz: http://orcid.org/0000-0003-1507-6174

Csaba Tóth: http://orcid.org/0000-0001-5065-5177

References

[1] H. AzariJafari, F. Guo, J. Gregory and R. Kirchain, "Solutions to achieve carbon-neutral mixtures for the U.S. pavement network," The International Journal of Life Cycle Assessment, no. 28(4) (2021). https://doi.org/10.1007/s11367-022-02121-1

[2] V. Volkov, I. Taran, T. Volkova, O. Pavlenko, and N. Berezhnaya, "Determining the efficient management system for a specialized transport enterprise," Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, no. 4, pp. 185-191, 2020. https://doi.org/10.29202/nvngu/2020-4/8

[3] Hungarian Cement Concrete and Lime Association, Update 62: Durable and safe. Concrete pavements., CeMBeton (2023), in Hungarian

[4] R. Szpotowicz, Energy demand assessment of Hungarian road structures, Útügyi Lapok, pp. 30-50, (2020) in Hungarian https://doi.org/10.36246/UL.2020.2.03

[5] CEMBUREAU The European Cement Association, Activity Report, 2021 CEMBUREAU, Brussels (2022). https://cembureau.eu/library/reports/

[6] N. Madlool, R. Saidur, N. Rahim and M. Kamalisarvestani, An overview of energy savings measures for cement industries, Renewable and Sustainable Energy Reviews, vol. 19, pp. 18-29 (2012). https://doi.org/10.1016/j.rser.2012.10.046

[7] N. Madlool, R. Saidur, M. Hossain and N. Rahim, A critical review on energy use and savings in the cement industries, Renewable and Sustainable Energy Reviews, vol. 15, pp. 2042-2060 (2011). https://doi.org/10.1016/j.rser.2011.01.005

[8] J. B. Soares and M. T. Tolmasquim, Energy efficiency and reduction of CO2 Emissions through 2015: The Brasilian cement industry, Mitigation and Adaptation Strategies for Global Change, vol. 5, pp. 297-318 (2000). https://doi.org/10.1023/A:1009621514625

[9] A. Dodoo, L. Gustavsson and R. Sathre, Carbon implications of end-of-life management of building materials, Resources, Conservation and Recycling, p. 276–286 (2009). https://doi.org/10.1016/j.resconrec.2008.12.007

[10] N. Pardo, J. A. Moya and A. Mercier, Prospective on the energy efficiency and CO2 emissions in the EU cement industry, Energy, vol. 36, pp. 3244-3254 (2011). https://doi.org/10.1016/j.energy.2011.03.016

[11] R. Kumar, E. Althaqafi, S. G. K. Patro, V. Simic, A. Babbar, D. Pamucar, S. K. Singh, and A. Verma, "Machine and deep learning methods for concrete strength prediction: A bibliometric and content analysis review of research trends and future directions," Applied Soft Computing, vol. 164, 111956, 2024. https://doi.org/10.1016/j.asoc.2024.111956

[12] T. García-Segura, V. Yepes and J. Alcalá, Life cycle greenhouse gas emission of blended cement concrete including carbonation and durability, The International Journal of Life Cycle Assessment, vol. 19, pp. 3-12 (2014). https://doi.org/10.1007/s11367-013-0614-0

[13] C. S. Karadumpa and R. K. Pancharathi, Study on energy use and carbon emission from manufacturing of OPC and blended cements in India, Environmental Science and Pollution Research, p. 5364–5383 (2024). https://doi.org/10.1007/s11356-023-31593-3

[14] E.K. Anastasiou, A. Liapis and I. Papayianni, Comparative life cycle assessment of concrete road pavements using industrial by-products as alternative materials, Resources, Conservation and Recycling 101, pp. 1-8, (2015). https://doi.org/10.1016/j.resconrec.2015.05.009

[15] L. H. Pereira Silva, V. Nehring, F. F. Guedes de Paivaa, J. R. Tamashiro, A. P. Galvín and A. López-Uceda, Use of blast furnace slag in cementitious materials for pavements -

Systematic literature review and eco-efficiency, Sustainable Chemistry and Pharmacy, pp. 1-9 (2023). https://doi.org/10.1016/j.scp.2023.101030

[16] D. M. Kurhan, "Entropy Application for Simulation the Ballast State as a Railway Element," Acta Polytechnica Hungarica, vol. 20, no. 1, pp. 63-77, 2023. https://doi.org/10.12700/APH.20.1.2023.20.5

[17] Bundesministerium für Wirtschaft und Energie, Energiewende in der Industrie: Potenziale und Wechselwirkungen mit dem Energiesektor, Branchensteckbrief der Zement- und Kalkindustrie, Navigant Energy Germany GmbH (2020), in German

[18] Verein Deutsche Zementwerke, CEM II- und CEMIII/A- Zemente im Betonbau, Nachhaltige Lösunden für das Bauen mit Beton, Düsseldorf (2008), in German

[19] Útügyi Műszaki Előírás/Hungarian Technical Specifications for Roads, Design and Construction of Concrete and Composite Pavements / Beton- és kompozitburkolatok tervezése és építése, e-UT 06.03.37:2021 (2021) in Hungarian

[20] Hungarian Standards Institution, Concrete. Specification, performance, production and conformity and conditions of application of EN 206 in Hungary (2021).

[21] Hungarian Standards Institution, MSZ EN 197-1:2011, Cement Composition, specifications and conformity criteria for common cements (2011), in Hungarian

[22] Hungarian Cement Concrete and Lime Association, CEMBETON Guidance 2017, Budapest: Magyar Cement-, Beton- és Mészipari Szövetség (2017), in Hungarian

[23] Bundesministerium für Digitales und Verkehr, General Circular for Road Construction / Allgemeines Rundschreiben Straßenbau Nr. 04/2022 (StB 25/7182.8/3-ARS-22/3644896), Bonn (2022), in German

[24] E. Anastasiou, A. Liapis and I. Papayianni, Comparative life cycle assessment of concrete road pavements using industrial by-products as alternative materials, Resources, Conservation and Recycle, pp. 1-8 (2015). https://doi.org/10.1016/j.resconrec.2015.05.009

[25] R. J. Stammer and F. Stodolsky, Assessment of the Energy Impacts of Improving Highway-Infrastructure Materials, Center for Transportation Research, Argone National Laboratory, Illinois (1995). https://doi.org/10.2172/177967

[26] J. Chehovits and L. Galehouse, Energy Usage and Green House Gas Emission of Pavement Preservation Processes for Asphalt Concrete Pavements, Compendium of Papers from the First International Conference on Pavement Preservation, pp. 27-42, 15 4 (2010) Corpus ID: 106462011.

[27] T. Häkkinen and K. Mäkelä, Environmental adaptation of concrete: Environmental impact of concrete and asphalt pavements, VTT, Technical research centre of Finland (1996). https://publications.vtt.fi/pdf/tiedotteet/1996/T1752.pdf

[28] H. Stripple, Life Cycle Assessment of Road; A Pilot Study for Inventory Analysis, Swedish National Road Administration, Gothenburg, Sweden (2001). https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1550976&dswid=-3669

[29] Athena Institute, A life cycle perspective on concrete and asphalt roadways: Embodied primary energy and global warming potential, Cement Association of Canada, 2006.

[30] F. Gschösser, H. Wallbaum and M. E. Boesch, Life-cycle assessment of the production of Swiss road materials, Journal of materials in civil engineering vol. 24 (2), pp. 168-176 (2012). https://doi.org/10.1061/(ASCE)MT.1943-5533.0000375

[31] M. Chappat and J. Bilal, Environmental Road of the Future: Life cycle Analysis, Energy Consumption and Greenhouse Gas Emissions, Proceedings of the Fiftieth Annual Conference of the Canadian Technical Asphalt Association (CTAA) in Victoria, British Columbia, pp 1-26 (2005). https://trid.trb.org/View/849158

[32] P. Zapata and J. A. Gambatese, Energy consumption of asphalt and reinforced concrete pavement materials and construction, Journal of Infrastructure Systems, vol. 11, pp. 9-20 (2005). https://doi.org/10.1061/(ASCE)1076-0342(2005)11:1

[33] T. D. E. Deborah N. Huntzinger, A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies, Journal of Cleaner Production, pp. 668–675 (2008). https://doi.org/10.1016/j.jclepro.2008.04.007

[34] Útügyi Műszaki Előírás/Hungarian Technical Specifications for Roads, e-UT 05.02.42 Joint Filling Materials of Road Pavements (2008) in Hungarian

[35] Útügyi Műszaki Előírás/Hungarian Technical Specifications for Roads, e-UT 06.03.32 Concrete Subbases for Road Building Requirements, (1993) in Hungarian

[36] Útügyi Műszaki Előírás/Hungarian Technical Specifications for Roads, e-UT 06.03.33 Concrete Base Courses of Pavement Design Requirement (2008) in Hungarian

[37] I. Saukenova, M. Oliskevych, I. Taran, A. Toktamyssova, D. Aliakbarkyzy, and R. Pelo, "Optimization of schedules for early garbage collection and disposal in the megapolis," Eastern-European Journal of Enterprise Technologies, vol. 1, no. 3(115), pp. 13-23, 2022. https://doi.org/10.15587/1729-4061.2022.251082

[38] A. Benmeddah, V. Jovanović, S. Perić, M. Drakulić, A. Đurić, and D. Marinković, "Modeling and Experimental Validation of an Off-Road Truck's (4 × 4) Lateral Dynamics Using a Multi-Body Simulation," Applied Sciences, vol. 14, p. 6479, 2024. https://doi.org/10.3390/app14156479

[39] M. Barać, N. Vitković, Z. Stanković, M. Rajić, and R. Turudija, "Description and Utilization of an Educational Platform for Clean Production in Mechanical Engineering," Spectrum of Mechanical Engineering and Operational Research, vol. 1, no. 1, pp. 145-158, 2024. https://doi.org/10.31181/smeor11202413

[40] Útügyi Műszaki Előírás/Hungarian Technical Specifications for Roads, e-UT 06.03.53:2018 Requirements of non-bonded and hydraulic bonded concrete base (2018) in Hungarian

[41] Our Word in Data, https://ourworldindata.org, 2019, [cited 2023-07-30].

[42] Our Word in Data, https://ourworldindata.org, 2021, [cited 2023-07-30]. https://ourworldindata.org/grapher/annual-co2-cement?time=earliest..latest&country=~HUN

[43] S. Pranav, S. Aggarwal, E.-H. Yang, A. K. Sarkar, A. P. Singh and M. Lahoti, Alternative materials for wearing course of concrete pavements: A critical review, Construction and Building Materials, vol. 236, (2020). https://doi.org/10.1016/j.conbuildmat.2019.117609

[44] Y. Aoki, R. Sri Ravindrarajah, and H. Khabbaz, Properties of pervious concrete containing fly ash', Road Materials and Pavement Design, vol 13(1), pp. 1–11 (2012) https://doi.org/10.1080/14680629.2011.651834

[45] X. Chen, H. Wang, H. Najm, G. Venkiteela and J. Hencken, Evaluating engineering properties and environmental impact of pervious concrete with fly ash and slag, Journal of Cleaner Production, vol. 237 (2019). https://doi.org/10.1016/j.jclepro.2019.117714

[46] M. N.-T. Lam, D.-H. Le and S. Jaritngam, Compressive Strength and Durability Properties of Roller-Compacted Concrete Pavement containing Electric Arc Furnace Slag Aggregate and Fly Ash, Construction and Building Materials, pp. 912-922 (2018). https://doi.org/10.1016/j.conbuildmat.2018.10.080

[47] P. Suraneni, V. J. Azad, O. Isgor and W.J. Weiss, Use of Fly Ash to Minimize Deicing Salt Damage in Concrete Pavements, Transportation Research Record, 2629(1), pp. 24-32 (2017) https://doi.org/10.3141/2629-05

[48] A. Aghaeipour and M. Madhkhan, Effect of ground granulated blast furnace slag (GGBFS) on RCCP durability, Construction and Building Materials, vol. 141, pp. 533-541 (2017). https://doi.org/10.1016/j.conbuildmat.2017.03.019

[49] L. Nicula, O. C. Corbu and M. Iliescu, Influence of Blast Furnace Slag on the Durability Characteristic of Road Concrete Such as Freeze-Thaw Resistance, Procedia Manufacturing, vol. 46, pp. 194-201 (2020). https://doi.org/10.1016/j.promfg.2020.03.029

[50] G. L. Golewski, Energy Savings Associated with the Use of Fly Ash and Nanoadditives in the Cement Composition, Energies, vol. 13(9), pp. 1-20 (2020) https://doi.org/10.3390/en13092184

[51] J. Skarabis and C. Gehlen, "Durability of pavements concrete made with fly ash, 3rd International fib Congress and Exhibition, Incorporating the PCI Annual Convention and Bridge Conference 2010 (2010).