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

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18

19 **Abstract**

20

21 This study evaluates the effects of high percentages of different by-products, including blast
22 furnace slag (BFS) and fly ash (FA), on the structural performance, energy requirement and
23 environment impacts of a concrete heavy-duty pavement (HDP) at various curing
24 temperatures. The results of the structural performance indicate that HDP containing up to
25 70% BFS and HDP containing 30% FA can be comparable in controlling the HDPs designed
26 for highways and airports. Moreover, the results of the environmental impact assessment
27 indicate that the synergy of the by-product and warm water can reduce the energy
28 requirement and CO₂ footprint by 5.77% to 56.54% and 8.16% to 55.5% for the highway and
29 airport HDPs, respectively. Although the elevated curing temperature improves the structural
30 performance and sustainability of the concrete pavements, any delay in concrete production
31 increases energy consumption accordingly. Moreover, a new parameter (∇_{TE}), which is the
32 time gradient per unit energy consumption developed based on the Laplace transformation, is

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

38
39 **Keywords:** Resource management, Sustainable practice, Sustainable infrastructure asset,
40 Low energy pavement,

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42

43 **1. Introduction**

44

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

60 It should be noted that a major part of this estimated investment is utilized for maintenance
61 and rehabilitation of highways and bridges. Therefore, a substantial budget is required to
62 supply materials for construction, maintenance, and rehabilitation of pavements and bridges.
63 One of the alternatives to reduce the expenditure is the utilization of industrial by-products as
64 supplementary materials. Another significant advantage of incorporating the by-products is
65 the reduction of the ever-increasing demand on nonrenewable natural resources. It should be
66 noted that direct diversion of by-products in other industries into pavement construction
67 projects not only reduces CO₂ footprint, but also increases the productivity because such
68 materials are no longer wasted. For example, blast furnace slag (BFS) and fly ash (FA) are
69 typical industrial by-products that can be used as alternative materials in the infrastructure
70 asset construction. BFS, as a by-product of metallurgical processes, is ranked as the second
71 most desirable waste material for highway pavement constructions from a technical
72 viewpoint, while it is ranked fifth and sixth in economic and environmental perspectives,
73 respectively (Ahmed 1993). It is estimated that 2 to 4 tonnes of waste material per one tonne
74 of steel is produced during the manufacturing of steel (Das et al. 2007). The results of a study
75 showed that the concrete pavements incorporating 50% by-products, such as BFS and FA,
76 can be used for airports (Godiwalla 2004). In a similar study, Jamshidi et al. (2015) found
77 that the structural performances of airport pavements incorporating BFS can be comparable
78 to that of traditional pavements.

79 Furthermore, coal-fired power plants produce approximately half of the total electricity in the
80 United States, which results in over 134 million tonnes of coal-combustion by-products per
81 annum consisting of almost 50% FA (Lav et al., 2006). Cetin et al. (2012) studied the effects
82 of FA on the leachate of the base layer. The results indicated that metal concentration of the
83 leachate increases with the increase in the FA content, which implies that the metal content of
84 the soil increases. The results also showed that Cr, Sb, Va, Mn, and Fe were lower than the

85 requirements prescribed by the U.S Environmental Protection Agency. It should be noted that
86 the required structural performance of the base thickness incorporating FA depends on the
87 pavement applications (Jamshidi et al. 2015). Martin et al., (2017) reported that the cement
88 mortar with 7.5 mass-% fly ash showed higher compressive strength than the samples without
89 fly ash when the water to cement ratio (W/C) ratio was kept constant. Moreover, soft clay
90 samples incorporating blend of cement kiln dust and FA had unconfined compressive
91 strength than the samples modified by ordinary Portland cement (Yoobanpot et al., 2017).

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

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

110 and curing temperature of by-products on the structural performance and sustainability of
111 HDPs designed for highways and airports. Ultimately, a new parameter is proposed to
112 characterize the effects of the delay on energy consumption of the HDPs.

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

119 **3. Materials and Methods**

120

121 **2.1. Materials**

122

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

125

126 **2.1.1. Cement**

127

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

131

132 **2.1.2. By-products**

133

134 2.1.2.1. Blast Furnace Slag

135

136 In this study, granulated BFS, hereinafter BFS, is used. The specific gravity of the BFS was
137 2.91 g/cm^3 . The replacement ratios of the BFS were 0%, 50%, and 70% of the cement,

138 hereinafter the samples, containing 0% (control), 50%, and 70% BFS. Table 2 lists the
139 chemical composition of the BFS.

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141
142
143

2.1.2.1. Fly Ash

144 Table 3 lists the chemical compositions of the cement and the by-products. In this study, 15%
145 and 30% of the cement were substituted by the FA. The specific gravity of the FA was 2.33
146 g/cm³.

147
148
149

2.2. W/C Ratio and Water Curing Condition

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

2.3. Structural Performance

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

$$\text{MR} = K \sqrt{f'_c} \quad [1]$$
$$\text{Working Stress} = \frac{\text{MR}}{\text{SF}} \quad \text{Packard (1973)} \quad [2]$$

161
162
163

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.

164 **2.4. Reinforcing Steel**

165

166 The following three types of reinforcements with different performances were designed for
167 the pavements: 1) dowel bar, 2) tie bar, and 3) wire fabric or bar mat reinforcement. The
168 dowel bars were used as load-transfer devices from one slab to the adjacent one. Furthermore,
169 the dowel-group action prohibits faulting in the transverse joints. The tie bar steel was also
170 designed to hold the adjacent concrete slabs together. The wire fabric or bar mat
171 reinforcement was designed to control the temperature cracks. Therefore, such
172 reinforcements enhance the structural capacity of the pavement against warping, contraction,
173 and loading stresses. It is also assumed that the length of each panel of concrete pavement is
174 12 m.

175 **2.5. Highway**

176

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

181 To design the highway pavement, a 12 km dual carriage highway with three lanes in each
182 direction (each lane width is 3.65 m) was considered. The number of equivalent axle loads is
183 5,000,000, and the assumed reliability is 95%.

184 **2.6. Airport**

185

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

191 787 lighter, saving 20% on jet fuel and air emissions, and the design is considered sustainable
192 (Uddin, et al. 2013). It should be noted that there is a attitude evolved in selection of fleet in
193 the air transportation. In this regard, the airlines prefer to utilize narrow-body aircrafts, such
194 as Boeing 777 and Airbus A350, rather than the wide-body planes, e.g., Boeing 747(Jumbo
195 jet) or A380. The reason is the change of the general philosophy from the "hub-and-spoke" to
196 the "point-to-point". In other words, the airlines require relatively cost-effective aircrafts for
197 short ranges. This new philosophy has negatively affected marketing for the wide-body
198 aircrafts, which is usually used for a long range.

199 Table 4 lists the technical specifications of the design aircraft. The number of departures is
200 assumed 10,000. The structural design methodology used was based on the study by Packard
201 (1973).

202
203
204

2.7. Energy Analysis

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

2.7.1. Cement

209
210

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

2.7.2. By-products

215
216

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

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

224 **2.7.3. Water**

225

226 Each stage of water production, including water supply, treatment, use, and disposal,
227 consumes considerable energy. It should be noted that the water energy production may vary,
228 which depends on climate, water recourse, applied technology, and productivity of water
229 production infrastructure assets. It is reported that 7% of total worldwide generated electricity
230 is used for the production and distribution of water and treating of waste water (Young 2010).

231 In this study, the energy requirement for water can be divided into two parts.

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

233 In this study, the water is assumed to be supplied from wells. In this regard, the energy
234 requirements for the well and its pumping were 0.15 and 0.32 kwh/m³ (Elliott et al. 2003),
235 respectively. Furthermore, energy consumption for chlorination of the extracted water was
236 0.0024 kwh/m³ for a pump with a capacity of 3,780 m³/day (Plappally 2012). Moreover,
237 energy consumption of sedimentation varies from 0.0005 to 0.001 kwh/m³ (Plappally 2012);
238 0.0008 was chosen in this study. Therefore, the total energy consumption in this phase is
239 0.4732 kwh/m³.

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

242 The required heat energy was calculated using Equation 3:

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

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

247

248 **2.7.4. Aggregate**

249

250 Aggregate is ranked as the first nonfuel mineral material in terms of value and volume (Asif
251 2009). For example, the economic value of aggregate is €120 billion, whereas the values of
252 gold and iron are approximately €20 and €18 billion, respectively (Wellmer and Becker-
253 Platen 2002). Bleischwitz and Bahn-Walkowiak (2006) estimates that the annual aggregate
254 demand increases by 4.7%. There is a strong correlation between aggregate consumption and
255 construction of infrastructure assets. Aggregate production is an energy intensive task. For
256 example, Alcorn (2003) proposed an energy requirement of 40 MJ/tonne for aggregate
257 production, close to 38.18 MJ/tonne was reported by Stripple (2001), which covers blast
258 operation, transportation, and crushing the blast rock. Therefore, 40 MJ/tonne is chosen for
259 aggregate production in this study, which lies within the range of 22 to 500 MJ/tonne
260 recommended by Goodquary (2006). Moreover, it falls within the range of 21.1 MJ/tonne to
261 63.3 MJ/tonne suggested by NCSA (1977).

262

263 **2.7.4. Steel**

264

265 There are well-documented data on energy consumption for steel manufacturing. For
266 example, Stubbles (2000) recommended an energy requirement of 19 GJ/tonne, which lies
267 within the range of 18 GJ/tonne to 23 GJ/tonne recommended by Stammer and Stodolsky
268 (1995). In addition, Eriksson (2003) recommended 1.6 GJ/m². World Slag Association (2011)
269 reported that preliminary energy demand for the steel sections is 19.6 GJ/tonne, while the

270 corresponding value is 21.6 GJ/tonne for the steel manufactured using hot-rolled coils, which
271 falls within the range recommended by Stammer and Stodolsky (1995). In this study, 19
272 GJ/tonne is used, as recommended by Stubbles (2000).

273

274 **2.7.5. Pavement Construction**

275

276 The construction of pavement consists of the following two stages:

277 1) Mixture production: the cement, water, aggregate materials, admixtures, such as plasticizer
278 or superplasticizer, air entraining, water-reducing, retarding, accelerating, corrosion-
279 inhibiting materials are blended. It is clear that the adopted mixing process (e.g., central
280 mixed concrete plant or concrete dry batch plant) depends on the efficiency of mixing
281 machinery and W/C ratio, etc. The energy requirement for the concrete mixing process is
282 6.875 MJ/tonne, according to the field data surveyed from the contractors and reported by
283 Zapata and Gambatese (2005).

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

290

291 **2.8. Characterization of Delay**

292

293 As the delay time has no economic value, the effect of time should be converted to a quantity
294 that can be measured in terms of cost. In general, the effect of time needs to be characterized
295 based on indicators such as fuel consumption, environmental impact indicators, or any other

296 output to measure it in monetary terms. In this study, the energy requirement is chosen as an
297 indicator to measure the effect of delay.

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

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

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

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

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

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.

322
 323 The Laplace transformation is used instead of the simple integral (Equation 5), because the
 324 simple integral requires a specific upper limit for integration, but it is impossible to guess the
 325 exact value of the delay before the commencement of any paving project, and hence, defining
 326 a closed interval becomes difficult. However, based on the definition of the Laplace
 327 transformation, the delay time can vary from zero to infinity, which is the case practically
 328 observed in paving projects.

329

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

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

330

331 **2.9. Environmental Impact Assessment**

332

333 All energy requirement is converted to the industrial fuel type, natural gas in this study. Then,
 334 the GHG emissions, including CO₂, CH₄, and N₂O, are calculated using the proximity factors
 335 provided by DEFRA (2010) as listed in Table 6. Figure 3 represents a flowchart illustrating
 336 the analysis and discussions in this research.

337 3. Results and Discussion

338

339 3.1. Structural Performance

340

341 Figure 4 shows the structural design curves for highway and airport concrete pavements.

342 Figures 4(a) and 4(b) show that the lowest required slab thickness is for the pavement section

343 with a W/C ratio of 0.3 for all curing temperatures and pavement applications because the

344 lower W/C ratio increases concrete strength, however mix workability decreases. In contrast,

345 the required thicknesses increase as W/C ratio increases because the concrete porosity or air

346 void percentage increases due to more water content, thereby the values of parameters

347 indicating structural strength, such as compressive strength and the Young's modulus,

348 decrease.

349 However, the required thickness of highway pavement decreases with the increase in the

350 curing temperature (Figure (4a)). But, the curing temperature has no significant impact on the

351 control pavements designed for the airport (Figure 4(b)). For example, the required slab

352 thickness of the control airport pavements with a W/C ratio of 0.3, cured at 35 °C, is 29.97

353 cm (30 cm), and the thickness for the sample with the same W/C ratio, cured at 20 °C, is

354 30.98 (or 31 cm). In practice, the required thickness is rounded off to the nearest multiple of 5.

355 As a result, curing of control pavement sections mainly depends on W/C ratio rather the

356 curing temperature.

357 Figures 4(c) to 4(f) show the design charts for various BFS contents and curing temperatures.

358 It can be seen that the required thickness for the highway and airport pavements,

359 incorporating by-products and cured at 35 °C and 50 °C, are almost the same as that of the

360 control pavements, indicating that the structural response of the by-product pavements in

361 terms of the required thickness are comparable to the control pavement thickness. Moreover,

362 the figures show that the increase in the curing temperature slightly decreases the required

363 thickness. As a result, the pavement thickness is sensitive to the thermal gradient because of

364 the various curing temperatures. Figures 4(d) and 4(f) also indicate that the minimum
365 thicknesses are for the airport pavement sections containing 50% BFS or 15% FA,
366 conditioned at 35 °C. Beyond 50% BFS or 15% FA, the required thickness increases because
367 incorporating a higher percentage BFS and FA decreases the structural strength of the
368 concrete samples because such mixes require more time to gain the same strength as that of
369 the control pavement. This is because the hydration reactions and setting of blended cements
370 (cement included with by-product) is less than that of the control samples. One approach is to
371 accelerate strength gain or setting of by-product pavements by increase in the curing
372 temperature; hence, pavements constructed and conditioned at higher temperatures require
373 relatively lower thicknesses. In other words, the warm water can be considered as a catalyst
374 to enhance hydration rate in the concrete pavements incorporating BFS or FA. There are also
375 various types of chemical additives to increase the hydration process, however use of warm
376 water is relatively cost-effective way that requires neither particular technical skills nor
377 sophisticated technology. Furthermore, results of analysis of variance (ANOVA) listed in
378 Table 7 show that interaction between the by-product and curing temperature has a
379 significant factor on the Young's modulus of samples conditioned after curing for 180 days.
380 However, although the difference between the required thicknesses cannot be considered
381 insignificant, such small differences can significantly affect the environmental loadings
382 encountered throughout the life cycle of the pavement sections.

383
384
385

3.2. Energy Analysis and Environmental Impact Assessment

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

390 43.54% lower than that of the control pavements under the same curing conditions,
391 respectively. In another example, the pavement section incorporating 30% FA conditioned at
392 35 °C requires 9.77% energy, which is lower than that of the control pavement. Subsequently,
393 the carbon footprint decreases by 7.68%. In other words, incorporation of BFS or FA reduces
394 energy requirement in the raw material phase process (Figure 1) because less cement material
395 is needed.

396

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

411

412 Figure 6 shows that the high curing temperature dramatically increases the fuel requirement
413 for water, as one phase of raw material is processed for both by-product type and content.
414 Therefore, pertinent CO₂ footprint in water processing phase increases, as listed in Table 8.

415 However, the total fuel consumption, which covers the entire life cycle of the pavement,
416 including from cradle to the gate, reduces (Table 8). This may be because the high curing
417 temperature accelerates hydration and curing as a progressive phenomenon in the concrete
418 texture. Hence, the concrete pavement gains its strength faster. Therefore, a lower pavement
419 thickness is required owing to higher strength, thereby decreasing the amount of material used. For
420 example, the carbon footprint due to water processing for 50% BFS highway pavement is
421 1,174 kg at 20 °C, shown by grey colour, whereas the corresponding value is 39,148.9 kg and
422 79,293.2 kg for the curing temperatures 35 °C and 50 °C, respectively, which are 33.34 and
423 67.54 times higher than that of curing at 20 °C. In contrast, the total CO₂ footprint of the
424 pavements conditioned at the higher temperatures are much lower than sections cured at
425 20 °C. For example, the total CO₂ footprint of the highway pavement incorporating 70% BFS,
426 cured at 20 °C is 43.54% lower than that of the control pavement conditioned at the same
427 temperature (Table 9), while the corresponding values of the 70% BFS pavements
428 conditioned at 35 °C and 50 °C are, respectively, 55.73% and 56.54% less than that of the
429 control pavement, wherein the observed differences of 12.19% (55.73%-43.54%) and 13%
430 (56.54%-43.54%) stem from the elevated curing temperatures. A similar trend can be seen for
431 the FA and the other pavement types. Hence, synergy of use of the by-product, the water
432 temperature in concrete production and curing improved the sustainability of concrete
433 production.

434 Furthermore, it should be noted that reduction in percentage of CO₂ footprint due to elevated
435 curing temperature depends on the by-product content. For example, the reduction in CO₂
436 footprint of 15% FA highway pavement cured at 35 °C is 12.54 % lower than that of the
437 control pavement (Table 9), while the corresponding value for 30% FA pavement
438 conditioned at the same temperature is 17.51%, and 4.97% if the FA is increased further by
439 15%.

440 Moreover, the emission results can be validated by comparing the findings to a recently
441 published research on LCA (from cradle to gate) carried out by Scott and Durham (2016).
442 The results of this study indicated that CO₂ reduction for a 30-cm concrete pavement
443 incorporating FA is 11.23%, which is consistent with 11% CO₂ reduction reported by Scott
444 and Durham (2016) for the FA pavement with the same thickness. Moreover, the CO₂
445 emission reduction of the pavement incorporating 30% FA with almost the same thickness is
446 13.27%, which is very close to results obtained by Scott and Durham research for the
447 concrete pavement incorporating the same FA content. Furthermore, the results of this study
448 is relatively in harmony with results reported by Seto et al., (2017) indicated that the
449 reduction in environmental impacts of FA concrete depends on scenarios used for
450 construction.

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

456

457 **3.3. Characterization of Delay on Sustainability of HDP**

458

459 Figure 7 shows the amount of energy consumption at different delay times. It can be seen that
460 the energy consumption increases linearly for both by-product types and curing conditions,
461 which decreases the energy efficiency in pavement construction. For example, energy
462 requirement for 4 h delay in highway HDP containing 70% BFS, conditioned at 35 °C is 105
463 TJ, while it is 106.5 TJ for a 6 h delay (Figure 7(e)), which results in 39,162 m³ natural gas
464 loss because of a 2 h extra delay. Therefore, it is recommended to avoid any delays during the

465 mixing phase of concrete produced and conditioned using warm water. However, the delay is
466 often inevitable in paving projects; hence, it is recommended to estimate the delay time and
467 include its effects in terms of energy requirement or emissions.

468

469 From Figure 7, it can be seen that the energy consumption of some pavements conditioned at
470 different temperatures converge when the delay increases. Therefore, the energy requirement
471 for curing conditions can be equal for both curing temperatures, highlighted by red circle. For
472 example, in the control airport concrete pavement with a W/C ratio of 0.4 (Figure 7(i)),
473 energy requirement for various curing conditions are equal after a delay of 2 h. It can be
474 interpreted that if the concrete is produced using 50 °C water with a 2 h delay, the total
475 energy requirement to heat the water is equal to the concrete produced using 35 °C. Therefore,
476 a delay of 2 h can be tolerated in this case. Figure 7(e) shows that a delay of 3 h can be
477 tolerated for the highway concrete pavements incorporating BFS produced using water at
478 50 °C. However, the energy requirement due to delay in pavements containing 70% BFS
479 using 50 °C water is strictly higher than BFS pavements at 35 °C.

480 In the case of FA pavements, Figure 7(f) shows that the delay time can be tolerated for up to
481 6 h for the 15% FA pavements produced using 50 °C water, while it decreases to 2 h when
482 the FA content increases to 30% (Figure 7(g)), which is 67% lower than the 15% FA
483 pavement. Therefore, increase in the FA content decreases the delay that can be tolerated
484 during concrete production. Therefore, the tolerated delay depends on the HDP application,
485 by-product type, and content. As the water content, in terms of increase of W/C in concrete
486 production, increases, energy loss due to the delay rises because more heat energy is function
487 of material mass, the specific heat capacity and the target temperature, as shown by equation
488 (3).

489 Figure 8 shows the values of ∇T_E for various HDP types and conditioning temperatures. For
490 example, ∇T_E for the highway pavement incorporating 50% BFS, conditioned at 35 °C is
491 1.385 h/TJ, which implies that the time requirement for 1 TJ energy consumption is 1.387 h,
492 while the corresponding value at 50 °C is 0.675 h (Figure 8(a)). Therefore, the time
493 requirement for consumption of unit tera joule energy (1TJ) due to delay for pavements using
494 50 °C water is 51% less than those at 35 °C, because of higher water temperature. Hence,
495 when the curing temperature increases, energy is consumed due to the delay during concrete
496 mixing at a shorter time; consequently, the speed of energy consumption increases.

497

498 Figures 8(c) and 8(d) show that ∇T_E of the airport pavements are higher than those of the
499 highways, because the total material consumption, including water requirement, in the airport
500 pavements is much lower than that of the highway. Therefore, the energy required to keep the
501 water warm decreases, which means that ∇T_E depends on the HDP application. Moreover,
502 ∇T_E values decrease by approximately 50% while temperature increases from 35 °C to 50 °C;
503 hence, 15 °C increase in water temperature reduces the time requirement for 1 TJ energy
504 consumption by 50%. For example, ∇T_E of the pavements containing FA conditioned at
505 35 °C is 1.427 h/TJ, while the use of 50 °C water decreases ∇T_E to as low as 0.734 (Figure
506 8(b)), which is almost 50% lower than that conditioned at 35 °C. In other words, speed of
507 energy consumption due to delay increases, as water temperature increases. As a result, the
508 delay has more effect on energy consumption while warmer water curing is used in concrete
509 production. Therefore, the use of 50 °C water has no significant effects on reduction of
510 required thickness of HDP incorporating by-products (Figure 4). In addition, energy
511 requirement of water processing for all HDPs (Figures 6 and 7) and CO₂ footprint (Table 8)
512 increase and any delay in the construction results in a huge amount of energy loss (Figure 8).

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

515
516 **4. Conclusion**

517 Effects of synergy considering different contents of BFS and FA and water curing
518 temperatures on the structural performance, energy consumption, and environmental aspects
519 of HDP were evaluated in this research. The results of structural design clearly showed that
520 structural performance, in terms of required slab thickness, of HDP incorporating high
521 percentage of BFS and FA is comparable to the control HDP section for both the highway
522 and the airport. The strength gaining phenomenon, resulting from the hydration reaction, can
523 be accelerated via the use of warm water in concrete production and curing. Hence, BFS and
524 FA can be considered as alternative cementitious materials for HDP, saving huge amounts of
525 space in landfills and reducing the amount of natural materials to be mined. Furthermore,
526 construction of HDP, containing by-products and warm water, decreases energy requirement
527 and CO₂ footprint from 33% to 56.54% for highway HDP incorporating BFS and 0.54% to
528 18.16% for HDP containing FA; the corresponding values are 41.42% to 55.5% for the HDP
529 containing the BFS designed for the airport and 8.16% and 13.05% for the HDP containing
530 the FA. Although the elevated temperature of water for concrete production and curing
531 decreases energy requirement and emissions, any delay to use the warm water increases
532 energy requirement proportionately. To characterize the effect of delay, ∇_{TE} is proposed,
533 indicating the time required for 1 TJ energy consumption. The analysis of ∇_{TE} showed that
534 the time required for consumption of 1TJ, due to any delay, decreases by 50% as the water
535 temperature increases from 35 °C to 50 °C. Therefore, a temperature of 35 °C is
536 recommended for water curing because the structural performance is improved, and avoiding
537 any extra energy loss and CO₂ emissions due to delay.

539

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

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

556

557 **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.

558

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563

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661

662

663

Table 1: Chemical composition of cement

Chemical component	Weight (%)	Chemical component	Weight (%)
SiO ₂	21.45%	TiO ₂	0.23%
Al ₂ O ₃	5.69%	Na ₂ O	0.31%
Fe ₂ O ₃	2.68%	K ₂ O	0.48%
CaO	65.20%	SO ₃	1.92%
MgO	1.95%	P ₂ O ₅	0.20%
MnO	0.06%	Cl	0.016%

Table 2: Chemical composition of BFS

Chemical component	Weight (%)
SiO ₂	34.13
Al ₂ O ₃	13.84
Fe ₂ O ₃	0.70
CaO	43.73
MgO	6.71
TiO ₂	0.55
Na ₂ O	0.22
K ₂ O	0.32

Table 3: Chemical composition of FA

Chemical component	Weight (%)
SiO ₂	63.16
Al ₂ O ₃	25.25
Fe ₂ O ₃	5.51
CaO	1.45
MgO	0.76
TiO ₂	1.14
Na ₂ O	0.013
K ₂ O	1.42
S ₁ O ₃	0.219
P ₂ O ₅	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 ₂ e/unit)	N ₂ O(kg CO ₂ e/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 CO₂ 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 CO₂ 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 CO₂ footprint between the section and control pavement conditioned at 20 °C

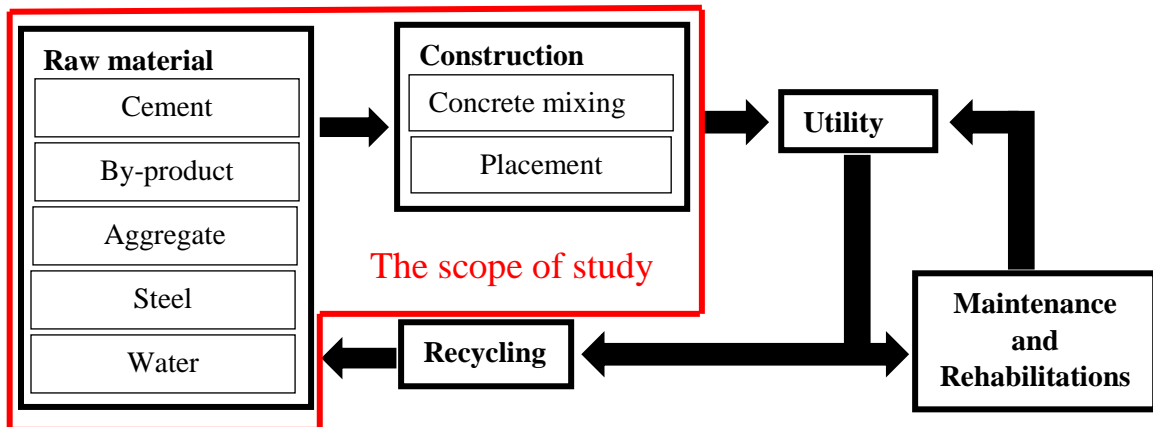


Figure 1: A typical life cycle for asphalt pavement.

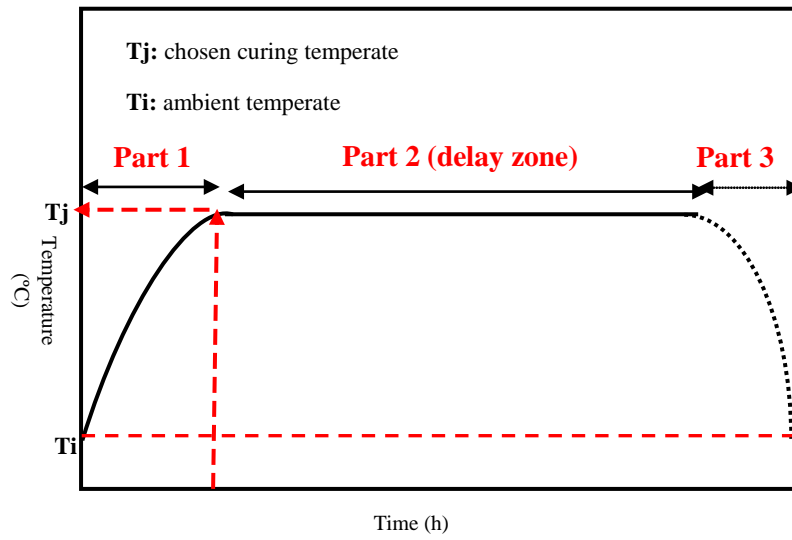


Figure 2: Schematic of temperature versus time during heating of water to the curing temperature

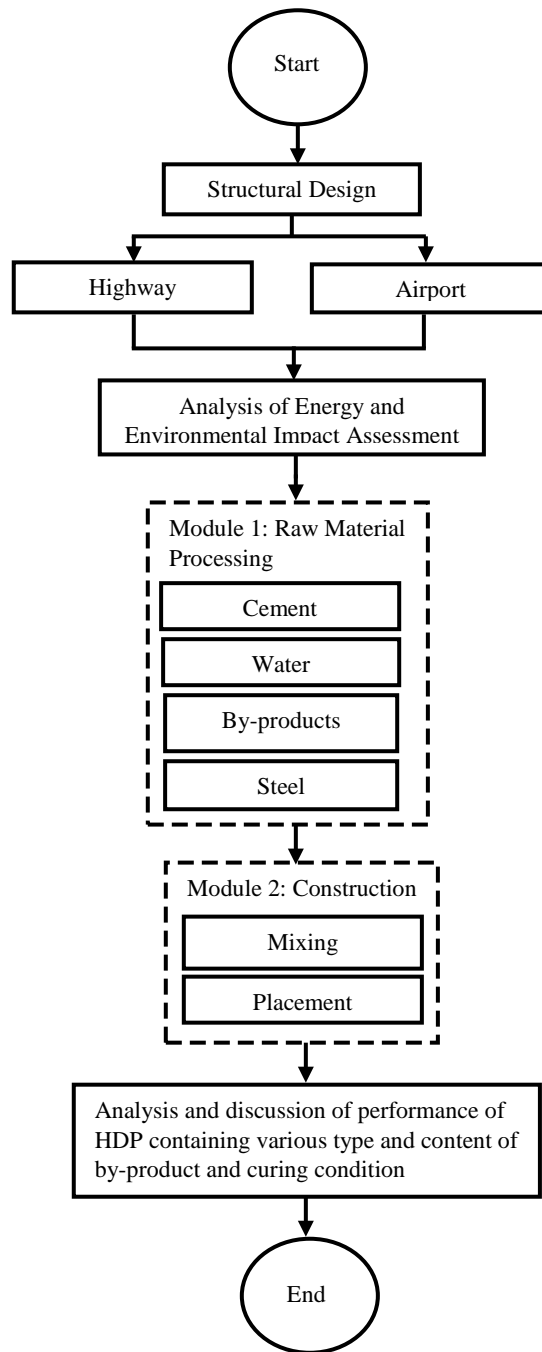
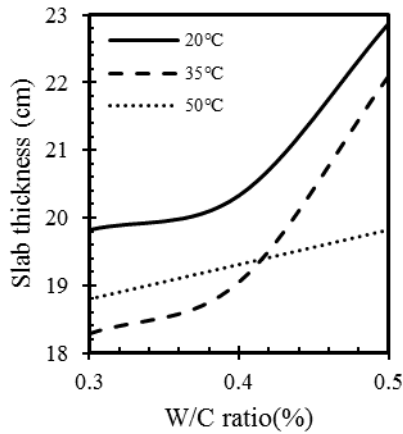
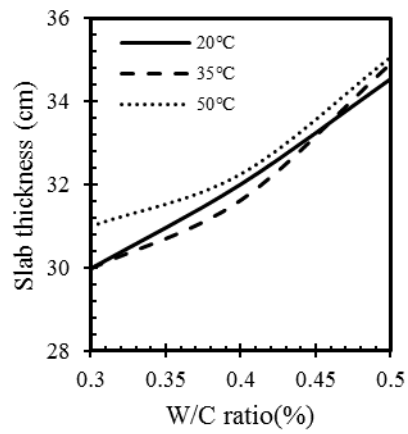


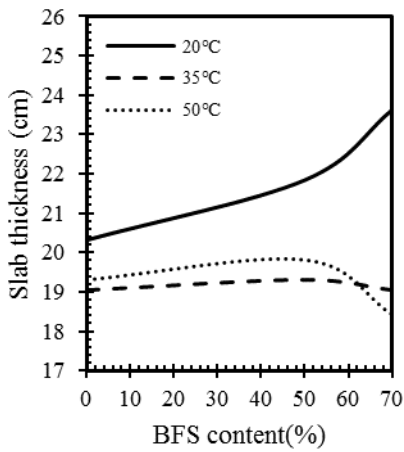
Figure 3: flowchart illustrating analysis and discussions of this research



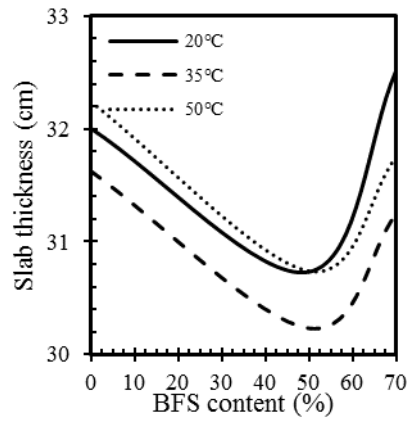
(a) control pavement for highway



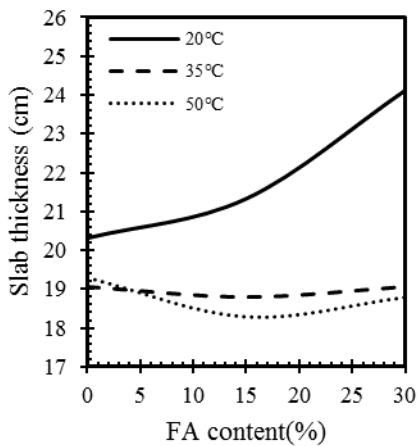
(b) control pavement for airport



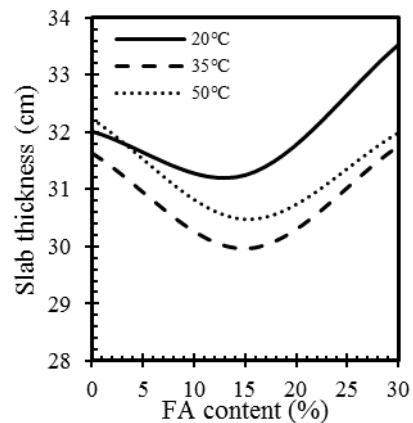
(c) BFS pavement for highway



(d) BFS pavement for airport

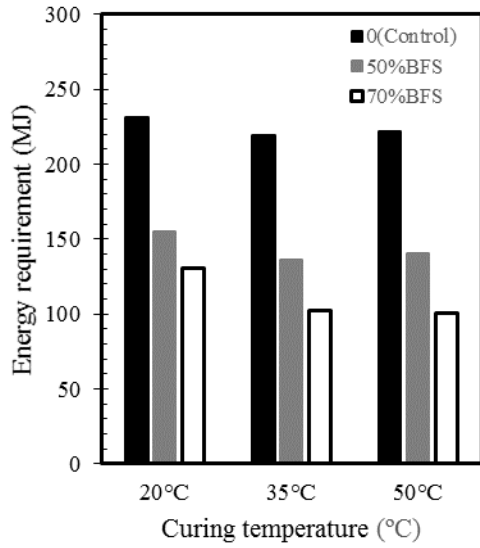


(e) FA pavement for highway

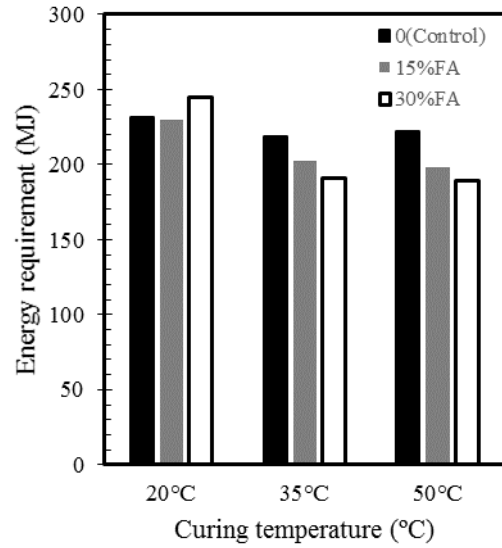


(f) FA pavement for airport

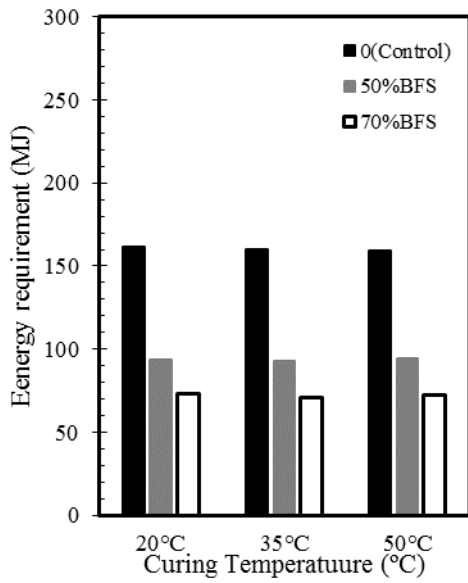
Figure 4: Structural design charts for highway and airport pavements



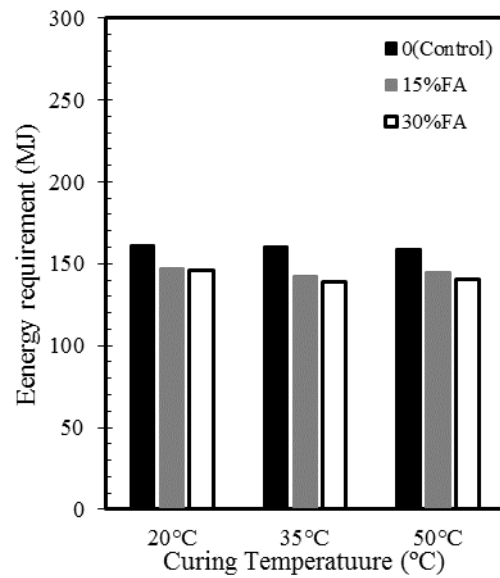
(a) BFS for Highway



(b) FA for Highway

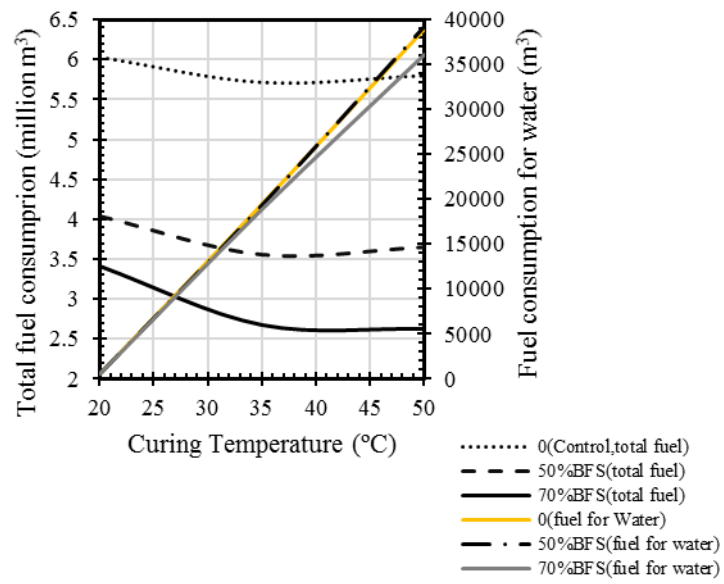


(c) BFS for Airport

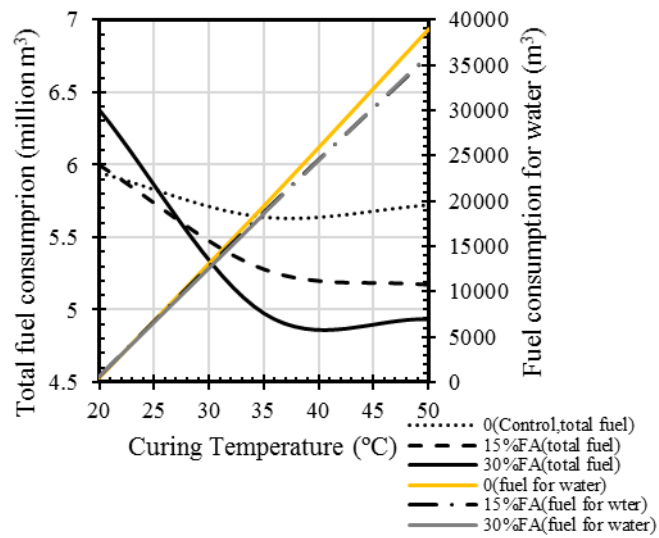


(d) FA for Airport

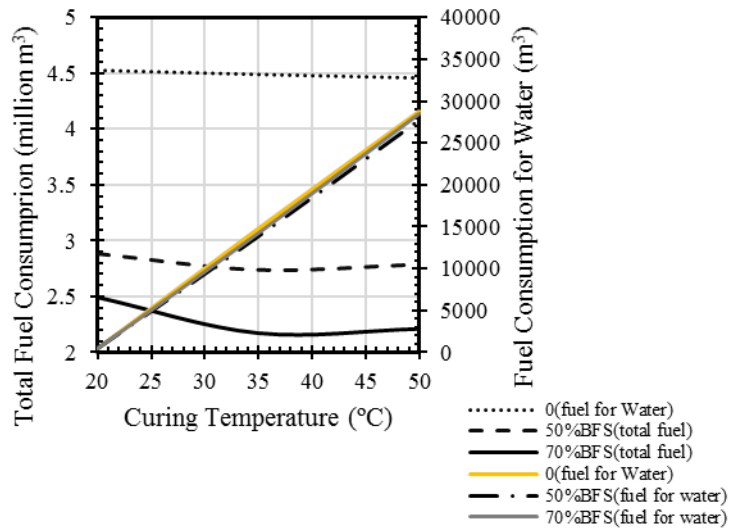
Figure 5: Energy requirement for the pavement incorporating various by-products



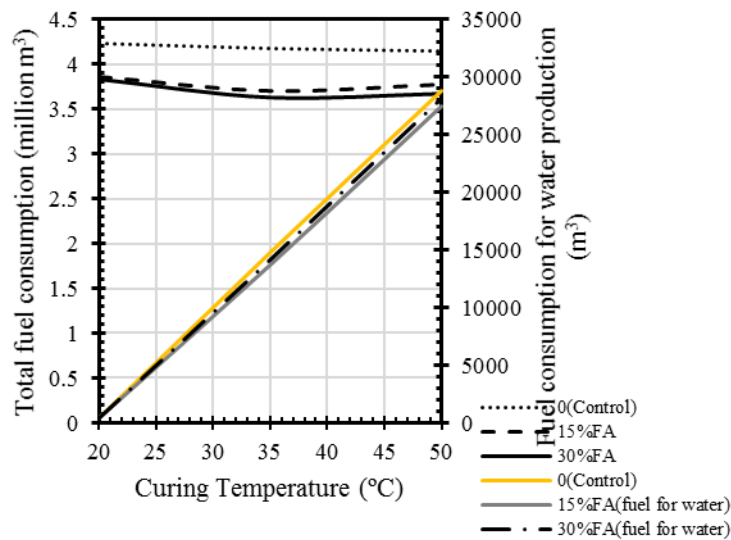
(a) BFS for Highway



(b) FA for Highway

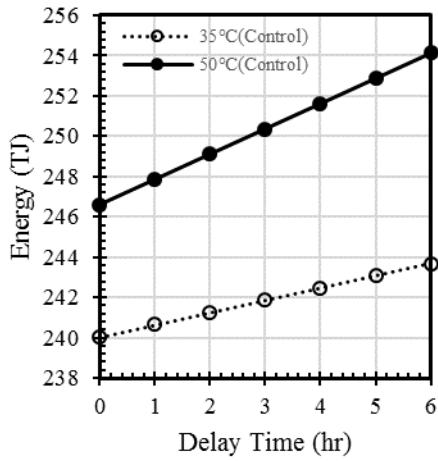


(c) BFS for Airport

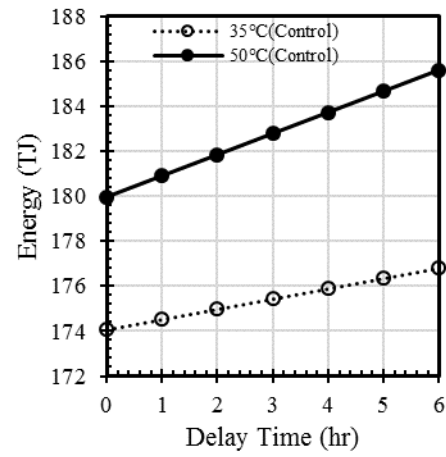


(d) FA for Airport

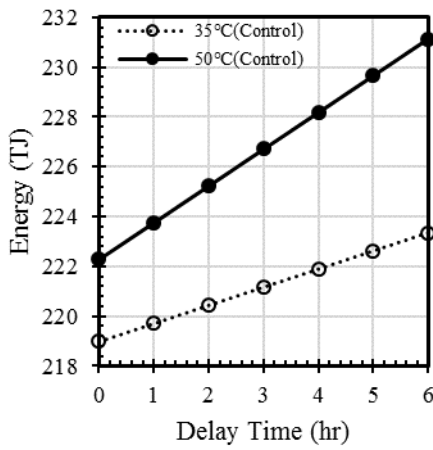
Figure 6: Effects of curing temperature on fuel requirement for water supply, total fuel requirement, and pavement construction



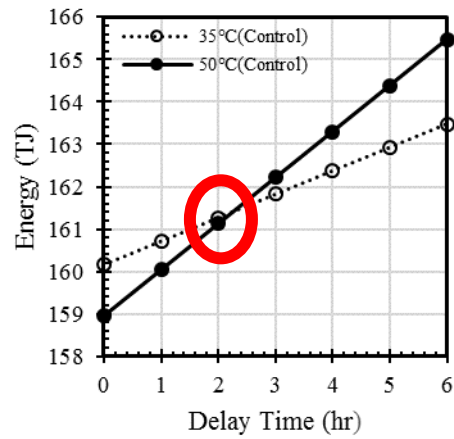
(a) Highway(W/C=0.3)



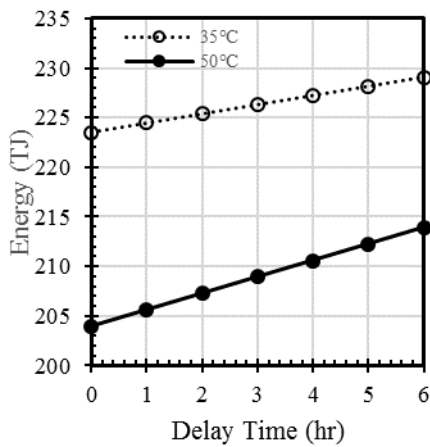
(h) Airport(W/C=0.3)



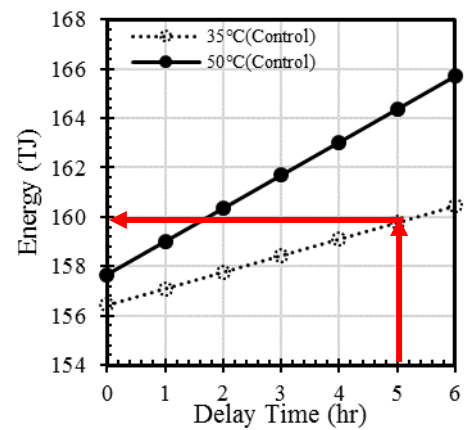
(b) Highway(W/C=0.4)



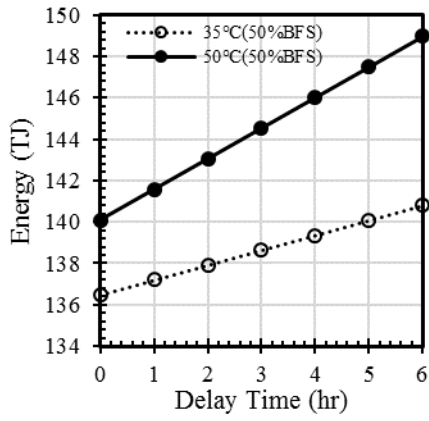
(i) Airport(W/C=0.4)



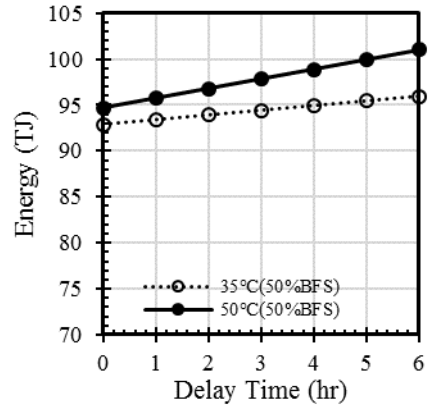
(c) Highway(W/C=0.5)



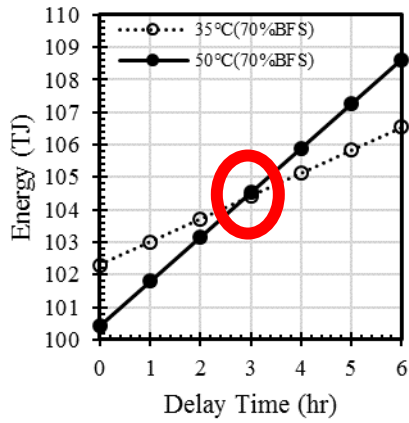
(j) Airport(W/C=0.5)



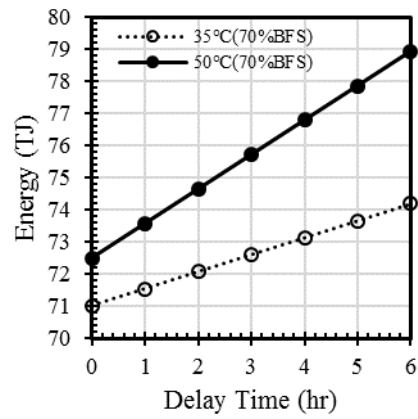
(d) Highway



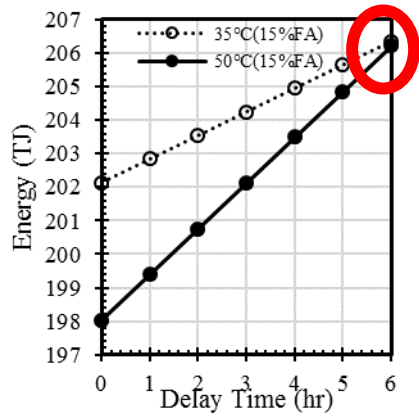
(k) Airport



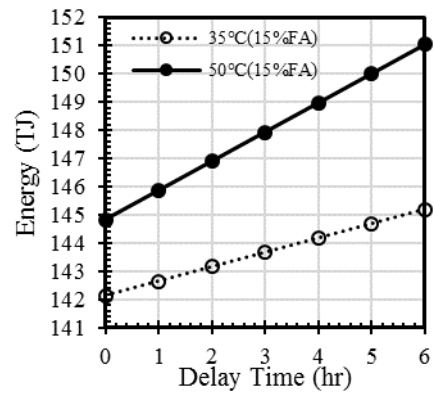
(e) Highway



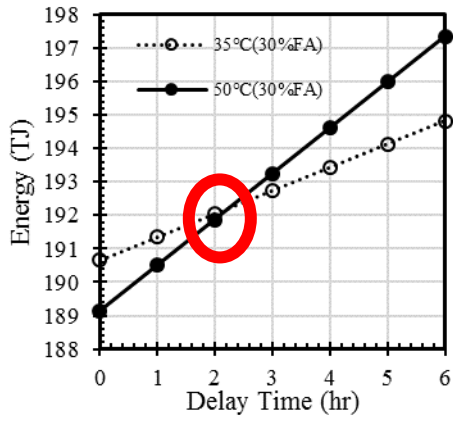
(l) Airport



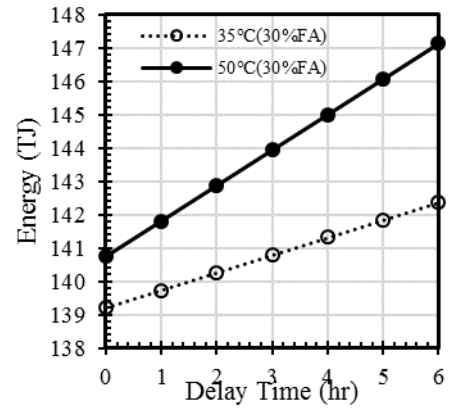
(f) Highway



(m) Airport

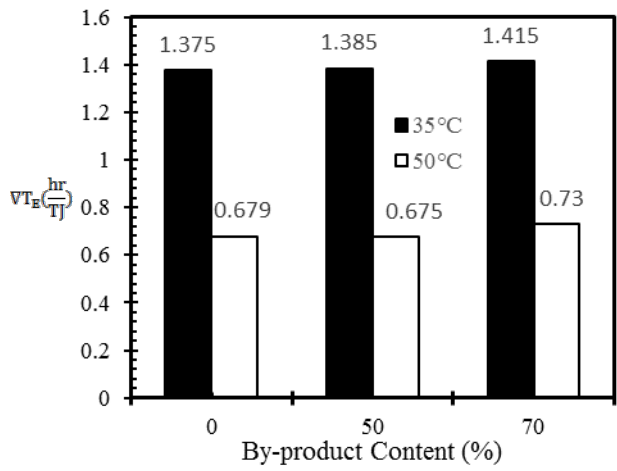


(g) Highway

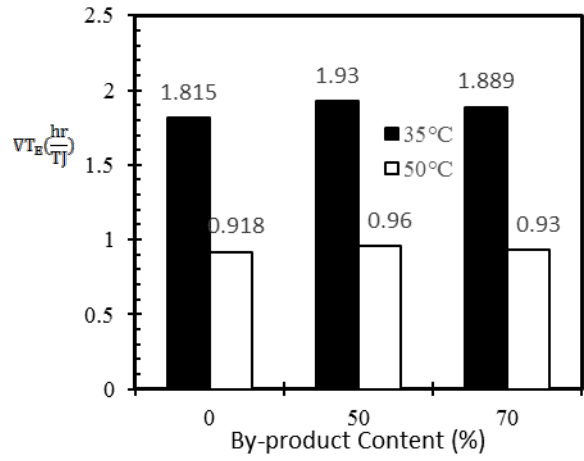


(n) Airport

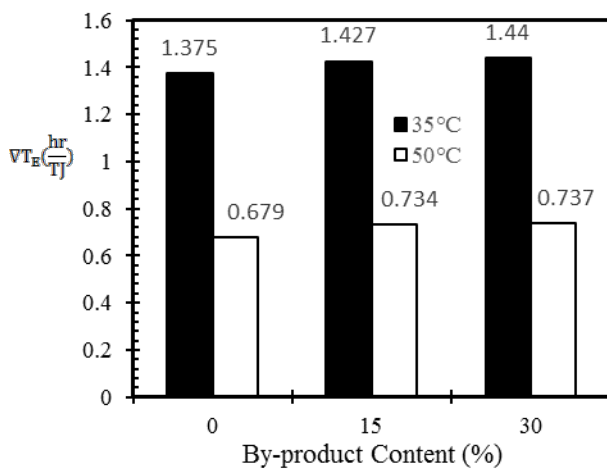
Figure 7: Energy consumptions due to delay in concrete production



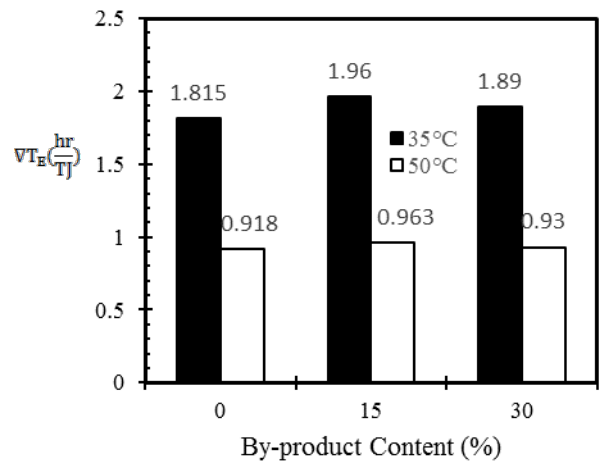
(a) Highway pavement containing BFS



(c) Airport pavement containing BFS



(b) Highway pavement containing FA



(d) Airport pavement containing FA

Figure 8: Relationship between \overline{VT}_E for various HDPs.