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Evaluation of Energy Requirement and Greenhouse Gas Emission of Concrete Heavy-Duty Pavements incorporating High Volume of Industrial By-products

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Abstract

This study evaluates the effects of high percentages of different by-products, including blast furnace slag (BFS) and fly ash (FA), on the structural performance, energy requirement and environment impacts of a concrete heavy-duty pavement (HDP) at various curing temperatures. The results of the structural performance indicate that HDP containing up to 70% BFS and HDP containing 30% FA can be comparable in controlling the HDPs designed for highways and airports. Moreover, the results of the environmental impact assessment indicate that the synergy of the by-product and warm water can reduce the energy requirement and CO_2 footprint by 5.77% to 56.54% and 8.16% to 55.5% for the highway and airport HDPs, respectively. Although the elevated curing temperature improves the structural performance and sustainability of the concrete pavements, any delay in concrete production increases energy consumption accordingly. Moreover, a new parameter (∇_{TE}), which is the time gradient per unit energy consumption developed based on the Laplace transformation, is

proposed to characterize the effect of the time delay in concrete production. This parameter indicates that the time required for a unit energy consumption (1 TJ) decreases by 50%, as the curing temperature increases. In conclusion, analysis of the structural design, carbon footprint, and the results of ∇_{TE} indicate that 35 °C can be proposed as the optimum water curing temperature for the HDP incorporating by-products.

Keywords: Resource management, Sustainable practice, Sustainable infrastructure asset, Low energy pavement,

1. Introduction

Construction of public infrastructure assets is a highly resource-intensive activity, i.e., it significantly depends on nonrenewable natural resources. Moreover, global demand for raw construction materials has been increasing because of the following two main reasons: 1) construction of infrastructure assets in developing countries is at a rapid pace, e.g., it is estimated that four billion tonnes of cement is produced annually, and the highest growth in cement production is predicted in China, India, and the middle eastern countries (Jamshidi et al. 2016; Schneider et al. 2011); 2) in developed countries, routine maintenance and rehabilitation of the infrastructure assets are required because of ageing. For example, in Germany, almost 14.3% of bridges on main highways are in unsatisfactory conditions (Uddin et al. 2013), which require a maintenance plan to extend serviceability of transportation networks. In addition, BMWi (2008) estimates that €83 billion is required to maintain serviceability of current transportation infrastructure assets. In addition, a recent estimation indicates that maintaining the U.S. national highway network at its current service condition required $95 billion in 2014, and it is predicted to increase to $109 billion by year 2020, which may increase further, if any improvement plans are included (Lohghalam et al. 2016).

It should be noted that a major part of this estimated investment is utilized for maintenance and rehabilitation of highways and bridges. Therefore, a substantial budget is required to supply materials for construction, maintenance, and rehabilitation of pavements and bridges. One of the alternatives to reduce the expenditure is the utilization of industrial by-products as supplementary materials. Another significant advantage of incorporating the by-products is the reduction of the ever-increasing demand on nonrenewable natural resources. It should be noted that direct diversion of by-products in other industries into pavement construction projects not only reduces CO_2 footprint, but also increases the productivity because such materials are no longer wasted. For example, blast furnace slag (BFS) and fly ash (FA) are typical industrial by-products that can be used as alternative materials in the infrastructure asset construction. BFS, as a by-product of metallurgical processes, is ranked as the second most desirable waste material for highway pavement constructions from a technical viewpoint, while it is ranked fifth and sixth in economic and environmental perspectives, respectively (Ahmed 1993). It is estimated that 2 to 4 tonnes of waste material per one tonne of steel is produced during the manufacturing of steel (Das et al. 2007). The results of a study showed that the concrete pavements incorporating 50% by-products, such as BFS and FA, can be used for airports (Godiwalla 2004). In a similar study, Jamshidi et al. (2015) found that the structural performances of airport pavements incorporating BFS can be comparable to that of traditional pavements.

Furthermore, coal-fired power plants produce approximately half of the total electricity in the United States, which results in over 134 million tonnes of coal-combustion by-products per annum consisting of almost 50% FA (Lav et al., 2006). Cetin et al. (2012) studied the effects of FA on the leachate of the base layer. The results indicated that metal concentration of the leachate increases with the increase in the FA content, which implies that the metal content of the soil increases. The results also showed that Cr, Sb, Va, Mn, and Fe were lower than the requirements prescribed by the U.S Environmental Protection Agency. It should be noted that the required structural performance of the base thickness incorporating FA depends on the pavement applications (Jamshidi et al. 2015). Martin et al., (2017) reported that the cement mortar with 7.5 mass-% fly ash showed higher compressive strength than the samples without fly ash when the water to cement ratio (W/C) ratio was kept constant. Moreover, soft clay samples incorporating blend of cement kiln dust and FA had unconfined compressive strength than the samples modified by ordinary Portland cement (Yoobanpot et al., 2017).

In another study, Nassar and Soroushian (2012) evaluated the performance of highway concrete pavements incorporating high percentage of FA. Structural variables, such as compressive and flexural strengths, were more than those of control samples after 90 days. In addition, the analysis of the abrasion loss test showed that the FA concrete samples were less prone to abrasion in comparison to the control samples, which was consistent with the results obtained by the field investigations. The analysis of the environmental impact assessment conducted by Anastasiou et al. (2015) showed that the distance of FA transportation has no effect on GHG emissions in the life cycle of concrete pavements.

However, incorporating the industrial by-products, such as BFS and FA, into pavement construction require up-to-date laboratory and field investigations on structural consistency and environmental performances including the energy use, emissions, and leaching. Despite several studies on the structural performance of paving materials, there is lack of research on the effect of curing temperature on the structural performance and sustainability of heavy-duty pavements (HDPs) containing different type and content of by-products. Moreover, delays are unpredictable during pavement construction, which affect energy consumption and greenhouse gas (GHG) emissions of paving projects. There is a lack of study on the characterization of construction delay on the sustainability of HDPs incorporating by-products. This study attempts to bridge these gaps by analyzing the effects of type, content, and curing temperature of by-products on the structural performance and sustainability of HDPs designed for highways and airports. Ultimately, a new parameter is proposed to characterize the effects of the delay on energy consumption of the HDPs.

The scope of this study covers the raw material and construction phases; hence, the utility, recycling, maintenance, and rehabilitation phases are out of the current scope (Figure 1). In addition, the effect of cumulative delay, hereinafter delay, on the energy required to heat the water to the curing temperature is characterized. Hence, the effects of delay on material supply and construction are out of scope of the study. Also, effects of BFS and FA on leachate of the concrete pavement is out of the scope.

3. Materials and Methods

2.1. Materials

This research attempts to meet the requirements of pavement projects for high structural performance and sustainable HDPs.

2.1.1. Cement

Ordinary Portland cement type I was used in this study. Table 1 lists the results of the X-ray fluorescence analysis for the chemical properties of the cement. The specific gravity of cement was 3.17 g/cm^3.

2.1.2. By-products

2.1.2.1. Blast Furnace Slag

In this study, granulated BFS, hereinafter BFS, is used. The specific gravity of the BFS was 2.91 g/cm^3. The replacement ratios of the BFS were 0%, 50%, and 70% of the cement, hereinafter the samples, containing 0% (control), 50%, and 70% BFS. Table 2 lists the chemical composition of the BFS.

2.1.2.1. Fly Ash

Table 3 lists the chemical compositions of the cement and the by-products. In this study, 15% and 30% of the cement were substituted by the FA. The specific gravity of the FA was 2.33 g/cm^3.

2.2. W/C Ratio and Water Curing Condition

W/C ratios for the control samples were 0.3, 0.4, and 0.5, while it was 0.4 for the samples containing the by-products. However, the samples incorporating the by-products were compared to the control samples prepared using the same W/C ratio (0.4). Water temperatures for concrete production were 20 ºC, 35 ºC, and 50 ºC. The samples were demolded after 24 h, and then moist-cured at the same construction temperatures in the moisture tank for 90 and 180 days.

2.3. Structural Performance

The average compressive strength and the Young’s modulus of the cylindrical samples were determined at each curing condition and temperature. The rupture modulus and working stresses of the samples were calculated using Equations (1) and (2).

$$\mathrm{MR} = \mathrm{K}\sqrt{f'_c} \qquad [1]$$

Packard (1973)

$$\text{Working Stress} = \frac{\mathrm{MR}}{\mathrm{SF}} \qquad [2]$$

where MR is the rupture modulus; K is a constant value (from 8 to 10); f'_c is the compressive strength (psi); SF is the safety factor.

2.4. Reinforcing Steel

The following three types of reinforcements with different performances were designed for the pavements: 1) dowel bar, 2) tie bar, and 3) wire fabric or bar mat reinforcement. The dowel bars were used as load-transfer devices from one slab to the adjacent one. Furthermore, the dowel-group action prohibits faulting in the transverse joints. The tie bar steel was also designed to hold the adjacent concrete slabs together. The wire fabric or bar mat reinforcement was designed to control the temperature cracks. Therefore, such reinforcements enhance the structural capacity of the pavement against warping, contraction, and loading stresses. It is also assumed that the length of each panel of concrete pavement is 12 m.

2.5. Highway

In this study, the pavement design method of the American Association of State Highway and Transportation Officials (AASHTO) was used. Therefore, an equivalent single axle load (ESAL) of 8.2 t was chosen to estimate the required thickness of highway concrete pavements according to AASHTO.

To design the highway pavement, a 12 km dual carriage highway with three lanes in each direction (each lane width is 3.65 m) was considered. The number of equivalent axle loads is 5,000,000, and the assumed reliability is 95%.

2.6. Airport

In this research, the vehicle design for the airport pavement is the Boeing 787 Dreamliner. In other words, it is the design aircraft for the structural design of the airport taxiway pavements (as functional unit) with a length of 2,000 m and a width of 60 m. The reason for the selection of Dreamliner is that the entire fuselage and most parts of the wings are built from carbon fiber-reinforced plastics, which are four times more than Boeing 777. This makes the Boeing

787 lighter, saving 20% on jet fuel and air emissions, and the design is considered sustainable (Uddin, et al. 2013). It should be noted that there is a attitude evolved in selection of fleet in the air transportation. In this regard, the airlines prefer to utilize narrow-body aircrafts, such as Boeing 777 and Airbus A350, rather than the wide-body planes, e.g., Boeing 747(Jumbo jet) or A380. The reason is the change of the general philosophy from the "hub-and-spoke" to the "point-to-point". In other words, the airlines require relatively cost-effective aircrafts for short ranges. This new philosophy has negatively affected marketing for the wide-body aircrafts, which is usually used for a long range.

Table 4 lists the technical specifications of the design aircraft. The number of departures is assumed 10,000. The structural design methodology used was based on the study by Packard (1973).

2.7. Energy Analysis

Recently, pavement-energy nexus has gathered considerable attention. It covers raw material supply and processing, pavement construction, utility, and recycling. The data of the energy requirements for various raw material processing, production, and construction operations were collected from the literature as follows:

2.7.1. Cement

Cement manufacturing industry is ranked as the seventh most energy-intensive manufacturing industry in the United States (Zapata and Gambatese 2005). Cement is used as a binder in the concrete products. The average energy requirements for the production of cement is 6.36 GJ/tonne, according to Twinshare (2003).

2.7.2. By-products

The BFS is required to be processed before using in the concrete manufacturing process. The processing involves quenching and granulating at the steel mill, transporting to the grinding facility, and completing the grinding process in the material processing phase. It is estimated that the input energy for the processing of slag is 722 kJ/kg (Lippiatt 2007).

The FA is also required to be upgraded to meet the standards of cement manufacturing, which depend on the adopted technology and cement type. It is estimated that the energy requirement for the FA upgrading process is above 3.98 GJ/tonne (Vargas and Halog 2015).

2.7.3. Water

Each stage of water production, including water supply, treatment, use, and disposal, consumes considerable energy. It should be noted that the water energy production may vary, which depends on climate, water recourse, applied technology, and productivity of water production infrastructure assets. It is reported that 7% of total worldwide generated electricity is used for the production and distribution of water and treating of waste water (Young 2010). In this study, the energy requirement for water can be divided into two parts.

1) Water production: the energy requirement for raw water production and treatment.

In this study, the water is assumed to be supplied from wells. In this regard, the energy requirements for the well and its pumping were 0.15 and 0.32 kwh/m^3 (Elliott et al. 2003), respectively. Furthermore, energy consumption for chlorination of the extracted water was 0.0024 kwh/m^3 for a pump with a capacity of 3,780 m^3/day (Plappally 2012). Moreover, energy consumption of sedimentation varies from 0.0005 to 0.001 kwh/m^3 (Plappally 2012); 0.0008 was chosen in this study. Therefore, the total energy consumption in this phase is 0.4732 kwh/m^3.

2) Water curing: the energy required for heating the water to the curing temperatures is as follows.

The required heat energy was calculated using Equation 3:

$$Q = mc\Delta\theta \qquad [3]$$

where Q is the required heat energy to increase or decrease the temperature (J); m is the mass of water (kg); c is the specific heat capacity of water (J/kgºC); $\Delta\theta$ is the temperature difference (ºC) between the ambient water temperature, 20ºC in this study, and the target temperatures (curing temperature), which is 35ºC and 50ºC.

2.7.4. Aggregate

Aggregate is ranked as the first nonfuel mineral material in terms of value and volume (Asif 2009). For example, the economic value of aggregate is €120 billion, whereas the values of gold and iron are approximately €20 and €18 billion, respectively (Wellmer and Becker-Platen 2002). Bleischwitz and Bahn-Walkowiak (2006) estimates that the annual aggregate demand increases by 4.7%. There is a strong correlation between aggregate consumption and construction of infrastructure assets. Aggregate production is an energy intensive task. For example, Alcorn (2003) proposed an energy requirement of 40 MJ/tonne for aggregate production, close to 38.18 MJ/tonne was reported by Stripple (2001), which covers blast operation, transportation, and crushing the blast rock. Therefore, 40 MJ/tonne is chosen for aggregate production in this study, which lies within the range of 22 to 500 MJ/tonne recommended by Goodquary (2006). Moreover, it falls within the range of 21.1 MJ/tonne to 63.3 MJ/tonne suggested by NCSA (1977).

2.7.4. Steel

There are well-documented data on energy consumption for steel manufacturing. For example, Stubbles (2000) recommended an energy requirement of 19 GJ/tonne, which lies within the range of 18 GJ/tonne to 23 GJ/tonne recommended by Stammer and Stodolsky (1995). In addition, Eriksson (2003) recommended 1.6 GJ/m^2. World Slag Association (2011) reported that preliminary energy demand for the steel sections is 19.6 GJ/tonne, while the corresponding value is 21.6 GJ/tonne for the steel manufactured using hot-rolled coils, which falls within the range recommended by Stammer and Stodolsky (1995). In this study, 19 GJ/tonne is used, as recommended by Stubbles (2000).

2.7.5. Pavement Construction

The construction of pavement consists of the following two stages:

1) Mixture production: the cement, water, aggregate materials, admixtures, such as plasticizer or superplasticizer, air entraining, water-reducing, retarding, accelerating, corrosion-inhibiting materials are blended. It is clear that the adopted mixing process (e.g., central mixed concrete plant or concrete dry batch plant) depends on the efficiency of mixing machinery and W/C ratio, etc. The energy requirement for the concrete mixing process is 6.875 MJ/tonne, according to the field data surveyed from the contractors and reported by Zapata and Gambatese (2005).

(2) Concrete mix placement: The produced mix is spread for paving surfaces. The energy requirement for spreading the mixture depends on the workability of the mixture, size of the concrete slab, position of the construction joint, machine efficiency, capacity, and speed of the machine. Zapata and Gambatese (2005) recommend 34 MJ/tonne of energy for the placement of the concrete pavement, which is adopted in this research. In summary, table 5 lists all the ranges of energy requirements used for the various components.

2.8. Characterization of Delay

As the delay time has no economic value, the effect of time should be converted to a quantity that can be measured in terms of cost. In general, the effect of time needs to be characterized based on indicators such as fuel consumption, environmental impact indicators, or any other output to measure it in monetary terms. In this study, the energy requirement is chosen as an indicator to measure the effect of delay.

The energy consumed for heating the water consists of two parts: 1) warming from the ambient temperature to the required curing temperature (Part 1); 2) keeping the water warm (Part 2), as shown in Figure 2. It is clear that without additional energy to maintain the temperature of water, the temperature decreases back to the ambient temperature (Part 3). The ideal condition is that once the temperature increases and reaches the curing temperature, the warm water is promptly used to produce concrete. However, it is possible that there is a delay in using this water. Therefore, the water should be kept warm until the aggregate materials and cement are blended, and hence, Part 2 or delay zone may appear. Any delay in using the warm water results in more energy consumption in the pavement construction. Hence, the delay not only leads to economic loss, but it also decreases the sustainability of pavement construction. Therefore, the longer the delay, the higher the energy consumption.

The additional energy consumption due to delay is a function of the total time of delay and the mass of water. A short delay in the mixing process of huge amount of concrete can lead to considerable energy loss.

Moreover, it should be noted that the delay for each functional unit of a paving project varies from zero, no delay condition, to hundreds or thousands of hours (infinite). Therefore, a mathematical energy requirement function based on the delay time should be obtained. From a mathematical viewpoint, the energy requirement is a function of the delay considering the real value. Then, the effect of the delay from zero to infinity can be estimated using the Laplace transformation (Equation 4), which depends on the mode and type of function of energy requirement, i.e., linear or polynomial.

Hence, the result of the transformation, time gradient per unit energy consumption (∇T_E), is proposed as an indicator explaining the time requirement for 1 TJ energy consumption during pavement construction based on the Laplace transformation (Equation 4).

$$\nabla T_E = \frac{\Delta T}{\Delta E} = \frac{\partial_T}{\partial_E} = L\big(f(t)\big) = \int_{T_0=0}^{T_n=+\infty} e^{-st} f(t)\,dt \qquad (4)$$

where ∇T_E is the time gradient per unit energy consumption (h/1 TJ); ΔT is the total delay time (h); T_0 is the initial delay time (it is assumed zero as ideal condition); T_n is the final delay time; ΔE is the unit energy consumption (1 TJ); f(t) is the mathematical correlation of the chosen indicator (energy in this study) as a function of delay; s is the chosen indicator such that the delay is converted to energy.

The Laplace transformation is used instead of the simple integral (Equation 5), because the simple integral requires a specific upper limit for integration, but it is impossible to guess the exact value of the delay before the commencement of any paving project, and hence, defining a closed interval becomes difficult. However, based on the definition of the Laplace transformation, the delay time can vary from zero to infinity, which is the case practically observed in paving projects.

$$\nabla T_E = \int_a^b f(t)\,dt \qquad a \leq t \leq b \qquad (5)$$

where t is the delay time, varying between a and b

2.9. Environmental Impact Assessment

All energy requirement is converted to the industrial fuel type, natural gas in this study. Then, the GHG emissions, including CO_2, CH_4, and N_2O, are calculated using the proximity factors provided by DEFRA (2010) as listed in Table 6. Figure 3 represents a flowchart illustrating the analysis and discussions in this research.

3. Results and Discussion

3.1. Structural Performance

Figure 4 shows the structural design curves for highway and airport concrete pavements. Figures 4(a) and 4(b) show that the lowest required slab thickness is for the pavement section with a W/C ratio of 0.3 for all curing temperatures and pavement applications because the lower W/C ratio increases concrete strength, however mix workability decreases. In contrast, the required thicknesses increase as W/C ratio increases because the concrete porosity or air void percentage increases due to more water content, thereby the values of parameters indicating structural strength, such as compressive strength and the Young's modulus, decrease.

However, the required thickness of highway pavement decreases with the increase in the curing temperature (Figure (4a)). But, the curing temperature has no significant impact on the control pavements designed for the airport (Figure 4(b)). For example, the required slab thickness of the control airport pavements with a W/C ratio of 0.3, cured at 35 °C, is 29.97 cm (30 cm), and the thickness for the sample with the same W/C ratio, cured at 20 °C, is 30.98 (or 31 cm). In practice, the required thickness is rounded off to the nearest multiple of 5. As a result, curing of control pavement sections mainly depends on W/C ratio rather the curing temperature.

Figures 4(c) to 4(f) show the design charts for various BFS contents and curing temperatures. It can be seen that the required thickness for the highway and airport pavements, incorporating by-products and cured at 35 °C and 50 °C, are almost the same as that of the control pavements, indicating that the structural response of the by-product pavements in terms of the required thickness are comparable to the control pavement thickness. Moreover, the figures show that the increase in the curing temperature slightly decreases the required thickness. As a result, the pavement thickness is sensitive to the thermal gradient because of the various curing temperatures. Figures 4(d) and 4(f) also indicate that the minimum thicknesses are for the airport pavement sections containing 50% BFS or 15% FA, conditioned at 35 °C. Beyond 50% BFS or 15% FA, the required thickness increases because incorporating a higher percentage BFS and FA decreases the structural strength of the concrete samples because such mixes require more time to gain the same strength as that of the control pavement. This is because the hydration reactions and setting of blended cements (cement included with by-product) is less than that of the control samples. One approach is to accelerate strength gain or setting of by-product pavements by increase in the curing temperature; hence, pavements constructed and conditioned at higher temperatures require relatively lower thicknesses. In other words, the warm water can be considered as a catalyst to enhance hydration rate in the concrete pavements incorporating BFS or FA. There are also various types of chemical additives to increase the hydration process, however use of warm water is relatively cost-effective way that requires neither particular technical skills nor sophisticated technology. Furthermore, results of analysis of variance (ANOVA) listed in Table 7 show that interaction between the by-product and curing temperature has a significant factor on the Young's modulus of samples conditioned after curing for 180 days. However, although the difference between the required thicknesses cannot be considered insignificant, such small differences can significantly affect the environmental loadings encountered throughout the life cycle of the pavement sections.

3.2. Energy Analysis and Environmental Impact Assessment

Figure 5 shows the results of the total energy consumption for various pavements. It can be seen that the incorporation of the by-products decreases the energy consumption and GHG emissions, irrespective of by-product type. For example, the energy requirement and carbon footprint of pavements incorporating 70% BFS and conditioned at 22 ºC are 51.20% and

43.54% lower than that of the control pavements under the same curing conditions, respectively. In another example, the pavement section incorporating 30% FA conditioned at 35 ºC requires 9.77% energy, which is lower than that of the control pavement. Subsequently, the carbon footprint decreases by 7.68%. In other words, incorporation of BFS or FA reduces energy requirement in the raw material phase process (Figure 1) because less cement material is needed.

It can be misleading that lower cement consumption results in lower energy consumption and GHG emissions. However, Figure 5(b) shows that the energy requirement and emissions for the pavement incorporating 30% FA conditioned at 20 ºC is slightly higher than that of the control pavement. Consequently, the FA pavement cannot be considered as sustainable because the pertinent carbon footprint is approximately 6% higher than that of the control pavement, as shown in Figure 5(b); however, the cement consumption decreases by 30%. As the curing temperature increases up to 35 ºC or 50 ºC, the energy requirement significantly decreases for 30% FA pavement. For example, the carbon footprint decreases by 15.3%, as the curing temperature increases from 22 ºC to 35 ºC. This can be interpreted as an abnormal phenomenon where increasing the temperature results in lower emission; consequently, the sustainability increases. The reason behind this phenomenon lies in the raw material processing phase of the pavement. Figure 6 shows the correlation between various curing temperatures, total fuel requirement for water processing phase, and the pavement construction.

Figure 6 shows that the high curing temperature dramatically increases the fuel requirement for water, as one phase of raw material is processed for both by-product type and content. Therefore, pertinent CO_2 footprint in water processing phase increases, as listed in Table 8.

However, the total fuel consumption, which covers the entire life cycle of the pavement, including from cradle to the gate, reduces (Table 8). This may be because the high curing temperature accelerates hydration and curing as a progressive phenomenon in the concrete texture. Hence, the concrete pavement gains its strength faster. Therefore, a lower pavement thickness is required owing to higher strength, thereby decreasing the amount of material used. For example, the carbon footprint due to water processing for 50% BFS highway pavement is 1,174 kg at 20 °C, shown by grey colour, whereas the corresponding value is 39,148.9 kg and 79,293.2 kg for the curing temperatures 35 °C and 50 °C, respectively, which are 33.34 and 67.54 times higher than that of curing at 20 °C. In contrast, the total CO_2 footprint of the pavements conditioned at the higher temperatures are much lower than sections cured at 20 °C. For example, the total CO_2 footprint of the highway pavement incorporating 70% BFS, cured at 20 °C is 43.54% lower than that of the control pavement conditioned at the same temperature (Table 9), while the corresponding values of the 70% BFS pavements conditioned at 35 °C and 50 °C are, respectively, 55.73% and 56.54% less than that of the control pavement, wherein the observed differences of 12.19% (55.73%-43.54%) and 13% (56.54%-43.54%) stem from the elevated curing temperatures. A similar trend can be seen for the FA and the other pavement types. Hence, synergy of use of the by-product, the water temperature in concrete production and curing improved the sustainability of concrete production.

Furthermore, it should be noted that reduction in percentage of CO_2 footprint due to elevated curing temperature depends on the by-product content. For example, the reduction in CO_2 footprint of 15% FA highway pavement cured at 35 °C is 12.54 % lower than that of the control pavement (Table 9), while the corresponding value for 30% FA pavement conditioned at the same temperature is 17.51%, and 4.97% if the FA is increased further by 15%.

Moreover, the emission results can be validated by comparing the findings to a recently published research on LCA (from cradle to gate) carried out by Scott and Durham (2016). The results of this study indicated that CO_2 reduction for a 30-cm concrete pavement incorporating FA is 11.23%, which is consistent with 11% CO_2 reduction reported by Scott and Durham (2016) for the FA pavement with the same thickness. Moreover, the CO_2 emission reduction of the pavement incorporating 30% FA with almost the same thickness is 13.27%, which is very close to results obtained by Scott and Durham research for the concrete pavement incorporating the same FA content. Furthermore, the results of this study is relatively in harmony with results reported by Seto et al., (2017) indicated that the reduction in environmental impacts of FA concrete depends on scenarios used for construction.

It should be noted that there are the other approaches to increases hydration in the concrete mixes, which resulted in the higher early-aged strength. For example, Hanif et al. (2017) reported that the FA cement pastes containing nano-silica had higher mechanical performance. However, the use of the warm water is a more cost-effective and easier way to increases the sustainability than the use of nano-materials.

3.3. Characterization of Delay on Sustainability of HDP

Figure 7 shows the amount of energy consumption at different delay times. It can be seen that the energy consumption increases linearly for both by-product types and curing conditions, which decreases the energy efficiency in pavement construction. For example, energy requirement for 4 h delay in highway HDP containing 70% BFS, conditioned at 35 °C is 105 TJ, while it is 106.5 TJ for a 6 h delay (Figure 7(e)), which results in 39,162 m^3 natural gas loss because of a 2 h extra delay. Therefore, it is recommended to avoid any delays during the mixing phase of concrete produced and conditioned using warm water. However, the delay is often inevitable in paving projects; hence, it is recommended to estimate the delay time and include its effects in terms of energy requirement or emissions.

From Figure 7, it can be seen that the energy consumption of some pavements conditioned at different temperatures converge when the delay increases. Therefore, the energy requirement for curing conditions can be equal for both curing temperatures, highlighted by red circle. For example, in the control airport concrete pavement with a W/C ratio of 0.4 (Figure 7(i)), energy requirement for various curing conditions are equal after a delay of 2 h. It can be interpreted that if the concrete is produced using 50 °C water with a 2 h delay, the total energy requirement to heat the water is equal to the concrete produced using 35 °C. Therefore, a delay of 2 h can be tolerated in this case. Figure 7(e) shows that a delay of 3 h can be tolerated for the highway concrete pavements incorporating BFS produced using water at 50 °C. However, the energy requirement due to delay in pavements containing 70% BFS using 50 °C water is strictly higher than BFS pavements at 35 °C.

In the case of FA pavements, Figure 7(f) shows that the delay time can be tolerated for up to 6 h for the 15% FA pavements produced using 50 °C water, while it decreases to 2 h when the FA content increases to 30% (Figure 7(g)), which is 67% lower than the 15% FA pavement. Therefore, increase in the FA content decreases the delay that can be tolerated during concrete production. Therefore, the tolerated delay depends on the HDP application, by-product type, and content. As the water content, in terms of increase of W/C in concrete production, increases, energy loss due to the delay rises because more heat energy is function of material mass, the specific heat capacity and the target temperature, as shown by equation (3).

Figure 8 shows the values of ∇T_E for various HDP types and conditioning temperatures. For example, ∇T_E for the highway pavement incorporating 50% BFS, conditioned at 35 °C is 1.385 h/TJ, which implies that the time requirement for 1 TJ energy consumption is 1.387 h, while the corresponding value at 50 °C is 0.675 h (Figure 8(a)). Therefore, the time requirement for consumption of unit tera joule energy (1TJ) due to delay for pavements using 50 °C water is 51% less than those at 35 °C, because of higher water temperature. Hence, when the curing temperature increases, energy is consumed due to the delay during concrete mixing at a shorter time; consequently, the speed of energy consumption increases.

Figures 8(c) and 8(d) show that ∇T_E of the airport pavements are higher than those of the highways, because the total material consumption, including water requirement, in the airport pavements is much lower than that of the highway. Therefore, the energy required to keep the water warm decreases, which means that ∇T_E depends on the HDP application. Moreover, ∇T_E values decrease by approximately 50% while temperature increases from 35 °C to 50 °C; hence, 15 °C increase in water temperature reduces the time requirement for 1 TJ energy consumption by 50%. For example, ∇T_E of the pavements containing FA conditioned at 35 °C is 1.427 h/TJ, while the use of 50 °C water decreases ∇T_E to as low as 0.734 (Figure 8(b)), which is almost 50% lower than that conditioned at 35 °C. In other words, speed of energy consumption due to delay increases, as water temperature increases. As a result, the delay has more effect on energy consumption while warmer water curing is used in concrete production. Therefore, the use of 50 °C water has no significant effects on reduction of required thickness of HDP incorporating by-products (Figure 4). In addition, energy requirement of water processing for all HDPs (Figures 6 and 7) and CO_2 footprint (Table 8) increase and any delay in the construction results in a huge amount of energy loss (Figure 8).

A temperature of 35 °C, as optimum temperature, can be recommended for construction and curing of HDP containing BFS or FA for highways and airports.

4. Conclusion

Effects of synergy considering different contents of BFS and FA and water curing temperatures on the structural performance, energy consumption, and environmental aspects of HDP were evaluated in this research. The results of structural design clearly showed that structural performance, in terms of required slab thickness, of HDP incorporating high percentage of BFS and FA is comparable to the control HDP section for both the highway and the airport. The strength gaining phenomenon, resulting from the hydration reaction, can be accelerated via the use of warm water in concrete production and curing. Hence, BFS and FA can be considered as alternative cementitious materials for HDP, saving huge amounts of space in landfills and reducing the amount of natural materials to be mined. Furthermore, construction of HDP, containing by-products and warm water, decreases energy requirement and CO_2 footprint from 33% to 56.54% for highway HDP incorporating BFS and 0.54% to 18.16% for HDP containing FA; the corresponding values are 41.42% to 55.5% for the HDP containing the BFS designed for the airport and 8.16% and 13.05% for the HDP containing the FA. Although the elevated temperature of water for concrete production and curing decreases energy requirement and emissions, any delay to use the warm water increases energy requirement proportionately. To characterize the effect of delay, ∇_{TE} is proposed, indicating the time required for 1 TJ energy consumption. The analysis of ∇_{TE} showed that the time required for consumption of 1TJ, due to any delay, decreases by 50% as the water temperature increases from 35 °C to 50 °C. Therefore, a temperature of 35 °C is recommended for water curing because the structural performance is improved, and avoiding any extra energy loss and CO_2 emissions due to delay.

This study offers the following suggestions for further research by considering the long-term economic and environmental consequences of sustainable heavy-duty pavements:

- The triple bottom line in the life cycle for both sustainable asphalt and concrete HDP incorporating various types of by-products should be conducted.
- It is recommended to analyze the effects of elevated curing temperature and by-product type and content on the microstructure of HDP sections.
- Characterization of by-product type, content, and W/C ratio, temperature of water curing on durability of HDP designed for highways and airports can be other subjects for future research.
- It is recommended to analyze the effect of delay for HDP prepared using different W/C ratios. Also, effect of delay on transportation and paving should be included.
- In this study, the function of energy versus delay time changes linearly. It is recommended to study ∇T_E when the function has different trends, e.g., polynominal and simple curve.
- It is recommended to characterize the effects of various by-product types, content and W/C ratios on the leachate of HDP at various service conditions.

Nomenclature

Name	definition
AASHTO	American association of state highway and transportation officials
ANOVA	analysis of variance
BFS	blast furnace slag
ESAL	equivalent single axle load
FA	fly ash
GHG	greenhouse gas
HDP	heavy-duty pavements
h	hour
LCA	life cycle analysis
SF	safety factor.
TJ	Tera joule
∇T_E	the time gradient per unit energy consumption
W/C	water to cement ratio

MR	rupture modulus
K	model constant value
f_c'	compressive strength
t	time delay
Q	required heat energy to increase or decrease the temperature
m	Mass of water
c	specific heat capacity of water
$\Delta\theta$	the temperature difference
ΔT	the total delay time
T_0	initial delay time (it is assumed zero as ideal condition)
T_n	final delay time
ΔE	unit energy consumption
f(t)	the mathematical correlation of the chosen indicator (energy in this study)
s	the chosen indicator such that the delay is converted to energy.

Acknowledgement

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Table 1: Chemical composition of cement

Chemical component	Weight (%)	Chemical component	Weight (%)
SiO_2	21.45%	TiO_2	0.23%
Al_2O_3	5.69%	Na_2O	0.31%
Fe_2O_3	2.68%	K_2O	0.48%
CaO	65.20%	SO_3	1.92%
MgO	1.95%	P_2O_5	0.20%
MnO	0.06%	Cl	0.016%

Table 2: Chemical composition of BFS

Chemical component	Weight (%)
SiO_2	34.13
Al_2O_3	13.84
Fe_2O_3	0.70
CaO	43.73
MgO	6.71
TiO_2	0.55
Na_2O	0.22
K_2O	0.32

Table 3: Chemical composition of FA

Chemical component	Weight (%)
SiO_2	63.16
Al_2O_3	25.25
Fe_2O_3	5.51
CaO	1.45
MgO	0.76
TiO_2	1.14
Na_2O	0.013
K_2O	1.42
S_1O_3	0.219
P2O5	0.691
MnO	0.058
SrO	0.074

Table 4: Some technical properties of the design aircraft (Boeing 2014).

Properties	Version
Maximum design taxiway weight (kg)	251,744
Main gear tyre pressure (kg/cm^2)	15.75
Nose gear tyre pressure (kg/cm^2	12.80

Table 5: Energy requirements for various components

Component	Energy requirement	Unit
Cement production	6.36	GJ/tonne
BFS	722	MJ/tonne
FA	3.98	GJ/tonne
Water production	0.4732	kwh/m^3
Aggregate production	40	MJ/tonne
Steel	19	GJ/tonne
Concrete mixing	6.875	MJ/tonne
Concrete placement	34	MJ/tonne

Table 6: Conversion factors for GHG

CO_2 (kg CO_2/unit)	CH_4 (kg CO_2e/unit)	N_2O(kg CO_2e/Unit)
2.023	0.003	0.0012

Table 7: Results of ANOVA for elastic modulus of 180-day conditioned samples

Parameters	Type III Sum of Squares		df	Mean Square		F		Sig.	
	BFS	FA		BFS	FA	BFS	FA	BFS	FA
Corrected Model	1100.154	1154.132	8	138	144.267	9	31.377	0	.000
Intercept	29115.025	26480.246	1	29115.025	26480.246	1930.989	5759.253	.000	.000
By-product	45.814	150.554	2	22.907	75.277	1.519	16.372	.246	.000
Temp	570.008	193.904	2	285.004	96.952	18.902	21.086	.000	.000
By-product * Temp	484.333	809.674	4	121.083	202.419	8.031	44.025	.001	.000
Error	271.400	82.761	18	15.078	4.598				
Total	30486.578	27717.140	27						
Corrected Total	1371.554	1236.894	26						

Table 8: Emission of CO_2 footprint of water processing and total phases of pavements

Pavement section	Application	Water Phase			Total Phase		
		20°C	35°C	50°C	20°C	35°C	50°C
Control(0.3)	Highway	947.8	32,999	66,933.5	13,582,618	12,674,411	13,021,764
Control (0.4)		1,114	39,426	78,845.8	12,204,128	11,562,477.8	11,737,426
Control (0.5		1,375	50,158	88,746	12,117,743	11,802,893	10,769,579
50% BFS		1,174	39,148	79,293	8,176,345	7,206,016	7,396,762
70% BFS		1,259	38,325	73,113	6,890,059	5,401,572	5,302,862
15%FA		1,143	37,995	72,956	12,138,093	1,0673,569	10,456,753
30%FA		1,263	37,632	73,276	12,908,425	10,066,818	9,986,851
Control(0.3)	Airport	654	24,695	50,388	9,188,419	9,213,213	9,502,153
0.4		802	29,885	58,267	8,554,076	8,479,625	8,392,041
0.5		949	36,197	71,695	8,171,704	8,285,293	8,324,820
50% BFS		754	27,990	56,167	4,966,935	4,925,556	5,000,015
70% BFS		791	28,700	57,560	3,866,785	3,773,180	3,828,064
15%FA		764	27,665	55,522	7,787,648	7,527,104	7,646,861
30%FA		801	28,639	56,971	7,715,354	7,373,013	7,431,219

Table 9: Reduction percentage of CO_2 footprint in the total phases of pavements

Pavement section	HDP Type	Total Phase		
		20°C	35°C	50°C
50% BFS	Highway	33	41	39.39
70% BFS		43.54	55.73	56.54
15%FA		0.54	12.54	14.31
30%FA		5.77	17.51	18.16
50% BFS	Airport	41.42	41.91	41.03
70% BFS		54.39	55.50	54.85
15%FA		8.160	11.23	9.82
30%FA		9.018	13.05	12.36

Note: the data presents the difference in CO_2 footprint between the section and control pavement conditioned at 20 °C

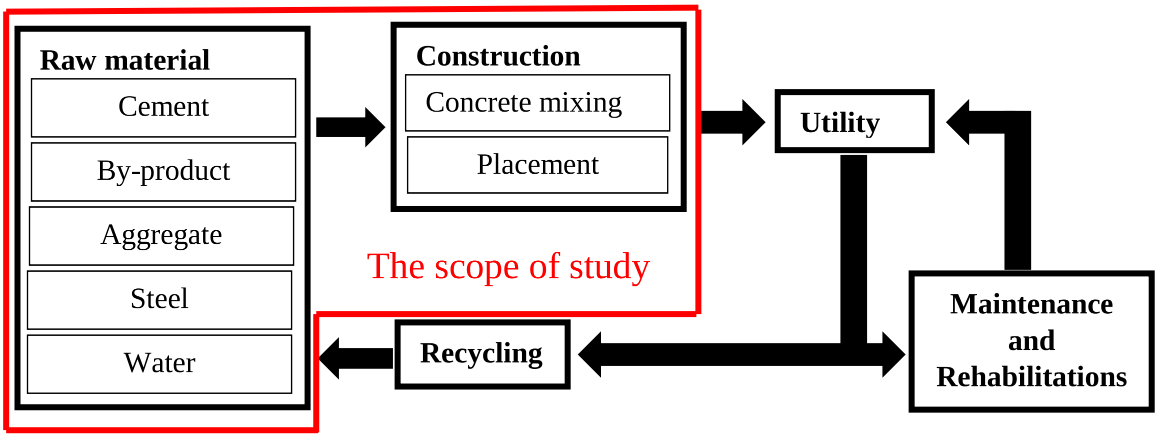


Figure 1: A typical life cycle for asphalt pavement.

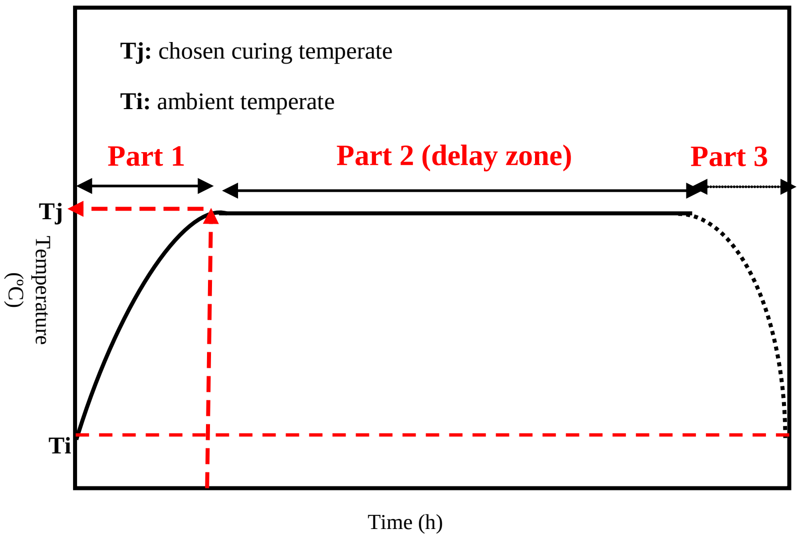


Figure 2: Schematic of temperature versus time during heating of water to the curing temperature

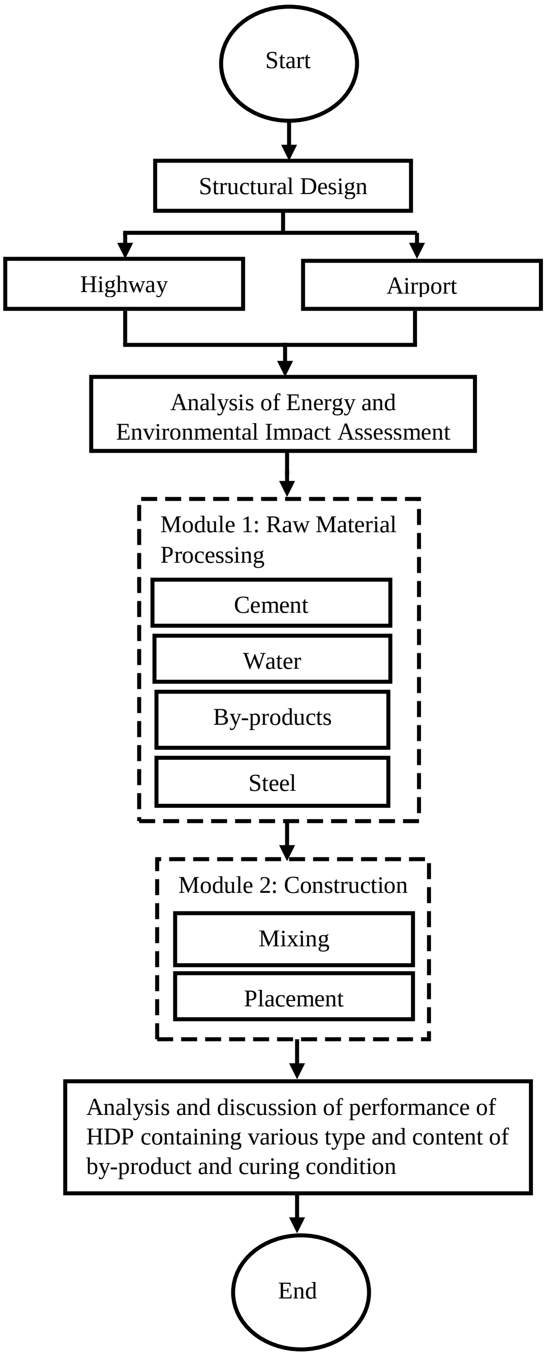
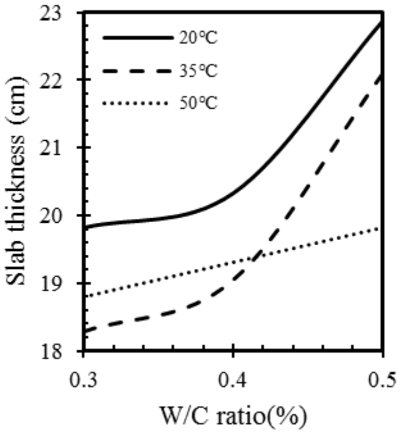
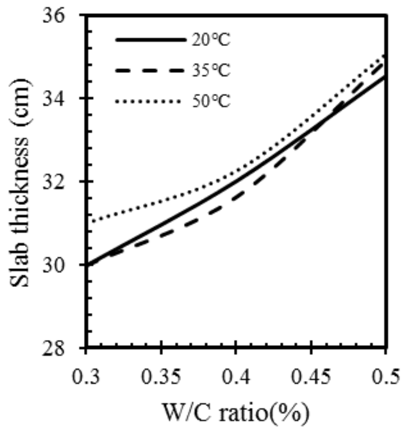


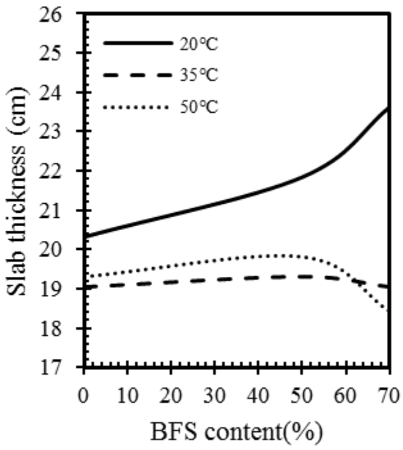
Figure 3: flowchart illustrating analysis and discussions of this research



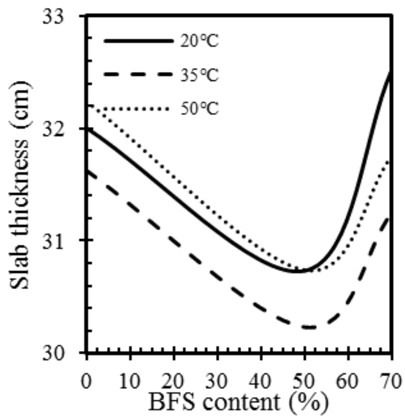
(a) control pavement for highway



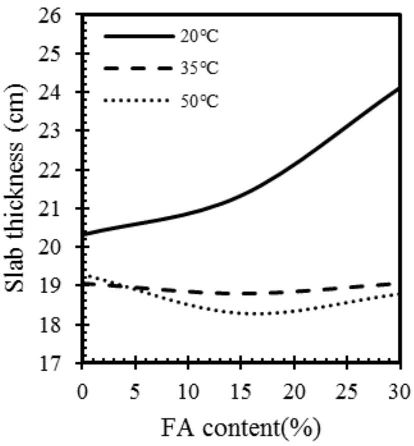
(b) control pavement for airport



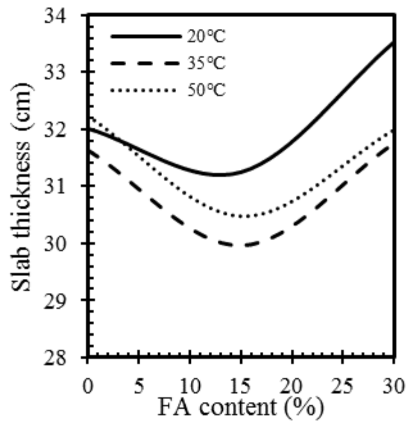
(c) BFS pavement for highway



(d) BFS pavement for airport

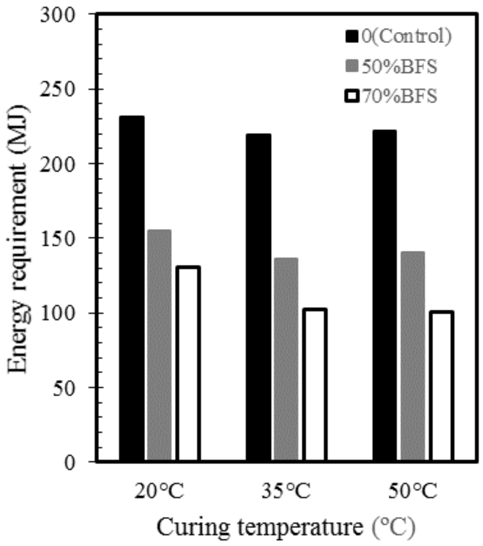


(e) FA pavement for highway

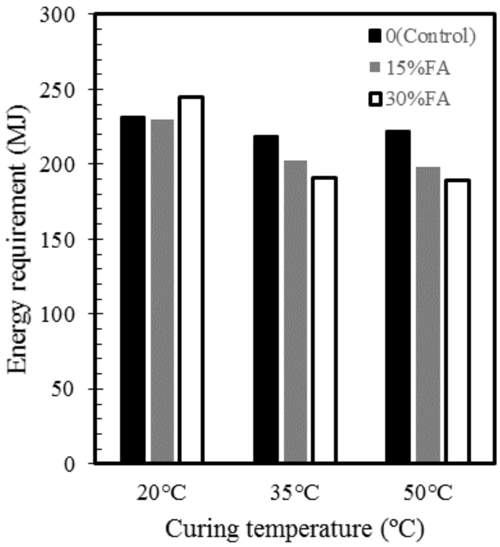


(f) FA pavement for airport

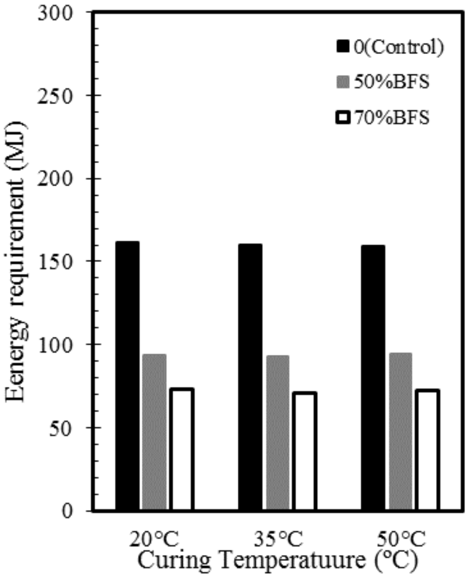
Figure 4: Structural design charts for highway and airport pavements



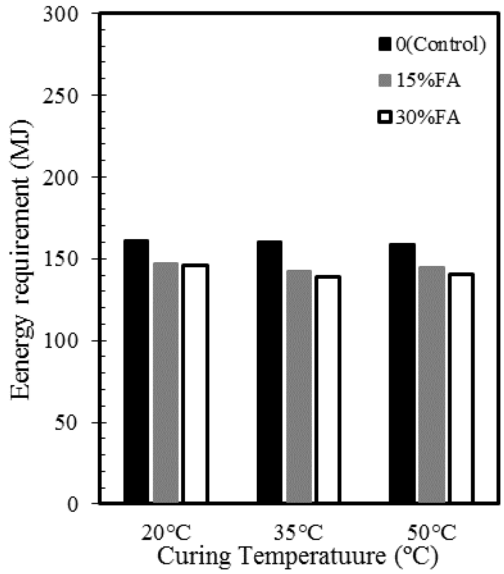
(a) BFS for Highway



(b)FA for Highway

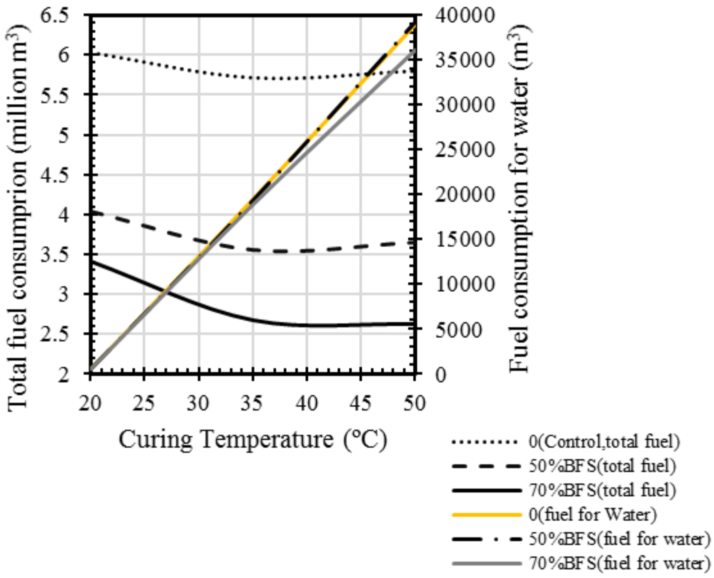


(c) BFS for Airport

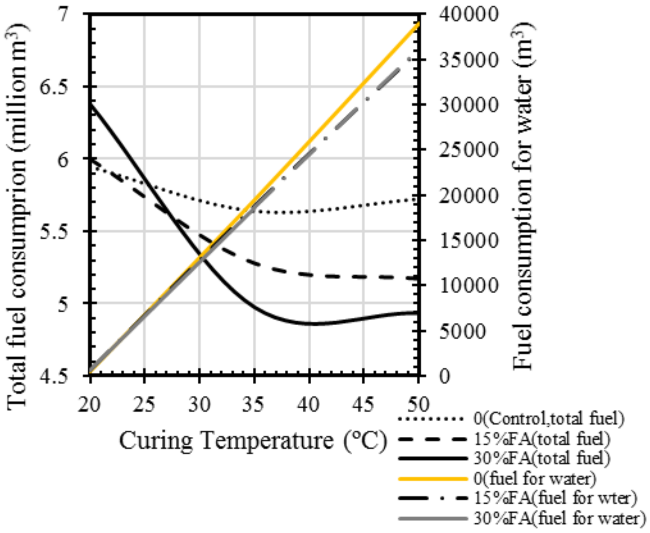


(d)FA for Airport

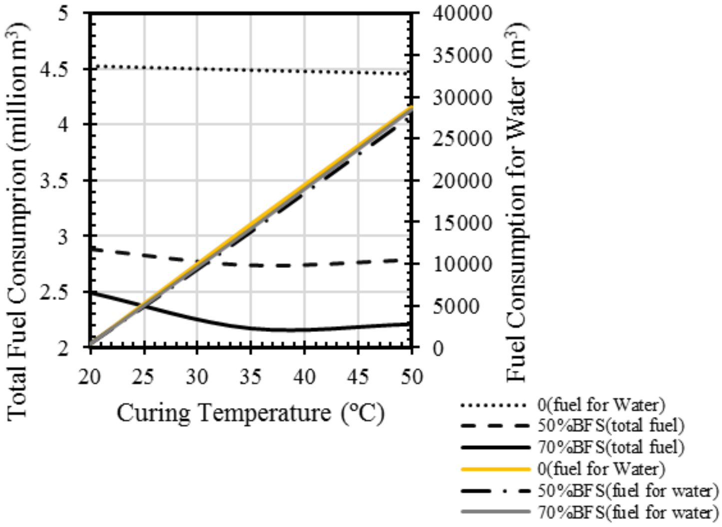
Figure 5: Energy requirement for the pavement incorporating various by-products



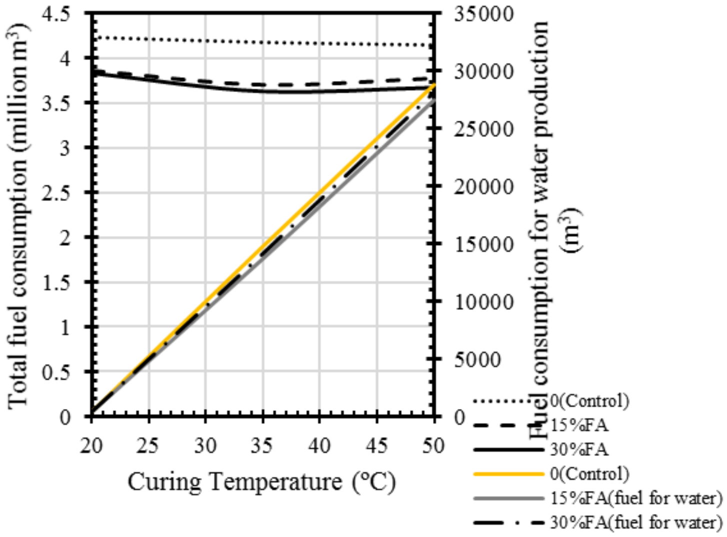
(a) BFS for Highway



(b) FA for Highway

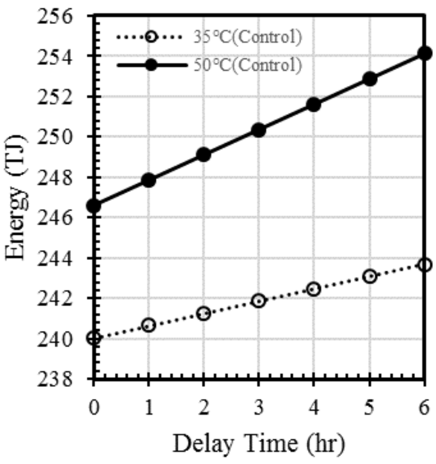


(c) BFS for Airport

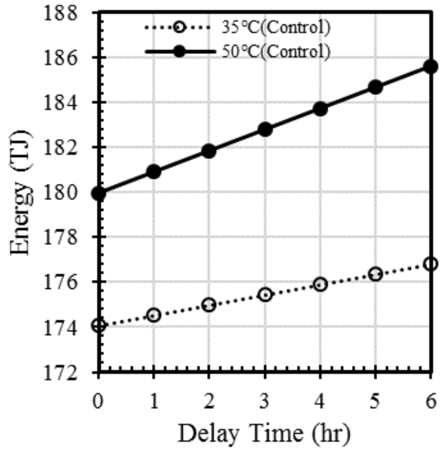


(d) FA for Airport

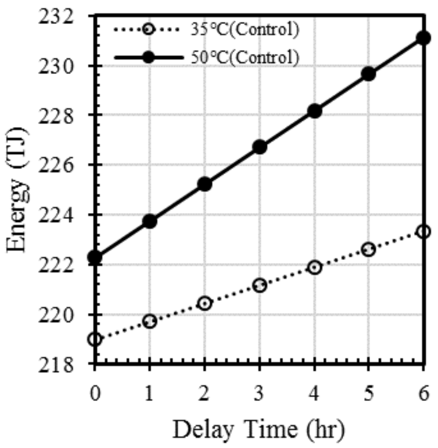
Figure 6: Effects of curing temperature on fuel requirement for water supply, total fuel requirement, and pavement construction



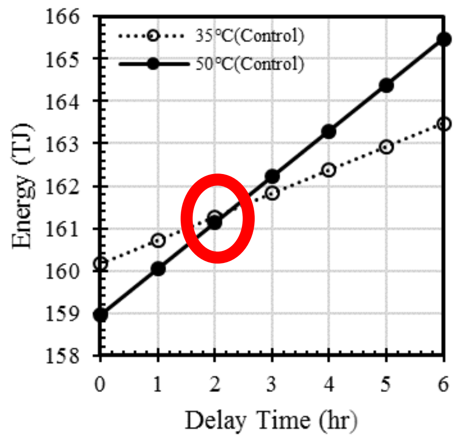
(a) Highway(W/C=0.3)



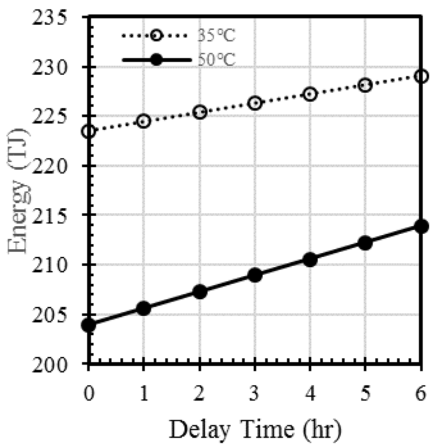
(h) Airport(W/C=0.3)



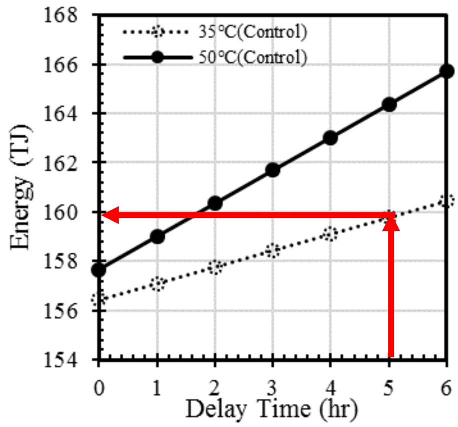
(b)Highway(W/C=0.4)



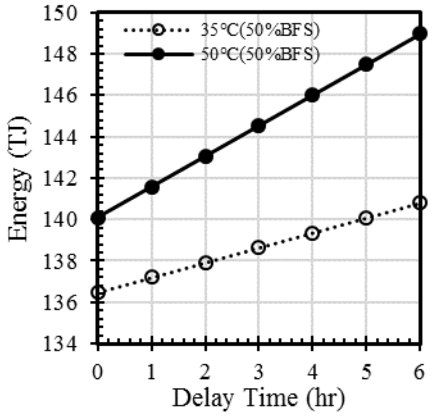
(i) Airport(W/C=0.4)



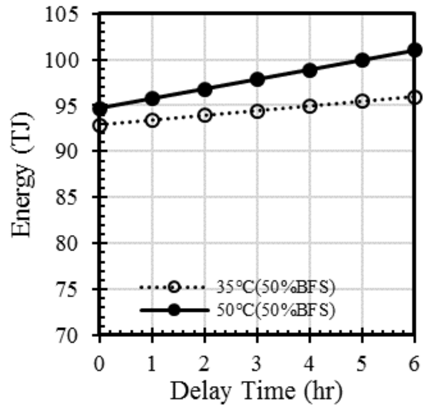
(c) Highway(W/C=0.5)



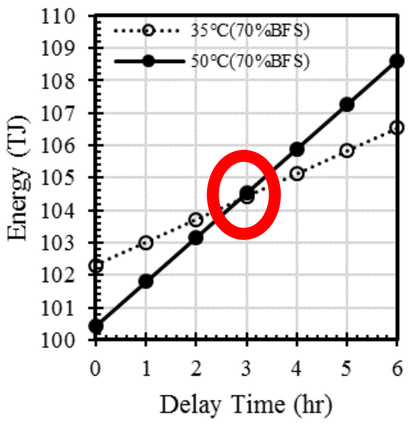
(j) Airport(W/C=0.5)



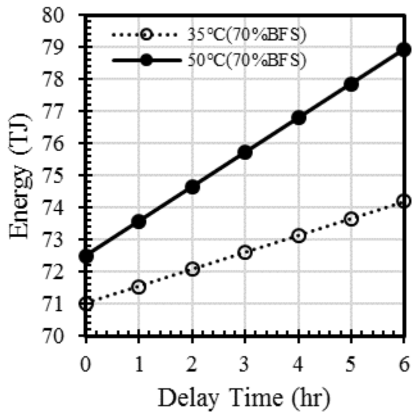
(d)Highway



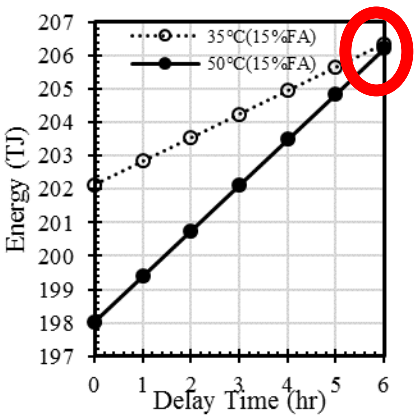
(k) Airport



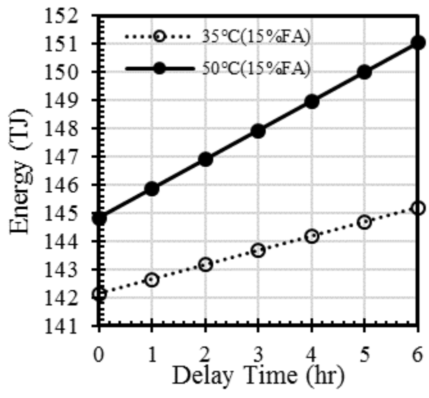
(e)Highway



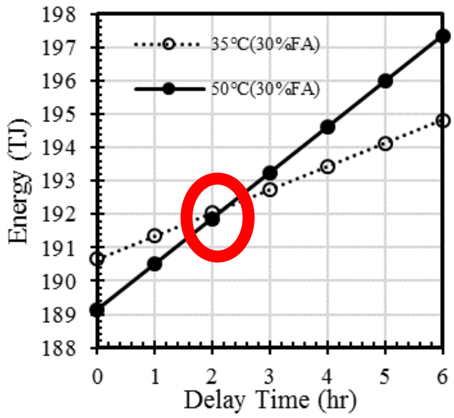
(l) Airport



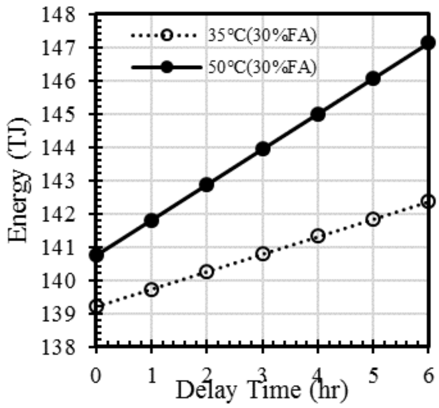
(f) Highway



(m) Airport

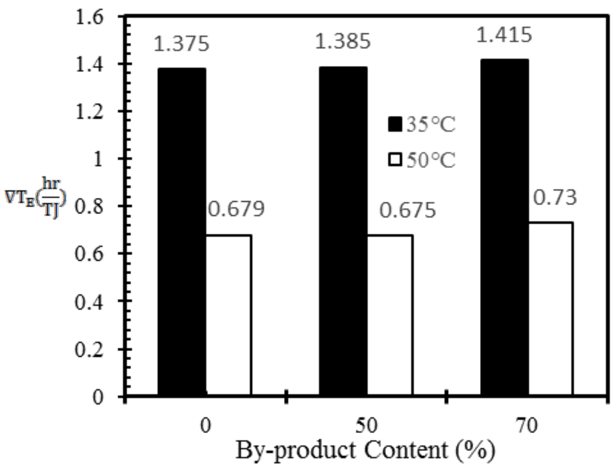


(g) Highway

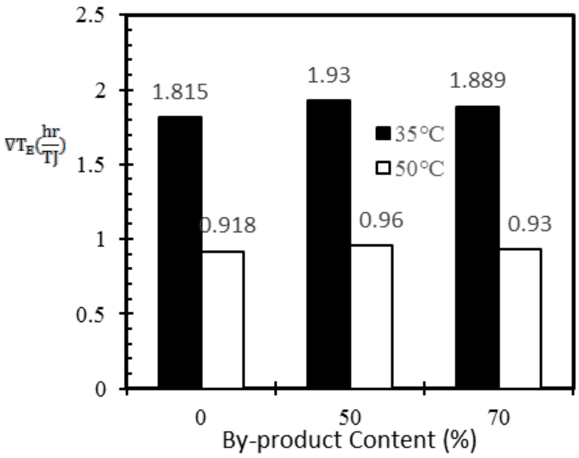


(n) Airport

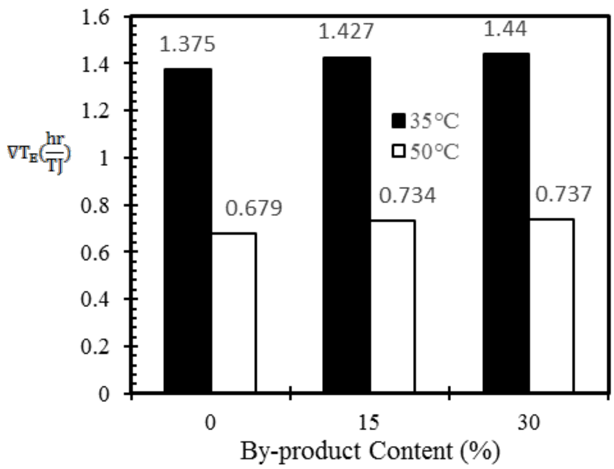
Figure 7: Energy consumptions due to delay in concrete production



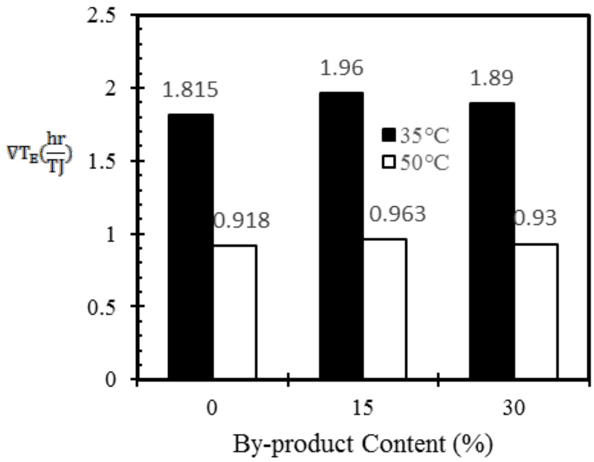
(a) Highway pavement containing BFS



(c) Airport pavement containing BFS



(b) Highway pavement containing FA



(d) Airport pavement containing FA

Figure 8: Relationship between ∇T_E for various HDPs.