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1 **Electrical and Mechanical Properties of Asphalt Concrete containing** 2 **Conductive Fibers and Fillers**

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4
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10 11 **ABSTRACT**

12 Electrically conductive asphalt concrete has the potential to satisfy multifunctional applications.
13 Designing such asphalt concrete needs to balance the electrical and mechanical performance of
14 asphalt concrete. The objective of this study is to design electrically conductive asphalt concrete
15 without compromising on the mechanical properties of asphalt concrete. In order to achieve this
16 goal, various tests have been conducted to investigate the effects of electrically conductive
17 additives (steel fiber and graphite) on the laboratory-measured electrical and mechanical
18 properties of asphalt concrete. The results from this study indicate that the critical embedded steel
19 fiber length is 9.6 mm to maximize the fiber's potential to bridge across the crack from single fiber
20 tensile test. Both steel fiber and graphite can produce conductive asphalt concrete with sufficiently
21 low resistivity, but steel fiber is much more effective than graphite to improve the conductivity of
22 asphalt concrete. A combination of steel fiber and graphite can precisely control the resistivity of
23 asphalt concrete over a wider range. Besides, asphalt concrete containing an optimized amount of
24 steel fibers has a significant improvement in Marshall Stability, rutting resistance, indirect tensile
25 strength, and low temperature cracking resistance compared to the plain concrete. The addition of

26 graphite could increase the permanent deformation resistance with compromised stability and low
27 temperature performance. Asphalt concrete containing steel fibers and graphite weakens the steel
28 fiber reinforcing and toughening effect, but still has a significant improvement in mechanical
29 performance compared to the plain concrete.

30

31 **Keywords:** Asphalt concrete, Electrical conductivity, Mechanical properties, Fiber, Graphite

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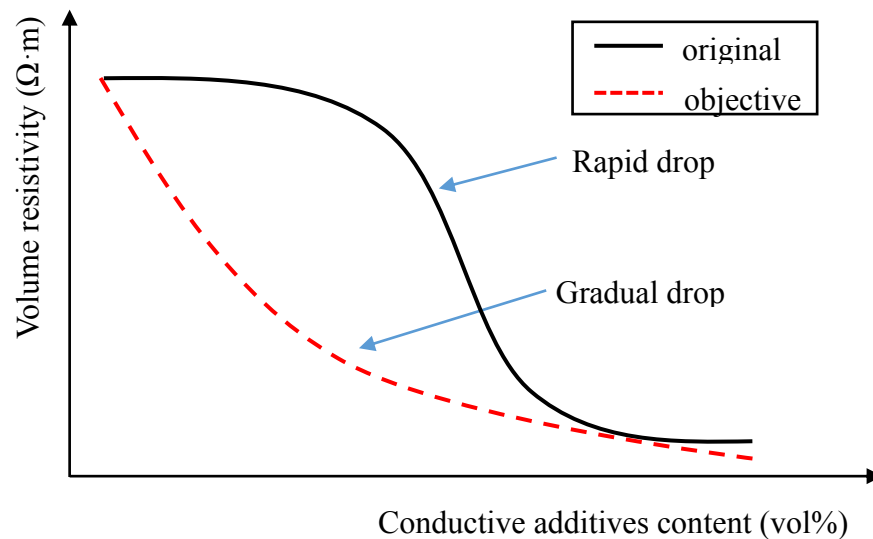
33 **1. Introduction**

34 Asphalt concrete (AC), contains two components, bitumen and aggregates. Bitumen is very
35 sensitive to temperature and behaves brittle at low temperature and viscous at relative high
36 temperature. Most of the deteriorations in asphalt concrete stem from the poor properties, also
37 including thermal sensitivity, of asphalt binder [1]. From a historical viewpoint of asphalt mixture
38 design technology, Roberts et al. [2] summarized that rather than mixture design, improvement of
39 binder properties using modifiers or additives will lead to a true revolution in paving technology.
40 According to Nichollos [3], the modifiers and additives are classified into four categories: (1)
41 polymer modifiers, including plastomers and elastomers, (2) chemical modifiers, such as sulphur,
42 copper sulphate, and other metallic compounds, (3) adhesion (anti-stripping) agents, like fatty
43 amidoamine, acids, amine blends and lime, (4) fiber additives. Due to the successful applications
44 of fiber reinforced concrete (FRC) in cement concrete [4], fibers have got much attention in
45 asphaltic materials recently. Researches show that fiber-reinforced asphaltic materials develop
46 good resistance to fatigue cracking, moisture damage, bending and reflection cracking [5, 6].

47 More recently, other promising applications of fibers in asphalt concrete have been claimed by
48 various researchers [7-13], such as the electrothermal applications of asphalt concrete using
49 conductive fibers (such as carbon fibers and steel fibers) and fillers. Electro-thermal conductivity
50 makes the multifunctional applications of asphalt concrete become a reality, such as snow and ice
51 removal, deicing [7], self-sensing of pavement integrity [8, 9], self-healing (induction heating)
52 [10, 11], and energy harvesting [12,13].

53 A prerequisite for enabling multifunctional applications is the ability to precisely control the
54 electrical conductivity of asphalt concrete. In many previous studies about electrically conductive
55 cement and asphalt systems [14-16], it has been demonstrated how the conductivity is proportional
56 to the volume content of conductive filler or fibers added. Figure 1 illustrates a typical pattern of

57 electrical resistivity variation with the addition of conductive fillers and/or fibers content
58 presented with solid line [16]. It can be seen from Figure 1 that the transition between insulated
59 phase and conductive phase is abrupt. Such a sudden decrease in electric resistivity is called the
60 percolation threshold [14], which is commonly observed in other studies on conductive asphalt
61 concrete [15, 16]. Also, the adjustable volume resistivity range of conductive asphalt near the
62 percolation threshold is quite narrow, which introduces limitations for developing various
63 multifunctional applications. For example, assuming the situation of heating asphalt pavement for
64 self-healing or deicing, the resistivity of asphalt pavement should be controlled properly to ensure
65 the safety as well as the good energy efficiency. Therefore, as illustrated in Figure 1, the rapid drop
66 of volume resistivity versus conductive additive content needs to be transformed into a curve
67 (dashed line) with gradual slope to enable precise manipulation of electrical resistivity over a wide
68 range [17].



69

70 **Figure 1** Objective of imparting conductivity (compared to the result of Gracia et al. [16])

71 As mentioned before, the principal function of conductive fibers and fillers is to make asphalt
72 concrete electrically conductive and suitable for its multifunctional applications. The addition of

73 conductive fibers and fillers will definitely influence the mechanical properties and durability of
74 asphalt mixture. Liu et al. [9] indicated how an excess of conductive particles can cause the
75 degradation of the pavement properties such as the strength or the workability of neat materials.
76 Also, some researches [7, 8, 14, 15] have demonstrated that different types and contents of
77 conductive fiber or filler have different effects on both electrical and engineering properties. In
78 most instances, the road performance of conductive asphalt concrete dominates the selection of
79 conductive additives. Therefore, the conductive additives are not supposed to influence the
80 engineering properties of asphalt concrete negatively, but to ensure that the mixture satisfies the
81 durability requirements.

82 To sum up, the key point of designing electrically conductive asphalt concrete is to optimize the
83 balance between mechanical properties and electrical performance. While economic efficiency is
84 certainly very important but not included in this study. On the basis of the above two
85 considerations, the objectives of this study are to (1) design electrically conductive asphalt
86 concrete with a gradual decrease of resistivity over a wide range, and (2) investigate the effect of
87 conductive additives on the properties of asphalt mixtures.

88 The effectiveness of additives was investigated through the electrical conductivity measurement
89 on mixtures at different additive contents. The effect of the additives on asphalt mixture
90 performance was evaluated through fiber-asphalt pull-out, Marshall test, wheel tracking, and
91 indirect tensile strength tests.

92

93 **2. Experimental investigation**

94 *2.1 Materials*

95 In this study, basalt aggregates and limestone fillers were used to product asphalt mixtures. The
 96 conventional asphalt binder used in this study was SHELL-70, which is equivalent to PG 64-22.
 97 The properties of asphalt binder are listed in Table 1.

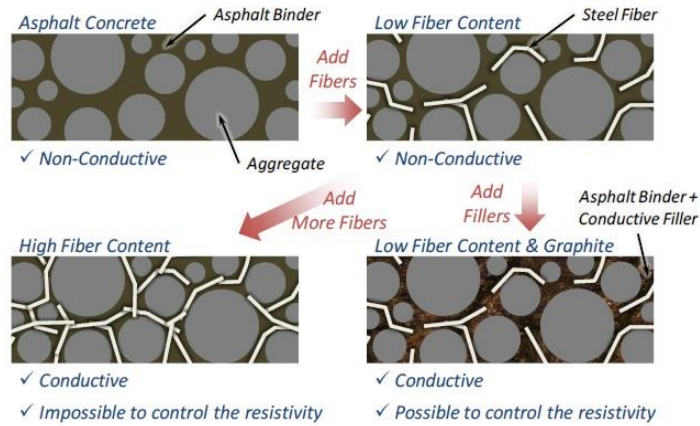
98 **Table 1** Basic properties of asphalt binder

Properties	Value
Penetration (25°C, 100 g, 5s, 0.1 mm)	71
Ductility (5 cm/min, 5°C, cm)	32.2
Softening point (R&B, °C)	47.5
Flash point (°C)	272
Rotational viscosity (60°C, Pa.s)	203
Wax content (%)	1.6
Density (15°C, g/cm ³)	1.032

99 With regard to the electrically conductive particles, conductive steel fibers and graphite were
 100 added to the mixture. The steel fibers of type 4 are graded as “Extra Coarse” with a diameter of
 101 0.10 ± 0.02 mm. They are low-carbon steel, with smooth face, resistivity of $7 \times 10^{-7} \Omega \cdot m$, and
 102 density of about 7.5 g/cm^3 . Graphite powder passing the No.200 sieve (0.075 mm) has a carbon
 103 content of 96.1%, an electrical resistivity of $10^{-4} \Omega \cdot m$ and a density of about 2.2 g/cm^3 . Graphite
 104 powder, together with the limestone, work as fillers in the mixture.

105 The reason for selecting steel fibers and graphite as conductive additives is explained as follows.
 106 One of the objective in this study was to design electrically conductive asphalt concrete with a
 107 gradual slope of resistivity versus additive content curve. Figure 2 illustrates the strategy
 108 employed for controlling the electrical resistivity of asphalt concrete, which was also
 109 recommended by Park. As illustrated in the bottom right part of Figure 2, the resistivity of the

110 asphalt mixture can be precisely controlled by filling the gap between aggregates and conductive
 111 fibers with conductive mastic.



112
 113 **Figure 2** Strategy for manipulating electrical resistivity of asphalt concrete [17]

114 *2.2 Mixture Design*

115 Dense asphalt concrete (AC-13) with 13.2-mm nominal maximum aggregate size was used in
 116 this research. Gradation is shown in Table 2 and was designed in accordance with standard
 117 Marshall Design method (ASTM D6926-04). The optimal asphalt content for the control mixture
 118 was 4.8%. No separate mix designs were performed for the mixtures containing conductive
 119 fillers/fibers. In order to compare the effects of conductive materials on electrical and mechanical
 120 performance of asphalt mixture, all the mixture samples were prepared with the same gradation
 121 and same asphalt content.

122 **Table 2** Gradation of AC-13

Gradation	Sieve size, mm (% passing)									
	16.0	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
AC-13	100	96.6	81.1	48.0	31.2	18.9	11.7	7.7	6.7	5.7

123
 124 *2.3 Test Sample Preparation*

125 Clumping or balling of fibers during mixing process is one of the important factors affecting the
 126 properties of fiber reinforced concrete [18]. The mixing procedure and dimension and amount of

127 fiber have critical influence on the mixing quality of fiber reinforced asphalt concrete. According
128 to the defined fiber distribution coefficient in previous study, the dry process and total mixing time
129 of 270 s were used as the optimal mixing procedure to obtain well-distributed fibers in asphalt
130 mixture [19]. Specifically, aggregates were first mixed with steel fibers for 90 s. Then, the liquid
131 asphalt was poured into the bowl with another 90 s' stir. Finally, fillers and graphite (if had) were
132 blended into the above mixture for 90 s' mixing.

133 It is known that the significant effect of fibers on fiber reinforced composites occurs in the
134 post-cracking phase, where fibers bridge crack and delay the failure process [20]. The joint of
135 fibers across a crack to transfer the load can be simulated by pull-out tests [21], in which a single
136 fiber is pulled out of asphalt binder rather than mixture for simulation convenience. Before the
137 mixture specimen preparation, fiber-asphalt pull-out test was conducted to determine the critical
138 embedded length of steel fiber. The detailed test description is presented in the following section.

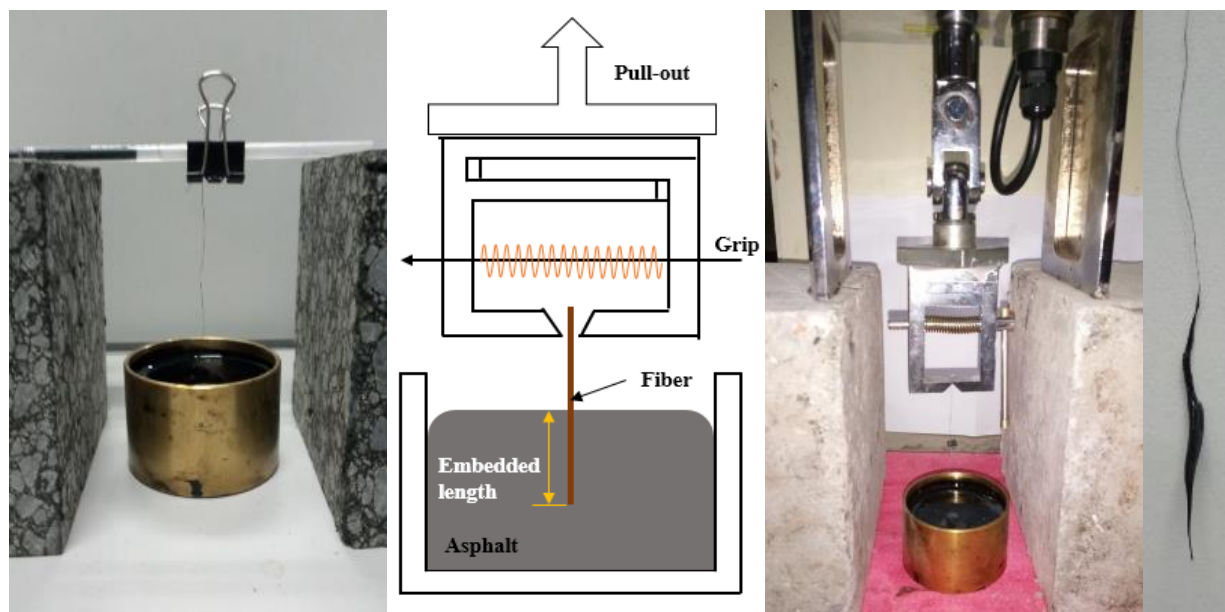
139 After proper fiber length was determined, different percentages of conductive additives were
140 added to the mixture. Cylindrical shape specimens with 100 mm diameter and 65 mm height were
141 fabricated for Marshall Stability, indirect tensile strength tests as well as electrical resistivity
142 measurement. The size of slab specimen for wheel tracking test is 300×300×50 mm (length ×
143 width × height). Specimens without fibers were also prepared in the same way to serve as control
144 specimens. Each type of specimen has two replicates.

145 *2.4 Test Methods*

146 ➤ Single Fiber Pull-out Test

147 To prepare a pull-out specimen, the conventional asphalt binder without additive was firstly heated
148 to 150±5 °C in an oil-bath heating container. It was then poured into a tin can with a diameter of 55
149 mm and a height of 35 mm used for penetration tests. The cleaned fibers were embedded at
150 different lengths into the hot asphalt at the center of the tin can as shown in Figure 3a. A clip was

151 held in place to prevent the fiber from sinking into the hot asphalt. After several hours cooling at
152 room temperature, a simple tensile testing system with a maximum force capacity of 100 N was
153 used to apply a constant displacement rate at 30 mm/min [17] to the test samples. Figure 3b and 3c
154 show the sketch and real setup of pull-out test respectively. A typical pulled-out steel fiber is
155 shown in Figure 3d. At relatively slow loading rate, the fiber's pull-out behavior depends mainly
156 on the viscoelastic properties of the matrix (binder). Each test was repeated at least three times for
157 each test condition.



158
159 (a)Fibers embedment (b)Schematic drawing of test setup (c) Photo in kind (d) Pulled-out steel fiber

160 **Figure 3** Pull-out test process

161 ➤ **Electrical Resistivity Measurement**

162 The two-probe method was used for electrical conductivity measurement. The electrical resistivity
163 measurements were done at room temperature of 15 °C. The electrical contact areas on the
164 specimens were first painted with highly conductive silver paint. Two copper plate electrodes
165 connected with the multimeter were placed at both ends of the cylindrical asphalt concrete samples.
166 An UNI-T modern digital multimeter was used to measure the resistivity below $40 \times 10^6 \Omega$. A

167 resistance tester was used to measure the resistance higher than this value. The contact resistance
168 between the two electrodes when directly connected is lower than 1 Ω , which is negligible with
169 respect to the great resistances studied (higher than $0.1 \times 10^6 \Omega$). The electric field of the resistance
170 tester is assumed constant and the end-effects are considered negligible.

171 After measuring the resistance, the electrical resistivity of sample was obtained from the second
172 Ohm-law in Equation 1:

$$173 \quad \rho = \frac{RS}{L} \quad (1)$$

174 Where ρ is the electrical resistance ($\Omega \cdot m$); L is the internal electrode distance (m); S is the
175 electrode conductive area (m^2) and R is the measured resistance (Ω).

176 ➤ **Marshall Test**

177 Marshall Stability (MS) is one of the most important properties of asphalt mixtures because of the
178 dynamic loads from vehicles, long-term static loads, stress caused by vehicle speeding and
179 stopping, and shear effects or aggregate loss [22]. Different Marshall Stability tests were
180 conducted at 60 °C to determine the optimum fiber content and compare the performance of
181 asphalt mixtures with different conductive additives from a mechanical point of view (ASTM D
182 6927-06).

183 ➤ **Wheel Tracking Test**

184 The wheel tracking test is applied to evaluate the permanent deformation characteristics of asphalt
185 mixtures. A contact pressure of 0.7 MPa and total wheel load of 0.78 kN was applied to the slab
186 specimens at 60 °C according to Chinese specification (JTG E20-2011). The test stops when either
187 test time reaches to 1 hour or the maximum deformation exceeds 25 mm. Dynamic stability (DS)
188 was calculated according to the plot of cumulative rut depths with number of loading applications
189 for the mix as Equation 2.

190
$$DS = \frac{(t_1 - t_2) \times N}{d_1 - d_2} \quad (2)$$

191 Where, t_1 and t_2 are the time at 45 min and 60 min, respectively; d_1 and d_2 are deformation or
192 rut depth at t_1 and t_2 ; N is the number of cycles of wheel passing over the sample per minute.

193 ➤ **Indirect Tensile Strength Test**

194 Indirect tensile strength (ITS) is a parameter that indicates the bond of the binder with aggregates
195 and the cohesion in the mastics. Indirect tensile strength test was conducted on Marshall samples at
196 -10 °C (ASTM D6391-2007) to examine cracking resistance at low temperature. The same
197 servo-hydraulic mechanical testing system (UTM-25, IPC) was used to apply a constant
198 displacement rate (50 mm/min) until the peak load was reached. The reaction force and vertical
199 displacement were recorded by a data acquisition system. From the measured data, the indirect
200 tensile strength could be calculated using Equation 3:

201
$$ITS = \frac{2F}{\pi DH} \quad (3)$$

202 Where ITS is the indirect tensile strength (MPa); F is the total applied vertical load at failure (N);
203 D is the diameter of specimen (m); H is the height of specimen (m).

204 The fracture energy (FE) and post-cracking energy (PE) were also calculated from the test
205 results. As suggested by Roque et al. [23, 24], FE is defined as the area under the stress-strain
206 curve up to the failure strain (ε_f), and is a good indicator of the cracking potential for asphalt
207 pavement. The area under the curve from ε_f to $2\varepsilon_f$ is called PE, which is representative of
208 ductility, especially useful to evaluate FRAC with post-cracking behavior. Toughness of the
209 mixture is defined as the sum of FE and PE.

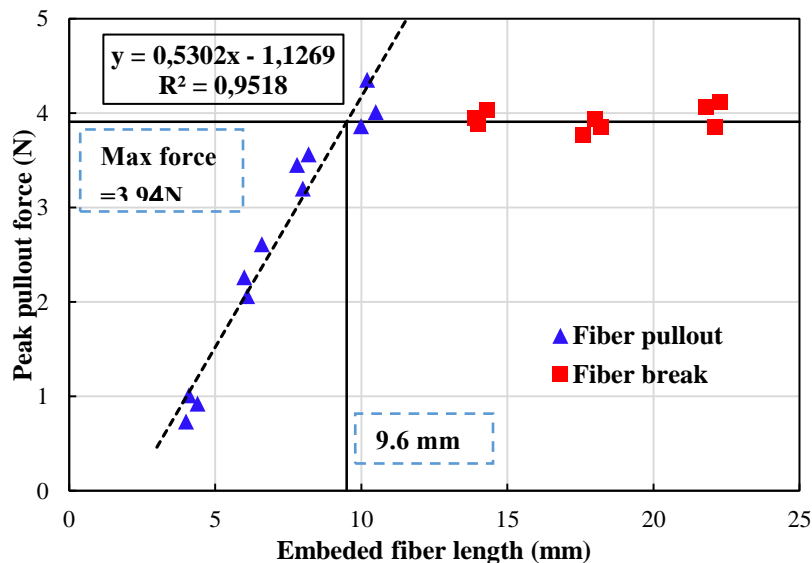
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211 **3. Results and discussions**

212 3.1 Single Fiber Pull-out Test

213 The planned lengths of embedded fiber were 4, 6, 8, 10, 14, 18, and 22 mm respectively.
214 However, precise control of the embedded depth during the specimen preparation is difficult
215 because of thermal shrinkage of asphalt during cooling. Therefore, the location of the matrix
216 surface was marked by painting the exposed part of the fiber just before the test, and the actual
217 embedded length could thus be identified and measured after the test.

218 From Figure 4, it can be found that the average maximum load at failure in fiber pull-out test
219 was 3.94 N. From the regression analysis between embedded fiber length and peak fiber pull out
220 load, the critical embedded length of fiber was calculated as 9.6 mm. That means when embedded
221 fiber length reaches approximate 9.6 mm or longer, fiber would rupture during the pull-out test. In
222 order to maximize the steel fiber's potential to bridge across the crack and delay the crack
223 propagation, the fiber length should not be shorter than 9.6 mm. Nevertheless, according to other
224 researchers' and previous studies [19, 25], asphalt mixture reinforced with long steel fibers may
225 influence the mixing quality and generate clumping or balling problems, which will definitely
226 affect the mechanical properties of the mixture. Considering these, the final steel fiber length was
227 chosen as 10 mm.



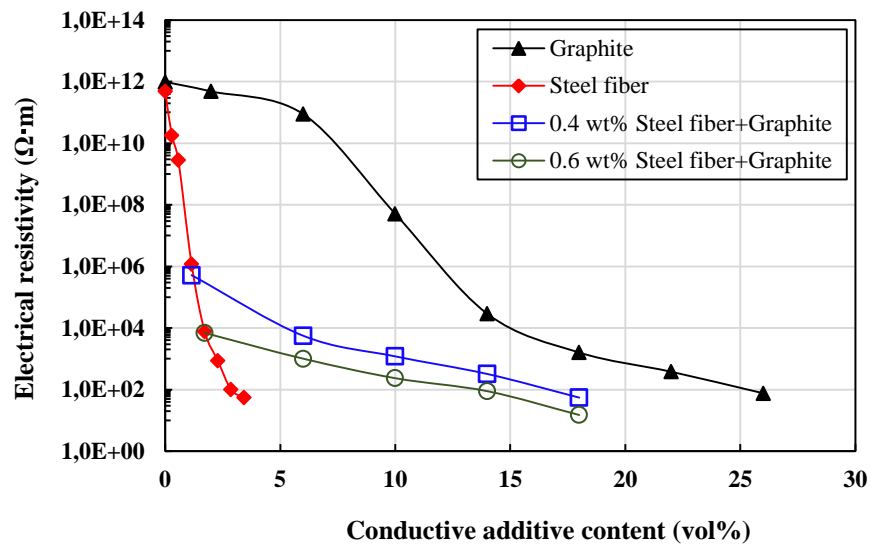
228

229 **Figure 4** Embedded fiber length determination in pull-out test

230 *3.2 Electrical Resistivity of Asphalt Mixture*

231 As mentioned before, conductive additives can transform insulated asphalt binder into electric
232 conductive material. Seven graphite contents (2%, 6%, 10%, 14%, 18%, 22%, and 26% by volume
233 of asphalt binders) and seven steel fiber content (0.1%, 0.2%, 0.4%, 0.6%, 0.8 %, 1.0% and 1.2%
234 by weight of asphalt mixture) were involved in this study.

235 The electrical resistivity of asphalt mixture with different contents of steel fiber and/or graphite
236 is displayed in Figure 5. It presents a typical pattern of electrical resistivity variation with the
237 addition of conductive fillers content, which can be divided into four phases: insulated phase,
238 transition phase, conductive phase, and excess of additives phase. When the graphite content
239 reached to 6 vol%, adding more graphite led to a rapid decrease in resistivity. Such a sudden
240 decline in resistivity is called the percolation threshold, as mentioned before. When the graphite
241 content rose to 18 vol%, the resistivity of asphalt concrete had already reached a relatively low
242 level, 1600 $\Omega\cdot\text{m}$. It can also be found that the variation in the resistivity of mixtures containing
243 steel fiber followed a similar pattern as the ones containing graphite. It seems that steel fiber has
244 greater effectiveness than graphite to improve the conductivity of asphalt mixture. When added a
245 small amount of steel fibers, like 0.6 wt% (1.72 % by volume of asphalt binder), the resistivity of
246 asphalt concrete reduced to 7600 $\Omega\cdot\text{m}$.



247

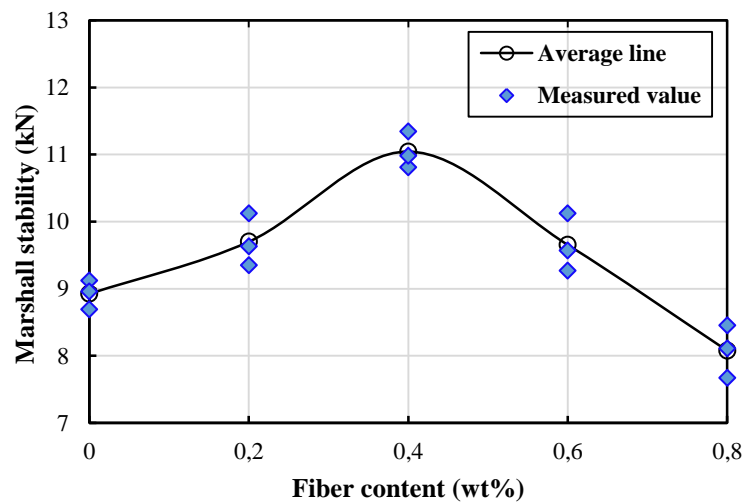
248 **Figure 5** Electrical resistivity of asphalt mixture with different contents of conductive additives

249 Sufficiently low electrical resistivity can be obtained by adding enough either graphite or steel
 250 fiber. However, the existence of the so-called threshold implies that it is difficult to manipulate its
 251 resistivity. In addition, these results support the hypothesis in Figure 2 that high steel fiber content
 252 can make asphalt concrete conductive, but that conductivity cannot be solely manipulated by the
 253 use of fibers. To enable precise conductivity manipulation, electrical resistivity needs to decrease
 254 gradually with the increase of conductive additive content. Therefore, the combination of fibers
 255 and fillers was investigated. For that, two sets of experiment were prepared: steel fiber content was
 256 fixed at 0.4% and 0.6% by weight of the mixture, then different volumes of graphite powder were
 257 added. With 0.4 wt% or 0.6 wt% steel fiber, the resistivity of asphalt concrete has already reached
 258 a certain low value. It seems as if a certain amount of steel fibers “help” the mixture only
 259 containing graphite pass over the percolation threshold. It was found from Figure 5 that the
 260 resistivity of asphalt concrete containing steel continued reducing gradually with the increase of
 261 graphite content. The slope of the resistivity variation curve of asphalt concrete with both fibers
 262 and fillers is much smaller than the ones with single fibers or fillers. At this point, the first
 263 objective of this study is attained.

264 3.3 Mechanical Properties of Conductive Asphalt Concrete

265 ➤ **Marshall Test**

266 Marshall test was conducted to have an approximate idea of the durability of conductive asphalt
267 concrete. Steel fibers added in the mixture are supposed to improve the electrical conductivity, and
268 more importantly, to strengthen the mechanical properties. Figure 6 illustrates the MS values of
269 asphalt concrete with different contents of steel fiber. With the increase of fiber content, the MS
270 values rose significantly, reaching the peak (11.1 kN) at the fiber content of 0.4 wt%. Adding
271 excess steel fibers resulted in decreases of MS values.



272

273 **Figure 6** Effect of fiber content on MS values

274 Combining with the electrical resistivity results, 0.4 wt% was selected as the optimal steel fiber
275 content. In this study, 0.4 wt% steel fiber cooperates with 14 vol% graphite to obtain a low
276 electrical resistivity of asphalt concrete (322 $\Omega \cdot m$), which could satisfy the requirements of
277 conductive asphalt concrete.

278 In order to compare the effects of different combinations of conductive additives on the
279 mechanical properties of asphalt concrete, four types of asphalt concrete specimens were prepared
280 to investigate the laboratory performance. The four types of specimens are plain asphalt concrete
281 as control one, steel fiber reinforced asphalt concrete (fiber content of 0.4 wt%), graphite modified

282 asphalt concrete (graphite content of 14 vol%), and composite asphalt concrete with 0.4 wt% steel
 283 fiber and 14 vol% graphite, respectively.

284 Table 3 presents the Marshall experimental parameters of control mixture and conductive
 285 asphalt mixture with different additives. The mixtures containing graphite have the lowest MS
 286 values, which is possibly due to the oil-absorbing property of graphite with high surface area, lead
 287 to adhesion force drop. In contrast, steel fibers significantly increase the stability of asphalt
 288 concrete by 18.7 % as compared to the control one due to the reinforcing effect. As expected, the
 289 MS values of asphalt concrete containing steel fiber and graphite fell in between the above two
 290 ones. In terms of volumetric properties, the addition of steel fiber increases the bulk density of
 291 asphalt concrete due to its higher density. AV and VMA of steel fiber reinforced asphalt concretes
 292 are higher than that control ones. This is because steel fibers play interferential effect inside the
 293 aggregates due to its higher stiffness, which makes asphalt concrete samples difficult to be
 294 compacted. Graphite does not change the AV of asphalt concrete because graphite powders were
 295 added in the mixture by replacing certain amount of fillers using isovolumetric method.

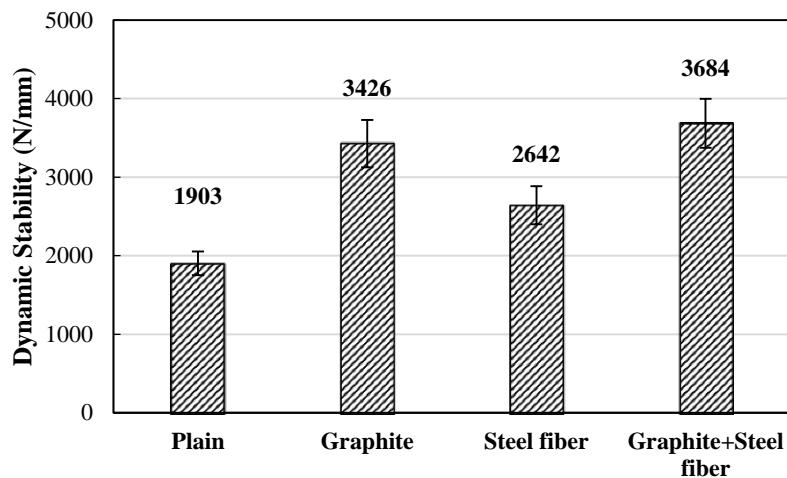
296 **Table 3** Marshall experimental parameters of different asphalt concrete samples

Parameters	Asphalt concrete with different conductive additives			
	Control	Graphite	Steel fiber	Graphite+Steel fiber
Bulk density(g/cm ³)	2.536	2.535	2.538	2.539
AV (%)	5.0	5.0	5.8	5.5
VMA (%)	16.9	16.8	18.2	17.5
VFA (%)	70.4	70.2	68.1	68.6
MS (kN)	8.95	7.65	10.62	9.35
FL (0.1mm)	32.3	34.9	33.2	35.7

297 Note: AV=air voids; VMA= voids in mineral aggregate; VFA= voids filled with asphalt; MS= Marshall
 298 stability; FL=flow value.

299 ➤ **Wheel Tracking Test**

300 The wheel tracking test is applied to evaluate the permanent deformation characteristics of asphalt
301 mixtures. The permanent deformation resistance is an important factor in asphalt pavement design,
302 especially highlighted with the increase of heavy traffic nowadays. In Figure 7, it can be found that
303 both steel fiber and graphite can significantly increase the DS values of asphalt concrete compared
304 to the control ones. In terms of asphalt mixtures containing graphite, it can be explained by the
305 stiffening effect of graphite powders, which can absorb most lightweight fraction of asphalt and
306 make asphalt stiffer. As for steel fiber reinforced asphalt concrete, steel fibers can transform more
307 free asphalt to structure asphalt due the extra interface bonding, Besides, well distributed steel
308 fibers can form 3-dimensional reticular structure, which can transfer more stress. So the rutting
309 resistance of asphalt mixture containing steel fibers will increase.



310

311

Figure 7 Dynamic stability of different asphalt concrete

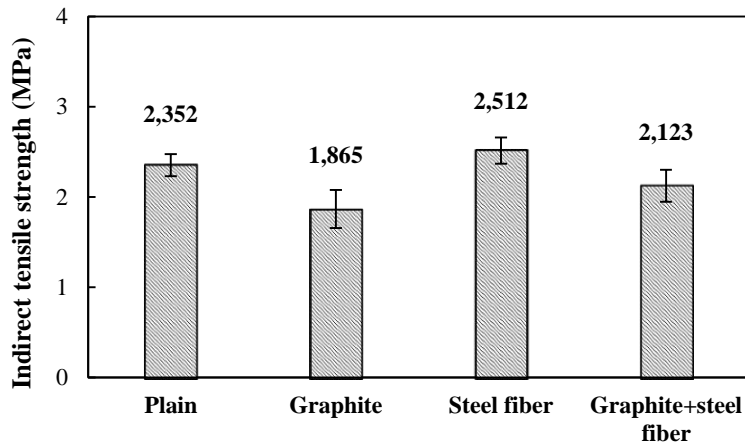
312 ➤ **Indirect Tensile Strength Test**

313 Focusing on low temperature cracking resistance, indirect tensile strength, fracture energy, and
314 post-cracking energy were obtained from indirect tensile strength tests at -10 °C.

315 Figure 8 compared the indirect tensile strength test results of conductive asphalt concrete
316 containing different additives to the control ones. As shown in Figure 8a, steel fiber reinforced

317 asphalt concrete has the highest ITS, while asphalt concrete containing graphite has the lowest
318 ITS.

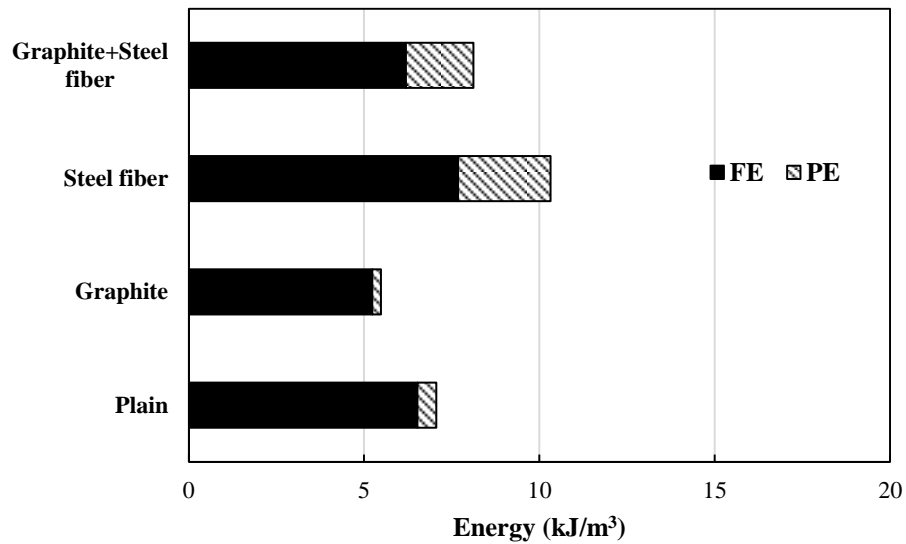
319 In Figure 8b, it can be seen that FE, PE, and toughness have good correlations with ITS for these
320 four asphalt concrete samples in this study. Due to the special layered structure of graphite powder,
321 there is molecular interactions between layered structures of graphite, which belongs to weak Van
322 der Waals force. So asphalt mastic containing graphite in the mixture is prone to produce interlayer
323 slide when asphalt concrete samples are under tensile forces. The graphite has a lubricating effect
324 to decrease the adhesion force between asphalt binder and aggregates. Therefore, the asphalt
325 concrete containing graphite has the lowest resistance to cracking.



326

327

(a) ITS



(b) FE, PE, and toughness

Figure 8 ITS and toughness of different asphalt concrete

328
 329
 330
 331 In contrast, steel fibers significantly improve the cracking resistance of asphalt concrete. It is
 332 known that steel fiber has a high tensile strength. The single steel fiber tensile strength can be
 333 calculated from Figure 4, about 502 MPa, which is much higher than that of asphalt concrete.
 334 Hence, well distributed steel fibers in asphalt concrete can form a 3-dimensional reticular structure.
 335 The meshed structure has both reinforcing and toughening effect in the mixture, which can
 336 increase the tensile strength and deformation resistance of asphalt concrete. Furthermore, a shift in
 337 fracture mode was observed in fiber reinforced specimens during the test. Unlike the control and
 338 graphite modified mixture specimens, which split into two parts along a diametrical line in a brittle
 339 manner, the fracture mode of fiber reinforced specimens is close to a localized punching failure
 340 around the loading strip, and is accompanied by significant amounts of crushing of asphalt
 341 concrete around the fracture surface. These observations support aforementioned analysis and
 342 imply that fracture of steel fiber reinforced asphalt concrete is a combination of fiber pull-out
 343 accompanied by localized crushing of asphalt concrete.

344

345 **4. Conclusions and recommendations**

346 Asphalt concrete generally behaves as an insulated material. The addition of electrically
347 conductive additives can endow the plain asphalt concrete with conductivity. This study intends to
348 provide a design methodology of asphalt concrete that concludes both good electrical and
349 mechanical properties. In order to achieve this goal, various tests have been conducted to
350 investigate both electrical and mechanical performance of asphalt concrete containing steel fiber
351 and/or graphite. Based on the testing results in this study, it is concluded:

352 (1) From the single fiber pull-out test results, the critical embedded steel fiber length is 9.6 mm,
353 which can maximize the steel fiber's potential to bridge across the crack and delay the crack
354 propagation.

355 (2) Electrical conductivity of asphalt concrete could be improved with the addition of either
356 steel fiber or graphite. However, it is much more effective to reach the desired conductivity with
357 steel fibers rather than graphite powders. A combination of steel fiber and graphite enables the
358 gradual decrease of the resistivity of asphalt concrete. The improvement mechanism can be
359 considered in view of the two following effects: conductive graphite powders exhibit the
360 short-range contacts in the form of clusters, whereas fibers exhibit the long-range bridging effect
361 and short-range contacting effect because of the high aspect ratio.

362 (3) An optimized amount of well-distributed steel fiber generally improves the mechanical
363 properties (such as stability, rutting resistance, and low temperature cracking resistance) of asphalt
364 concrete compared to the plain concrete due to the reinforcing effect. The addition of graphite
365 could increase the permanent deformation resistance with compromised stability and low
366 temperature performance. Asphalt concrete containing steel fibers and graphite weakens the steel
367 fiber reinforcing and toughening effect, but still has a significant improvement in mechanical
368 performance.

369 For future work, the authors intend to find a better conductive filler that can enhance both
370 electrical and mechanical performance of asphalt concrete. Also, due to the difficulty of sample
371 preparation and obtaining effective results of fiber pull-out test, a new multi-fiber pull-out test
372 needs to be put forward to investigate the interfacial action between fibers and asphalt matrix.

373

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