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alkaline resistance and performance of recycled polypropylene (PP) fibres
in 25 MPa and 40 MPa concrete, used for footpaths and precast panels,
respectively. The recycled PP fibre was found to have lower tensile
strength but higher Young's modulus than those of virgin PP fibre. The
recycled PP fibre was proven to have very good alkaline resistance in the
concrete and other alkaline environments. The recycled PP fibre showed
excellent post-cracking performance in concrete, bringing in significant
ductility. In the 40 MPa concrete the effectiveness of reinforcement of
PP fibres depended on their Young's modulus and tensile strength in the
crack mouth opening displacement (CMOD) test. Therefore, the recycled PP
fibre produced similar or slightly lower reinforcement than that of
virgin PP fibre. In the 25 MPa concrete, the Young's modulus of fibres
was more effective on their reinforcement than the tensile strength, thus
the recycled PP fibre produced better reinforcement than that of virgin
PP fibre.

1 # Comparative evaluation of virgin and recycled polypropylene fibre

2 # reinforced concrete

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8

9 ## Abstract

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11 significant economic and environmental benefits over traditionally used virgin plastic fibres or steel

12 fibre and mesh. However, wide adoption of recycled plastic fibres by the construction industries has

13 not yet been seen due to limited data available on their durability, mechanical properties and

14 performance in concrete. This paper reports the findings from a laboratory study on the alkaline

15 resistance and performance of recycled polypropylene (PP) fibres in 25 MPa and 40 MPa concrete,

16 used for footpaths and precast panels, respectively. The recycled PP fibre was found to have lower

17 tensile strength but higher Young's modulus than those of virgin PP fibre. The recycled PP fibre was

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19 recycled PP fibre showed excellent post-cracking performance in concrete, bringing in significant

20 ductility. In the 40 MPa concrete the effectiveness of reinforcement of PP fibres depended on their

21 Young's modulus and tensile strength in the crack mouth opening displacement (CMOD) test.

22 Therefore, the recycled PP fibre produced similar or slightly lower reinforcement than that of virgin

23 PP fibre. In the 25 MPa concrete, the Young's modulus of fibres was more effective on their

24   reinforcement than the tensile strength, thus the recycled PP fibre produced better reinforcement

25   than that of virgin PP fibre.

28

29   **1. Introduction**

30   Use of steel reinforcing mesh to reinforce concrete pavements requires labour time for laying,

31   cutting and tying of steel mesh before concrete is poured [1]. Moreover, steel is vulnerable to

32   corrosion and hence, reinforced concrete members if not designed and constructed properly can

33   deteriorate due to corrosion of steel. Production of steel mesh and fibre also produces significant

34   carbon footprint. For example, production process of steel mesh typically required to reinforce

35   100 m^2 of concrete footpath emits about 1250 kg of carbon dioxide [2]. Macro plastic fibers, such as

36   polypropylene (PP) [3], high-density polyethylene (HDPE) [4] and polyethylene terephthalate (PET)

37   fibres [5], therefore, have gradually become an attractive alternative to steel mesh and fibre for

38   construction of concrete footpaths, non-structural precast elements, and tunnels linings. Use of

39   macro plastic fibres in concrete has multiple advantages, such as ease of construction, reduced

40   labour time and lower time. These plastic fibres can effectively improve post-cracking performance

41   and control dry shrinkage of concrete [6]. They normally have a tensile strength of 300-600 MPa and

42   a Young's modulus of 4-10 GPa, and are made of virgin plastics [7].

43   In order to promote development of concrete industry, recycled plastic fibres have started attracting

44   attention around the world [8]. Ochi, Okubo [1] and Fraternali, Ciancia [9] produced recycled PET

45   fibres though a serial processes of extrusion, spinning and stretching. The recycled PET fibres

46   produced in both their studies achieved a tensile strength of over 450 MPa. Kim, Park [10] and Kim,

47   Yi [11] produced recycled PET fibre by melting waste PET bottles first, then pressing and rolling them

48   into a roll-type sheets, before slitting the sheets into thin strands. The recycled PET fibres produced

49   in this way had a tensile strength of more than 400 MPa and a Young's modulus of 10 GPa. de

50   Oliveira and Castro-Gomes [12] and Foti [5] produced recycled PET fibres by simply cutting waste

51   PET bottles, but these fibres had limited strength. Although recycled PET fibres have recently

52   become a focus of research, research on mechanical properties of recycled PP fibre and their

53   effectiveness as reinforcement in concrete is very limited.

54   Effectiveness of the fibres in reinforcing concrete is generally assessed through the crack mouth

55   opening displacement (CMOD) test and round determinate panel test (RDPT), which assess the post-

56   cracking performance of fibre reinforced concrete. CMOD test is suitable for determining how the

57   fibres control the cracks, as it demonstrates the association between cracking behaviour and residual

58   flexural strength. The CMOD test evaluates the capacity of fibres to bridge the cracks formed and

59   redistribute the stresses [13]. RDPT is also an effective method of assessing the performance of fibre

60   reinforced concrete. This technique is desirable because panels are subjected to a mixture of stress

61   actions that more accurately reflect the in-situ behaviour of concrete than other laboratory based

62   small-specimen mechanical tests. Significantly lower variability in post-cracking performance is also

63   seen in the RDPT than other tests, consequently, energy absorption in the RDPT is considered one of

64   the most reliable test methods of post-cracking performance assessment [14].

65   Durability of plastic fibres in highly alkaline cement matrix is another important factor that needs

66   proper consideration. Brown et al. [15] exposed virgin PP fibres to an ionic environment of sodium

67   and chloride ions created by salt water at 71 °C and -7 °C for six months, tensile properties of the PP

68   fibres remained unchanged. Elasto Plastic Concrete (EPC) Company [16] subjected virgin PP fibres to

69   an alkaline solution simulating alkaline environment of concrete mix. They reported that the PP

70   fibres can last up to 100 years in an alkaline environment without any reduction in strength. While it

71   is clearly demonstrated that the long-term durability is not a problem for the virgin PP fibres, the

72   durability of recycled PP fibres in the alkaline environment of concrete is still unknown.

73   This research, therefore, assesses the alkaline resistance of recycled PP fibre in four different alkaline

74   solutions to study degradation of the recycled PP fibre in different pH ranges and types. The post-

75   cracking performance of recycled PP fibre reinforced concretes was also quantified and compared

76   with that of virgin PP fibre reinforced concretes through the CMOD test and RDPT. In this study, two

77   volume percentages of fibres are chosen to reinforce 40 MPa and 25 MPa concrete, which are the

78   standard grades of concrete used in precast panels and concrete footpaths, respectively. The

79   effectiveness of the recycled PP fibres as reinforcement of the two different grades of concrete are

80   assessed in this research.

2. Materials properties

81

2.1 Recycled and virgin PP fibres

82

83   In this study the recycled PP fibre was produced by extruding, spinning and stretching recycled PP

84   granules, which are made of industrial PP waste (scrap off-cuts and off-specification items in the

85   manufacturing industry that are not used by the consumer). Initial extrusion of the PP granules was

86   carried out at 210-250 °C, spinning and stretching at 140-170°C, then stabilisation at 110-140 °C.

87   Smooth surface fibres, 0.8-0.9 mm in diameter, were then produced followed by indentation on the

88   surface using an indenting roller die to improve fiber-concrete bonding. After that, the fibre was

89   winded, polywrapped and finally cut into a specific length. Both recycled and virgin PP fibres were

90   produced by the same processes, thus having same geometry and dimensions (1.5 mm in width, 0.7

91   mm in thickness, and 47 mm in length), as shown in Fig. 1.

92   *(Insert Fig. 1 here)*

93   Tests on recycled and virgin PP fibres for tensile strength and Young's modulus were carried out as

94   per ASTM D3822-07 [17]. Tensile tests were undertaken using United Calibration Corporation United

95   STM 'Smart' Test Machine (STM-50 KN) with a 2 kN load cell and a data acquisition software. 30

96   samples of each of the fibre types were tested at room temperature of 20 ±2 °C. Gauge length of

97   25.4 mm was used with extension speed set at 60 % of the gauge length/min (15.24 mm/min) for all

98   the tests.

99   A brittle mode of failure can be seen in both types of fibres (Fig. 2), with a short elastic phase of

100   steep slope and a progression of sharply rising stress until fracture. Averages of the tensile strength

101   and Young's modulus are shown in Table 1 as well as the elongation at break and their standard

102   deviations. As can be seen, the recycled PP fibre shows lower tensile strength (284.1 MPa) but much

103   higher Young's modulus (4582 MPa) than those of virgin PP fibre. It is noteworthy that the recycle PP

104   fibre is not featured to have higher Young's modulus than that of virgin PP fibre. The tensile

105   properties of fibres mainly depend on the material properties and processing conditions. Our

106   previous research [18] has shown that the recycled PP fibre has lower molecular weight and shorter

107   molecular chains than those of virgin PP fibre. Under the same processing conditions, the shorter

108   molecular chains make the recycled PP fibre easier to be crystallised, thus producing higher Young's

109   modulus. The shorter molecular chains of recycle PP fibre have less molecular entanglement and

110   hence, producing lower tensile strength under the same processing conditions with the virgin PP

111   fibre. However, if the processing conditions or methods are changed, the properties of fibres are

112   changed, which is out of the scope of this paper.

113   *(Insert Fig. 2 and Table 1 here)*

114   **2.2 Concrete mix design**

115   Based on industry practise, standard mix designs for 40 MPa and 25 MPa concrete were used in this

116   study (as shown in Table 2). For the 40 MPa concrete mix design, 0.67 % in volume of PP fibres (6

117   kg/m^3) was mixed with concrete, which is normal dosage of PP fibres for 40MPa concrete

118   construction of precast panels. For the 25 MPa concrete, 0.45 % in volume of PP fibres (4 kg/m^3) was

119   mixed. This design is commonly used to construct concrete footpaths. Delivery of concrete was

120   carried out in a standard concrete truck from a Holcim Australia Pty. Ltd. batch plant and without PP

121   fibres. Average slump was 60 mm for the 40 MPa concrete and 100 mm for the 25 MPa concrete,

122   based on AS 1012.3.1-2014 [19]. PP fibres were then mixed with concrete in a drum mixer before

123   casting specimens. Fibres were gradually added to avoid clumping and ensure good dispersion.

124   Based on AS 1012.8.1:2014 [20], concrete beams, cylinders and round panel slabs were removed

125   from the moulds after 24 hours. All specimens were then cured in water at 23 $\pm$ 2 ℃ for 28 days.

126   *(Insert Table 2 here)*

127   ## 3. Alkali resistance of the recycled PP fibre

128   Alkali resistance test was conducted to study possible degradation of the recycled PP fibre in

129   concrete alkaline environment. The recycled PP fibre was immersed into a Lawrence solution [0.48

130   g/l $Ca(OH)_2$ + 3.45g/l KOH + 0.88 g/l NaOH, pH=12.9], which is considered to simulate pore water

131   composition of a fully hydrated cement paste [21]. The recycled PP fibre was also immersed in three

132   other alkaline solutions with pH value ranging from 12.3 to 13.5 to study degradation of the fibre in

133   different pH ranges and types. These three alkaline solutions used were $Ca(OH)_2$ saturated solution

134   (pH=12.3), 0.068 mol/l KOH solution (pH=12.83), and 0.28 mol/l NaOH solution (pH=13.45). The

135   recycled PP fibre was immersed into these four solutions for 28 days at ambient temperature. The

136   tensile strength and Young's modulus of recycled PP fibre were measured before and after

137   immersion.

138   As can be seen from Fig. 3, all the curves representing fibre immersion in the alkaline solutions

139   nearly overlap with the curves of fibre without immersion, indicating that the recycled PP fibre has

140   outstanding alkali resistance in the various alkaline environments. However, there still are some

141   minor changes on the mechanical properties after immersion. As shown in Table 3, the NaOH

142   solution slightly embrittles the recycled PP fibre, thus decreasing the tensile strength and increasing

143   the Young's modulus of fibre, due to its higher pH value. The KOH solution slightly decreases the

144   tensile strength of fibre. However, there is nearly no change after immersing the fibre in the

6

145   Lawrence solution which simulates a fully hydrated cement paste. Overall, the recycled PP fibre

146   shows good alkali resistance in all the alkaline environments tested.

147   *(Insert Fig. 3 and Table 3 here)*

4. Compressive strength of concrete

149   Compressive strength tests were performed according to AS 1012.9:2014 [22] on the PP fibre

150   reinforced concrete specimens. Testing was done on the 100 mm diameter by 200 mm length fibre

151   concrete cylinders after they had aged for 28 days. Cylindrical specimens were tested by axial

152   loading until failure by using a universal testing machine with a maximum load capacity of 2000 kN.

153   Results of compressive strength for concrete comprising each of the fibre varieties were based on

154   four specimen's average value.

155   The PP fibre reinforced concrete cylinder's compressive strength is shown in Fig. 4. This shows no

156   significant effect on compressive strength after addition of fibres. Concrete with low dosage of PP

157   fibres (4 and 6 kg/m^3) have no obvious effect on compressive strength, which has also been shown

158   by other research [23]. However, larger fibre doses (i.e. 13 to 18 kg/m^3) can lead to improper

159   distribution resulting in balling of fibres and air pockets, which adversely affects the compressive

160   strength of concrete [1]. Moreover, recycled and virgin PP fibre reinforced concrete cylinders had

161   comparable compressive strength results, as shown in Fig. 6. It should also be noted that during the

162   compression tests, the PP fibre reinforced concrete cylinder failure was characterised by numerous

163   minor surface cracks while the plain concrete cylinders failed catastrophically, at peak load, with a

164   large single crack. In other words, the fibre concretes displayed a more ductile mode of failure.

165   *(Insert Fig. 4 here)*

5. Residual flexural tensile strength with CMOD

167   To study post-cracking performance of the concrete beams reinforced with PP fibres, crack mouth

168   opening displacement (CMOD) tests were conducted according to BS EN 14651-2005+A1-2007 [24].

7

169 Flexural beam dimensions were 150 mm x 150 mm x 600 mm and a 25 mm deep and 2 mm wide

170 notch was cut at mid-span of each beam (Fig. 5). Each notched beam was loaded using a 500 kN

171 hydraulic testing machine on a three-point loading setup. The CMOD measurement was obtained by

172 installing two clip gauges at the notch centre and the averaged CMOD values were documented. The

173 clip gauges that were attached to the knife edges glued to the underside of beam were connected to

174 a data acquisition system. All the tests were displacement controlled to accomplish a constant rate

175 of 0.05 mm/min CMOD and were undertaken at the facilities of K&H Geotechnical Services Pty. Ltd.,

176 Australia. Three samples for each fibre and concrete type were tested, along with one plain concrete

177 beam was tested as a control specimen.

178   *(Insert Fig. 5 here)*

179 Fig. 6.a shows load-CMOD curves of 0.67 % PP fibres reinforced concrete beams of 40 MPa

180 compressive strength. The peak loads reached for all the recycled and virgin PP fibre reinforced

181 concrete beams were approximately 14.5 kN, followed by a sharp drop associated with the CMOD

182 range of 0.05 mm to 0.5 mm. Further, the CMOD from 0.5 mm to 3 mm was associated with

183 increased loads, which then remained flat at 4-8 kN on further loading. However, the load dropped

184 to zero for the plain concrete beam after the peak load was attained.

185 Fig. 6.b exhibits load-CMOD curves of 0.45% PP fibre reinforced concrete beams of target strength

186 25 MPa. The peak loads for all the beams were approximately around 12.5 kN, before a sudden drop.

187 The loads then just kept flat at 2-5 kN until failure, which is different from the increasing load at the

188 CMOD from 0.5 mm to 3 mm in the Fig. 6.a. This is because the 0.45% PP fibre reinforced 25 MPa

189 concrete beams have lower fibre dosage and concrete strength than those of 0.67 % PP fibre

190 reinforced MPa concretes. As expected, the load dropped to 0 kN soon after the peak load for the

191 plain concrete beam. Fig. 6.a and Fig. 6.b confirm the outstanding post-cracking performance of the

192 recycled and virgin PP fibre reinforced concrete beams.

193   Fig. 6.c compares the reinforcement of 0.45% recycled PP fibre in 25 and 40 MPa concrete. After the

194   peak load and the following sharp drop, the loads of fibre reinforced 40 MPa concrete slightly

195   increased and then kept flat, and showed slightly better post-cracking performance than that of the

196   fibres in 25 MPa concrete. This shows that with the increase in compressive strength of concrete the

197   performance of PP fibres is more pronounced.

198   *(Insert Fig. 6 here)*

199   Fig. 7 compares flexural tensile strength at the peak load (i.e. Limit of Proportionality, LOP) for the

200   recycled and virgin PP fibre reinforced concrete beams compared to the plain concrete beams. As

201   can be seen, for both 40 MPa and 25 MPa concrete beams, the recycled PP fibre reinforced concrete

202   beams have comparable LOP to that of virgin PP fibre reinforced concrete. Compared to 40 MPa and

203   25 MPa plain concrete beams, the LOP does not have obvious change after adding the PP fibres. This

204   is because the LOP reflects the flexural tensile strength of uncracked concrete beams, and thus it

205   mainly depends on the concrete material not the fibres. Only after the beams crack, will the fibre

206   hold the load and contribute to the residual flexural tensile strength. Therefore, the plain concrete

207   theoretically has equivalent LOP with the fibre reinforced concrete, and it is normal if the plain

208   concrete has slightly higher or lower LOP due to the micro defects or cracks of concrete.

209   *(Insert Fig. 7 here)*

210   Fig. 8 compares the residual flexural tensile strength of PP fibres reinforced concrete beams at

211    $CMOD_1$, $CMOD_2$, $CMOD_3$ and $CMOD_4$. As can be seen, for the 40 MPa concrete, the recycled PP fibre

212   reinforced concretes show comparable or only slightly lower residual flexural strength than that of

213   concretes reinforced by the virgin PP fibre. Moreover, from Fig. 8.a to Fig. 8.d, with the increase of

214   CMOD, the residual flexural tensile strength of the fibre reinforced 40 MPa concrete beam increases

215   from 1.5 MPa to 2.0 MPa. On the other hand, for the 0.45 % fibre reinforced 25 MPa concrete, the

216   average residual flexural tensile strength of recycled PP reinforced concretes is slightly higher that of

217   virgin PP fibre reinforced concretes. Furthermore, the residual flexural tensile strength just keeps

218   stable around 1.0 MPa from $CMOD_1$ to $CMOD_4$, instead of increasing.

219   It is noteworthy that the CMOD test has some variability even in the same batch of specimens due to

220   multiple reasons. Since the beam specimens are notched and subjected to mid-point loading in the

221   test, crack initiates at the notch-tip and propagates along the notch plane and hence, deformation is

222   always localised at the notch-plane and the rest of the beam does not undergo significant inelastic

223   deformations. Therefore, the results of the CMOD tests highly depend on the dispersion, amount

224   and orientation of the PP fibres only on the notch-plane with a small area of 150 mm x 125 mm.

225   Moreover, the tensile properties of individual PP fibre are also different, which can be reflected by

226   the deviation in Table 1. Therefore, the variability of dispersion, amount, orientation and tensile

227   properties of PP fibres on the notch-plane of concrete beam specimens lead to the variability of

228   results in Fig. 8.

229   *(Insert Fig. 8 here)*

230   Fig. 9 shows fracture faces of the fibre reinforced concrete beams. Fig. 9.a and Fig. 9.b represent the

231   fracture faces of recycled and virgin PP fibre reinforced 40 MPa concrete beams, respectively. As can

232   be seen, the amount of fibre breakage was higher than that of fibre pull-out, which indicates good

233   bonding of fibres with the 40 MPa concrete matrix. The tensile capacity of the broken PP fibres was

234   fully realised, thus producing good reinforcement. As the ultimate tensile capacity was reached in

235   the broken fibres, the performance of fibres depended on both their tensile strength and Young's

236   modulus. From Table 1, it can be seen that the recycled PP fibre has higher Young's modulus but

237   lower tensile strength than the virgin PP fibre. Although the lower tensile strength made the fibre

238   easier to be broken, the higher Young's modulus improved the performance of recycled PP fibre in

239   concrete before breaking. Consequently, the recycled PP fibre produced similar or slightly lower

240   performance than that of the virgin PP fibre in 40 MPa concrete beams. Moreover, the failure modes

241   of recycled and virgin PP fibre are different. In the case of recycled PP fibre reinforced concrete (Fig.

10

242 9.a) the fibres broke with relatively brittle mode of failure, while the broken virgin PP fibre was

243 stretched into massive split micro fibres, showing a more ductile failure (Fig. 9.b). This is because

244 the recycled PP fibre has very low elongation at break (6.2 %), while the virgin PP fibre is more

245 ductile and has much higher elongation at break at 12.6 %.

246 The fracture faces of 25 MPa concrete beams are different with those of 40 MPa concretes as shown

247 in Fig. 9.c and Fig. 9.d. In the low-strength concrete (25 MPa), nearly all the fibres were pulled out

248 without being broken, indicating that the low-strength concrete has a poor bonding with the fibres.

249 Because of the poor bonding, majority of the fibres remained unbroken, and thus their full tensile

250 capacity was not realised. Therefore, the Young's modulus of fibres is more effective on their

251 reinforcement than the tensile strength. The recycled PP fibre has higher Young's modulus than that

252 of virgin PP fibre, thus showing better reinforcement in the CMOD tests.

253   *(Insert Fig. 9 here)*

6. Flexural strength and toughness from RDPT

254

255 The RDPT samples were tested in flexure based on the ASTM C1550-12 [25] (Fig. 10). All of the

256 tested round panels were 800 mm in diameter with a thickness of 75 mm. The specimens were

257 mounted on three symmetrically arranged hinged supports, and tested using a central point load.

258 Load was applied using a 250 kN capacity hydraulic universal testing machine and the three pivoted

259 supports ensured that load distribution was always determinate. As specified in the standard,

260 maximum central displacement of 45.0 mm was achieved after application of displacement at a rate

261 of 4.0 mm/min. A displacement transducer, which was placed under the centre of the specimen, was

262 used to record the deflection. The tests were carried out at K&H Geotechnical Services Pty. Ltd.,

263 Australia.

264   *(Insert Fig. 10 here)*

265 Fig. 11 shows the energy absorption and load results of the RDPT with the increase of deflection. As

266 can be seen, all the fibre reinforced concrete panels reached a peak load at the deflection of 1 mm,

267 before a sudden drop to 5-8 kN. The loads then kept flat until deflection of 10 mm, before a stable

268 downward trend to about 1.5 kN.

269 The energy absorption is the area under the load curves, which reflects the performance of fibre

270 reinforcement in dissipating energy. As can be seen from Fig. 11.a, the recycled PP fibre had slightly

271 lower energy absorption than that of the virgin PP fibre, indicating that the recycled PP fibre

272 produced slightly lower post-cracking reinforcement than that of virgin PP fibre. This result is

273 consistent with CMOD results. The reinforcement of PP fibres in 40 MPa concrete depends on both

274 their Young's modulus and tensile strength. Although the recycled PP fibre had lower tensile

275 strength, its higher Young's modulus improved its reinforcing effects. Consequently, a comparable

276 reinforcement with virgin PP fibre was produced by the recycled PP fibre in the 40 MPa concrete.

277 For the 25 MPa concrete, the recycled PP fibre produced higher post-cracking reinforcement than

278 that of virgin PP fibre (Fig. 11.b). As discussed before, the PP fibres have poor bonding with concrete

279 matrix in the low-strength concrete and hence, the Young's modulus is more effective on the

280 reinforcement. The recycled PP fibre has higher Young's modulus, thus producing better

281 reinforcement.

282   *(Insert Figure 11 here)*

7. Conclusion

284 Significant environmental and economic benefits can be obtained through the use of macro recycled

285 plastic fibres over virgin plastic fibres, or the traditionally used steel mesh and fibre, for reinforcing

286 concrete footpaths and precast panels. However, the wide adoption of recycled plastic fibres has not

287 yet been adopted due to limited research focusing on their durability, performance in concrete, and

12

288   mechanical properties. This research studied the alkaline resistance and performance of recycled PP

289   fibres in concrete for footpaths and precast panels.

290   The alkali resistance of recycled PP fibre was tested by immersing the fibre in four different alkaline

291   solutions for 28 days. The comparison of tensile strength and Young's modulus of fibres before and

292   after immersion showed that the recycled PP fibre did not degrade in the alkaline concrete

293   environment.

294   The addition of recycled PP fibre at low dosage rate (4 and 6 kg/m^3) did not affect compressive

295   strength of concrete, however, it significantly improved the residual flexural tensile strength of

296   concrete. The CMOD tests on 40 MPa concrete beams with 6 kg/m^3 PP fibres (normally used for

297   precast concrete elements) showed that most of the fibres were broken instead of being pulled out

298   at the failure load. This inferred good bonding of fibres with concrete, hence the performance of PP

299   fibres was influenced by both Young's modulus and tensile strength of fibres. The recycled fibre had

300   higher Young's modulus but lower tensile strength than those of virgin PP fibre. Consequently,

301   recycled PP fibre showed slightly lower performance than that of virgin PP fibre in the 40 MPa

302   concrete. In the 25 MPa concrete, majority of fibres were being pulled out instead of breaking. As

303   the fibres did not reach their ultimate tensile strength, their Young's modulus was more influential.

304   The recycled PP fibre had higher Young's modulus and hence, performed better than virgin PP fibre

305   in the 25 MPa concrete.

306   The results of RDPT proved that the recycled PP fibre produced comparable post-cracking

307   performance with that of the virgin PP fibre in the 40 MPa concrete, and better performance than

308   that of virgin PP fibre in the 25 MPa concrete. This study proved that the post-cracking performance

309   of recycled PP fibre reinforced concrete is in par with the virgin PP fibre reinforced concrete.

310   Therefore, recycled PP fibre can be used to replace virgin PP fibres in the concrete footpaths and

311   precast panels.

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373

Captions for figures and tables

374

375   Fig. 1 Recycled (a) and virgin (b) PP fibres

376   Fig. 2 Typical stress-strain curves of PP fibres in tension

377   Fig. 3 Typical stress-strain curves of the recycled PP fibre in tension before and after immersing in

378   the alkaline solutions

379   Fig. 4 Compressive strength of 0.67% fibre reinforced 40 MPa concrete and 0.45% fibre reinforced

380   25 MPa concrete cylinders

381   Fig. 5 Test apparatus for the CMOD test

382   Fig. 6 Load-CMOD curves for (a) 0.67% PP fibre reinforced 40 MPa concrete, (b) 0.45% PP fibre

383   reinforced 25 MPa concrete, and (c) 0.45% recycled PP fibre reinforced 25 MPa and 40 MPa concrete

384   Fig. 7 LOP of 0.67% fibre reinforced 40 MPa concrete and 0.45% fibre reinforced 25 MPa concrete

385   beams

386   Fig. 8 Residual flexural tensile strength of 0.67% fibre reinforced 40 MPa concrete and 0.45% fibre

387   reinforced 25 MPa concrete beams at (a) $CMOD_1$, (b) $CMOD_2$, (c) $CMOD_3$ and (d) $CMOD_4$

388   Fig. 9 Fracture surfaces of PP fibres reinforced concrete beams: (a) 0.67% Recycled PP fibre, (b) 0.67%

389   Virgin PP fibre, (c) 0.45% Recycled PP fibre, and (d) 0.45% Virgin PP fibre

390   Fig. 10 Round panel determinate test setup

391   Fig. 11 Energy absorption and load curves from Round Determinate Panel Tests: (a) 0.67% PP fibre

392   reinforced 40 MPa concrete, and (b) 0.45% PP fibre reinforced 25 MPa concrete

393

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394   Table 1 Mechanical properties of PP fibres

395   Table 2 Concrete mix proportions

396   Table 3 Mechanical properties of the recycled PP fibre before and after immersing in the alkaline

397   solutions

398

Table 1 Mechanical properties of PP fibres

PP compositions	Tensile strength (MPa)		Young's Modulus (MPa)		Elongation at break (%)	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
Virgin PP Fibre	356.4	30.6	3129	564	12.6	2.8
Recycled PP Fibre	284.1	21.0	4582	1661	6.2	2.2

Table 2

Table 2 Concrete mix proportions

Material	40 MPa Concrete	25 MPa Concrete
0.6-4.75 mm Coarse sand (kg/m^3)	350	410
6.7-9.5 mm Concrete aggregate (kg/m^3)	950	260
0.3-5 mm Crusher dust (kg/m^3)	220	200
0.075-0.3 mm Fine sand (kg/m^3)	290	350
9.5-19 mm Concrete aggregate (kg/m^3)	-	690
Fly ash (kg/m^3)	130	134
Cement (kg/m^3)	256	186
Polyheed 8190 admixture (ml/ 100 kg cementitious materials)	337	281
Air entrapment admixture (ml/ 100 kg cementitious materials)	-	22
Water (l/m^3)	105	116
PP fibre (kg/m^3)	6	4

Table 3

Table 3 Mechanical properties of the recycled PP fibre before and after immersing in the alkaline solutions

|	Tensile strength (MPa)		Young's Modulus (MPa)		Elongation at break (%)	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
Without immersion	284.1	33.7	4582	268.9	6.2	2.3
Lawrence solution	284.7	22.7	4592	153.4	6.2	0.9
$Ca(OH)_2$ solution	273.4	34.7	4482	380.2	6.1	1.7
KOH solution	261.9	17.4	4516	114.5	5.8	1.0
NaOH solution	273.1	14.2	4965	214.2	5.5	1.1

Figure 1
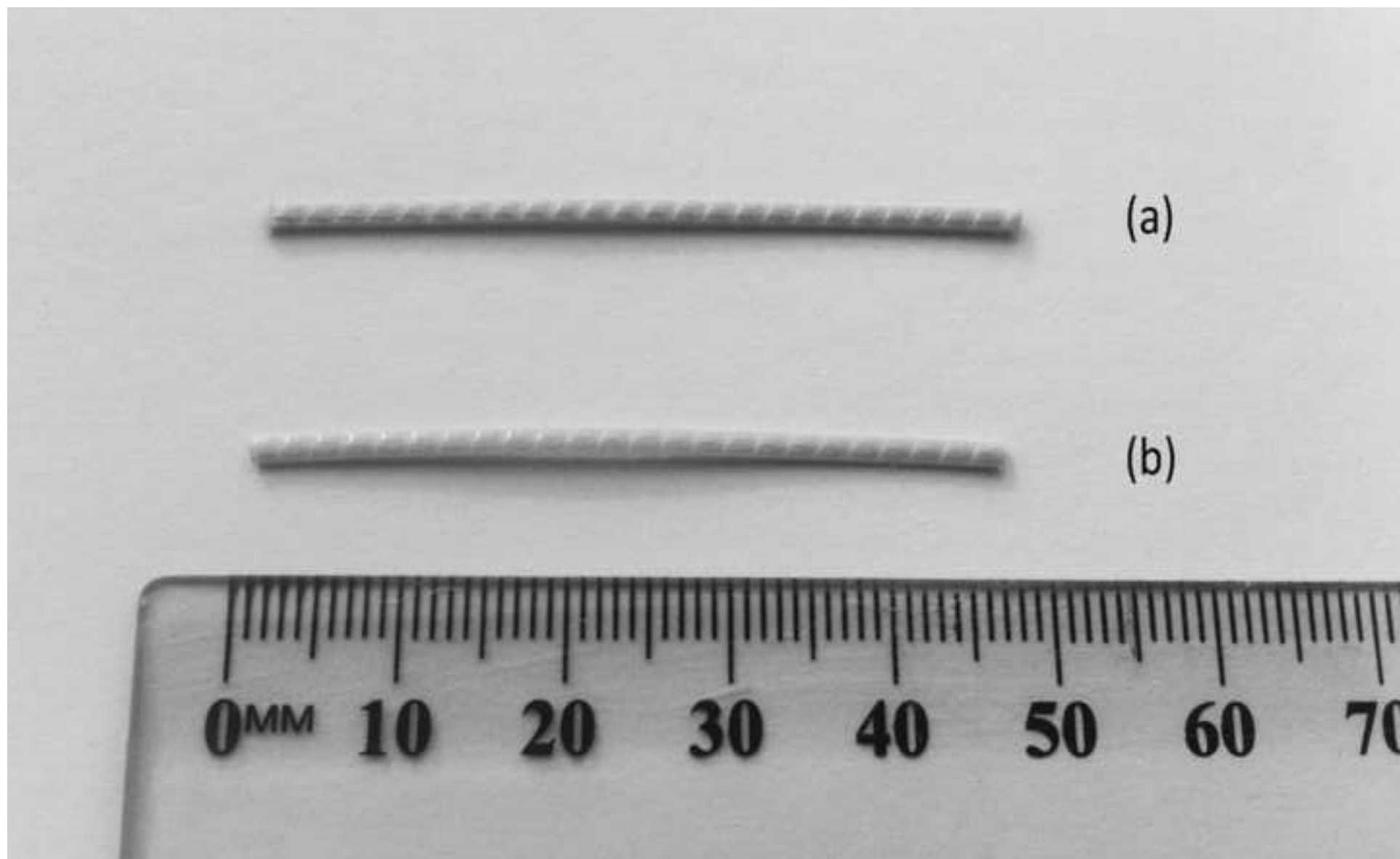
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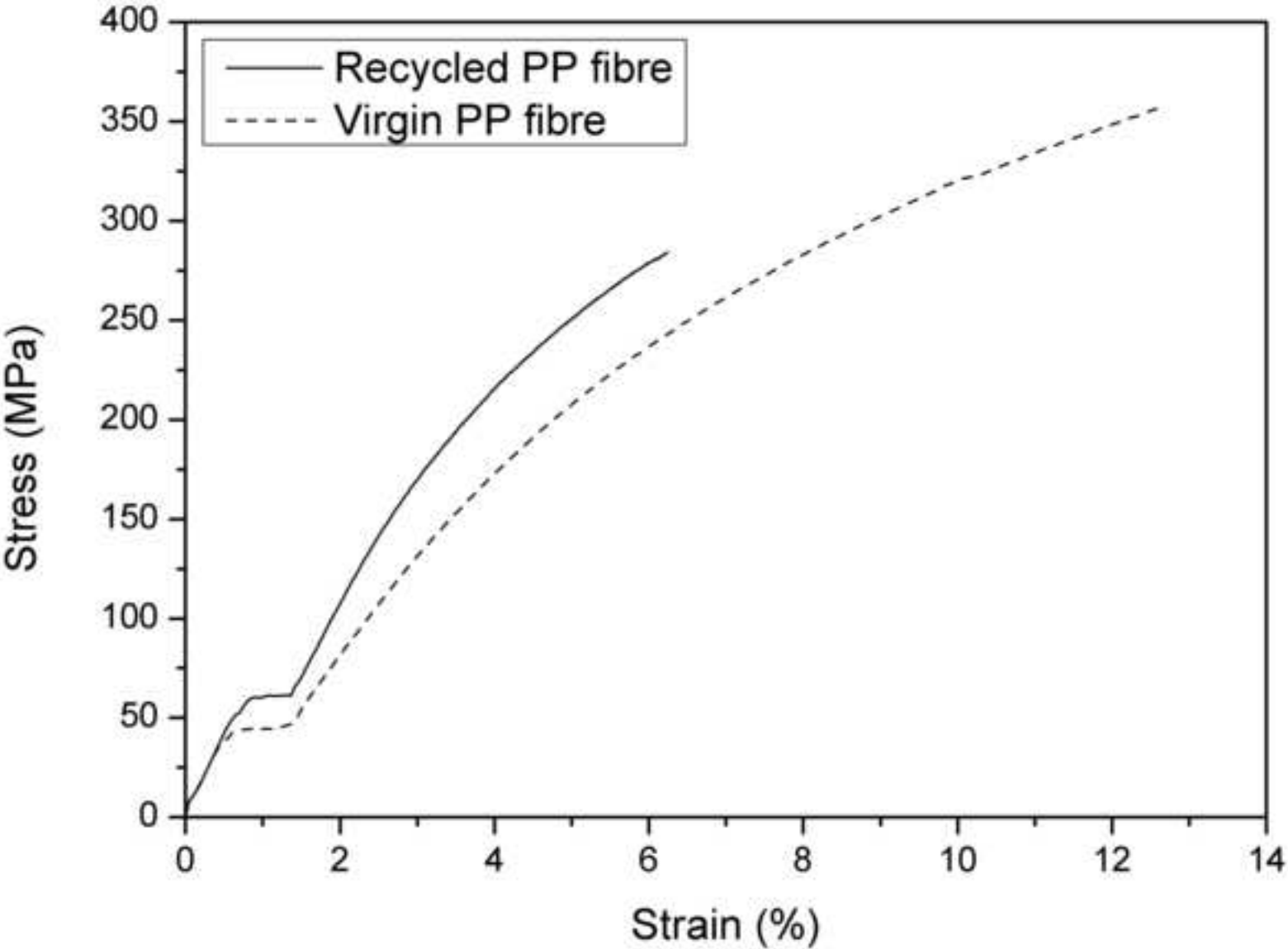
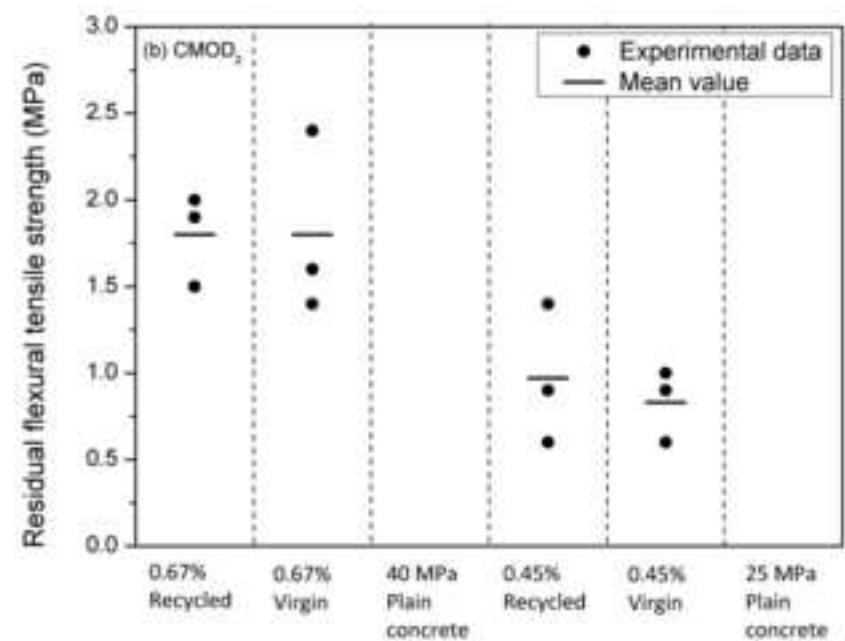**Figure 3**
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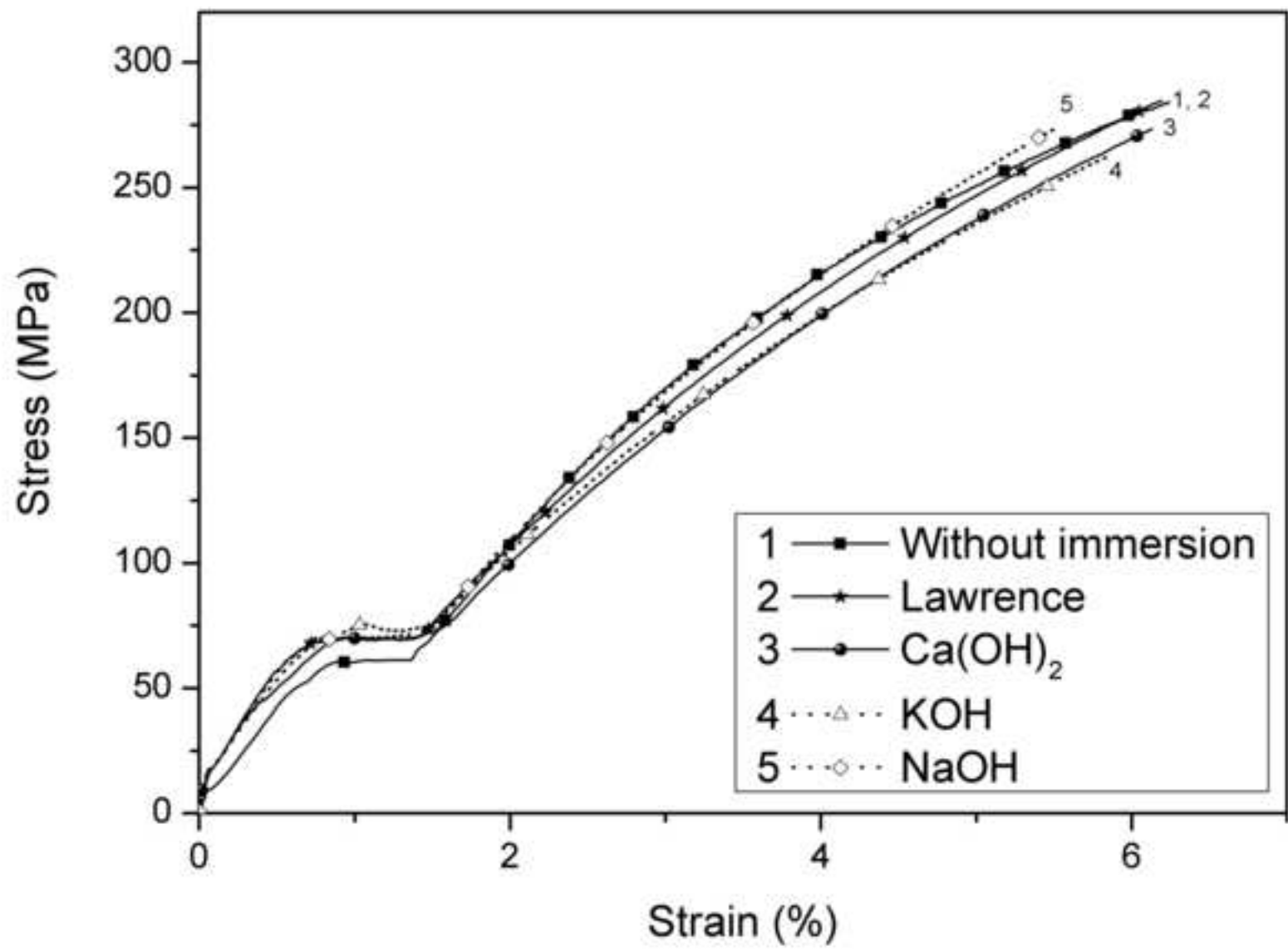
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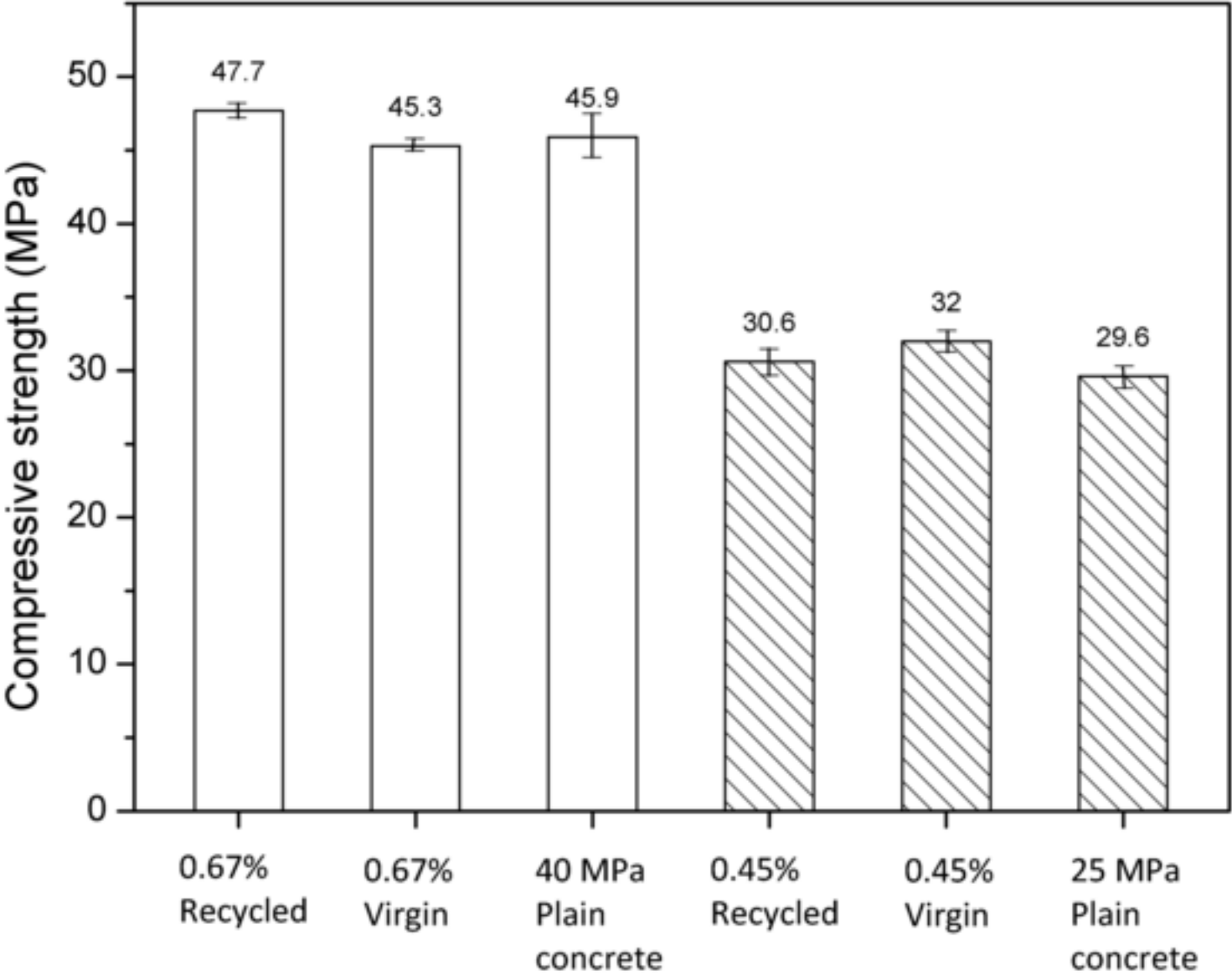
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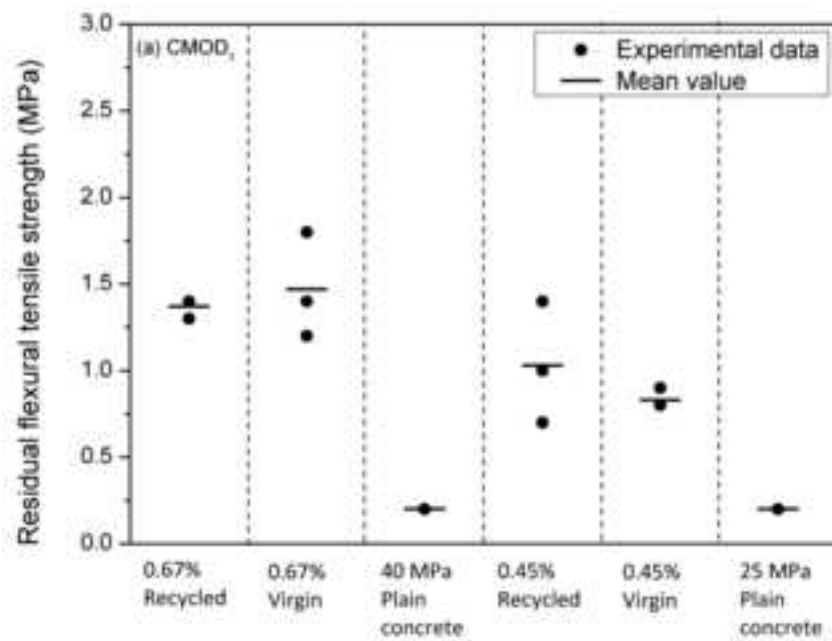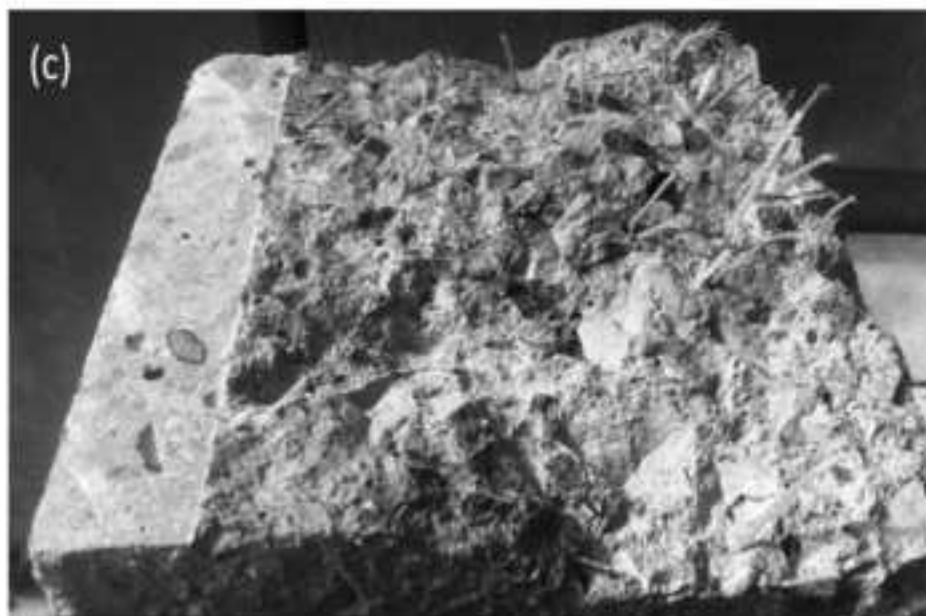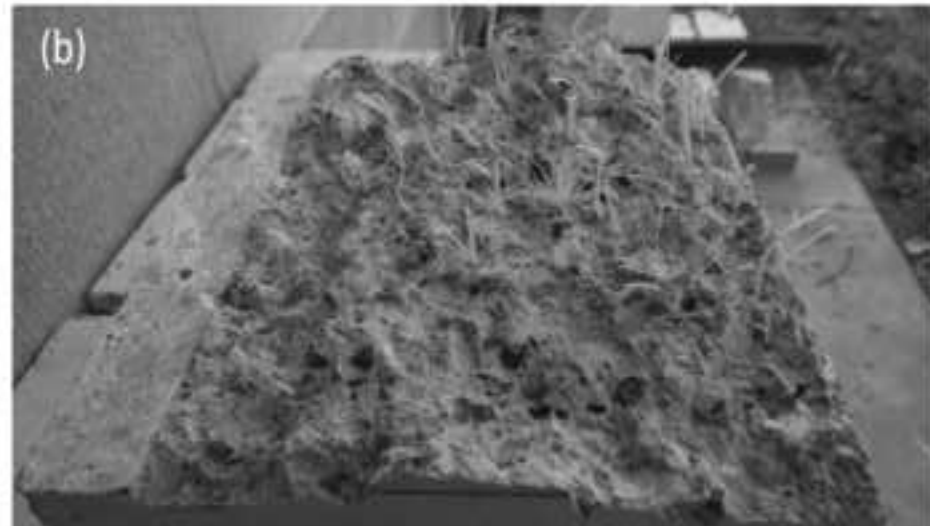**Click here to download high resolution image**

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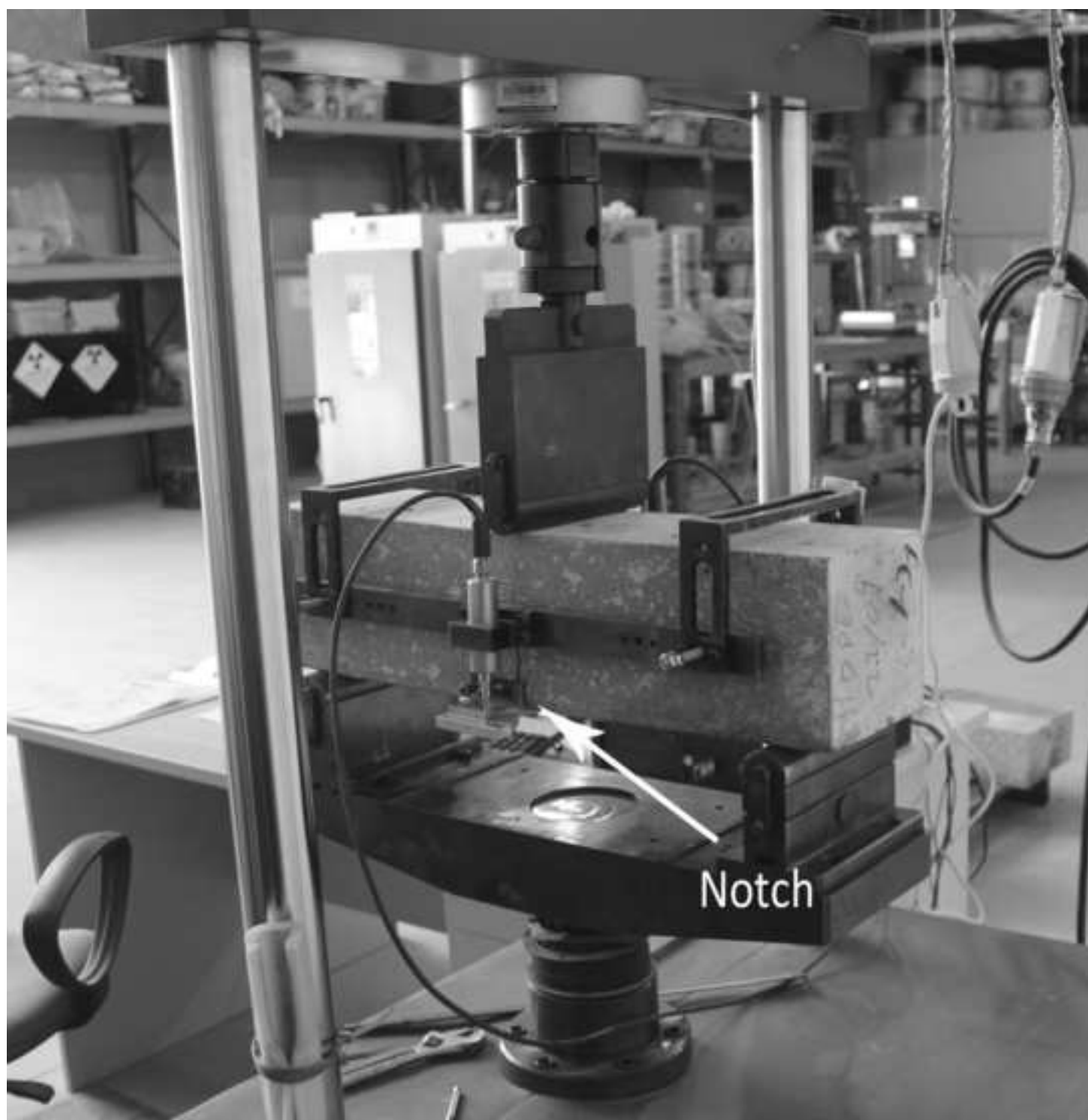
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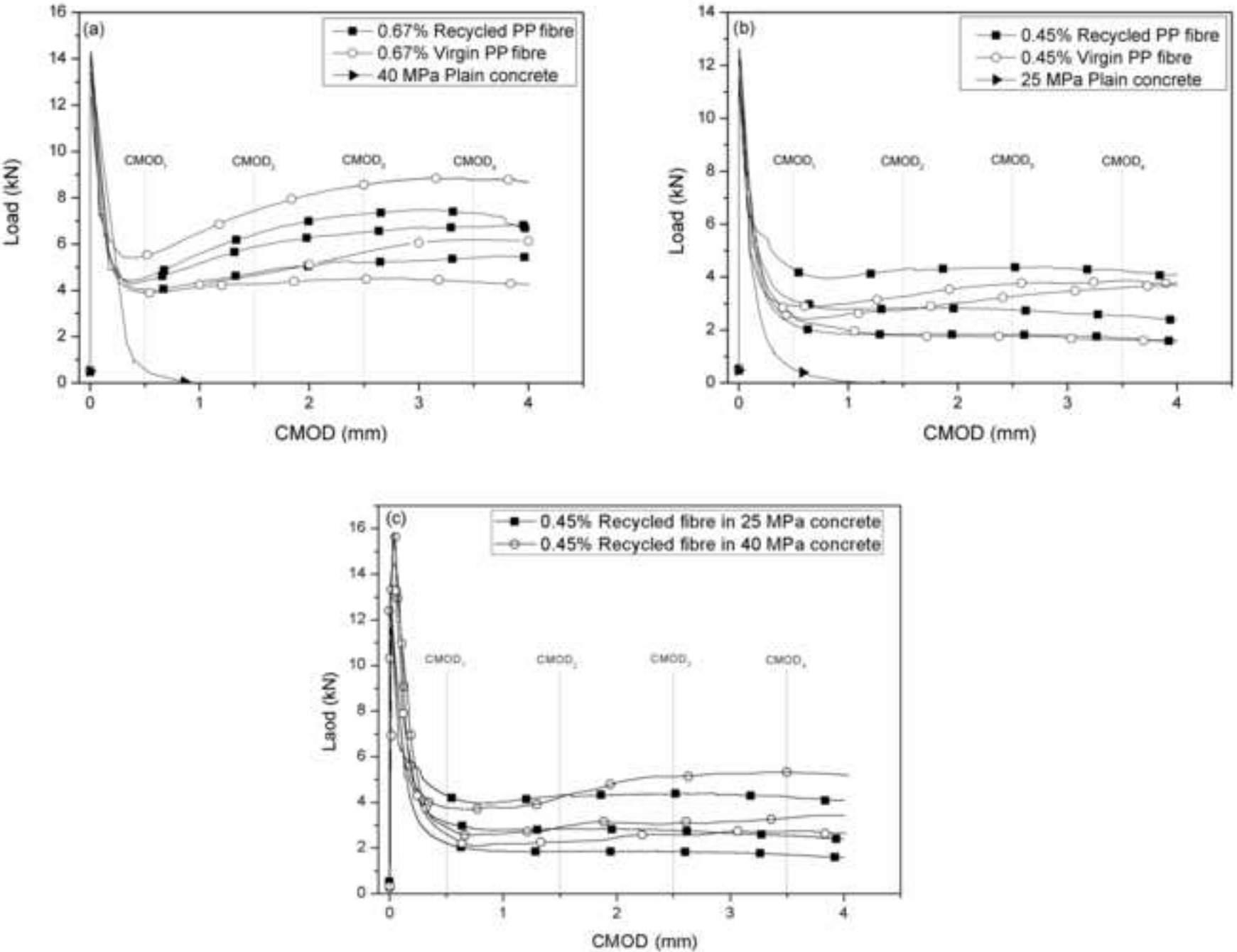
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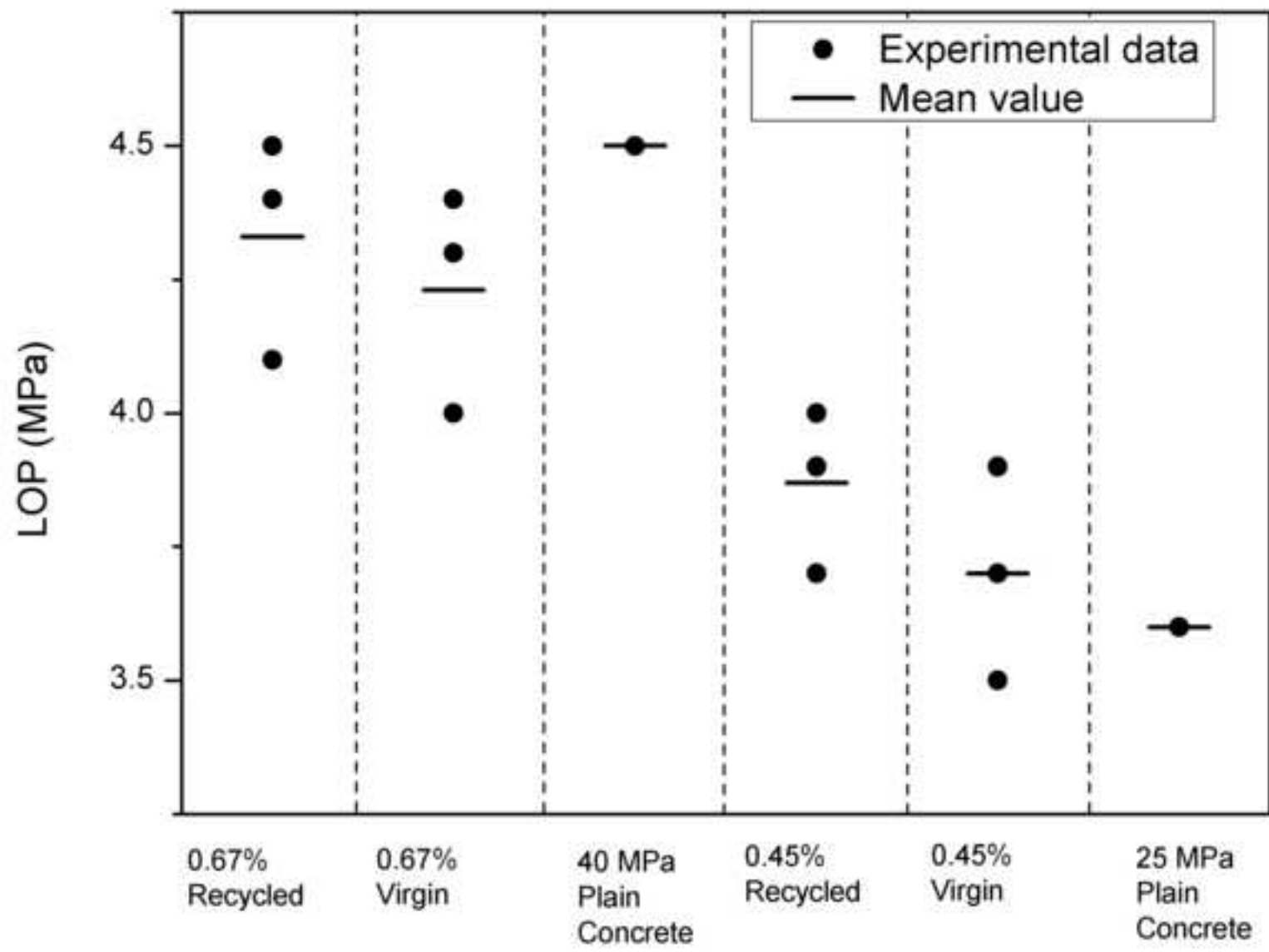
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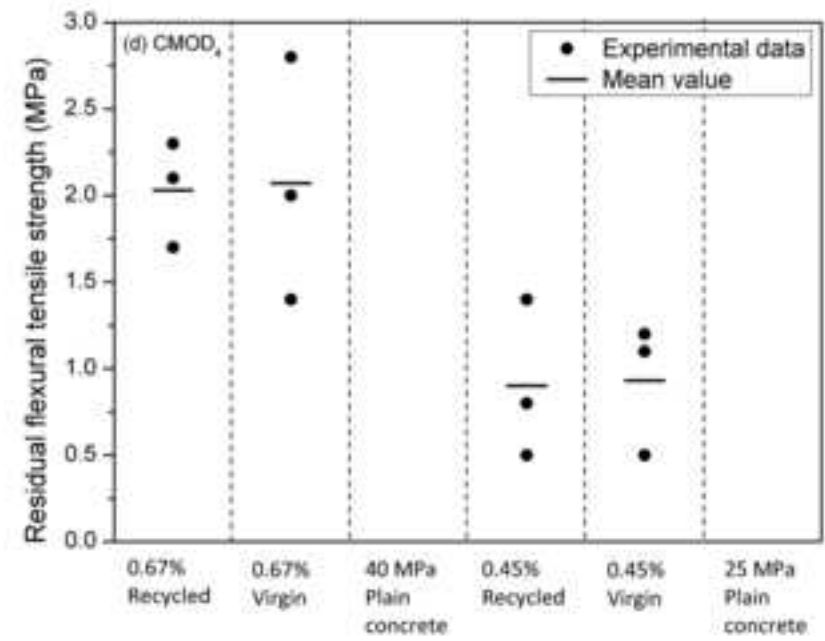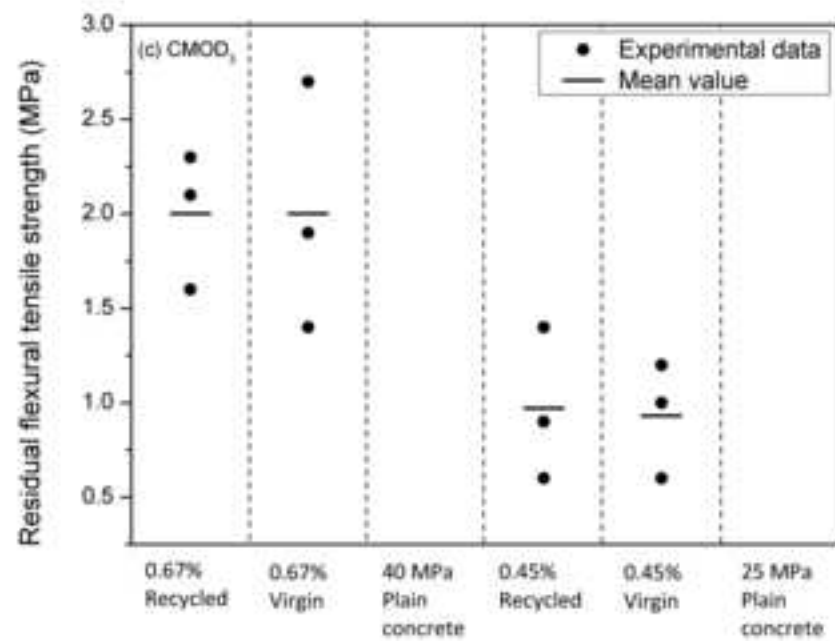
Figure 9

Figure 10
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