Experimental Strengthening of the Two-way Reinforced Concrete Slabs with High Performance Fiber Reinforced Cement Composites (HPFRCC) Prefabricated Sheets

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ABSTRACT

Reinforced concrete structures need to be strengthened and retrofitted for various reasons, including errors during design and/or construction, so in most cases strengthening of structural elements is much more economical than rebuilding the structure. Using HPFRCC with tensile stiffening behavior has been developed to strengthen the concrete structures over the recent few years. In this paper, the usage of HPFRCC for strengthening two-way reinforced concrete slabs has been studied. A total of five two-way slabs were constructed and tested to reach their own collapse stage, one of specimen was as non-strengthened control slab, and the others were strengthened in various forms. The strengthening was carried out in two ways; by installing precast plate in the tensile area and the other by installing precast plate in both tensile and compression area at two different percentages of the fiber. The bending behavior, cracking, yielding and rupture of the experimental specimens were evaluated. The results indicated that the installation of HPFRCC prefabricated laminates significantly improved the bending performance of reinforced slabs, so that the ductility, energy absorption value, cracking strength, and initial hardness of the slabs was increased and the crack width was decreased. Therefore, the proposed precast HPFRCC sheets can be used to strengthening the deficient slabs.

1. Introduction

For various reasons such as designing and/or construction errors, material deterioration in aggressive environment condition, damage due to earthquake, converting the application of structure as well as the loss of part of...
structural strength due to the corrosion of steel bars, many RC structures needs to be strengthened and retrofitted, and on the other hand, strengthening the structural members is much more economical than reconstructing the structure in most cases. For this purpose strengthening the RC structures has been much progressed during the recent years. However, few researches have been conducted on RC slabs, especially on strengthening of two-way slabs [1].

Strengthening the reinforced concrete slabs has been done by the various ways such as external post-tensioning, cross-sectional extending, reinforced cement cover, techniques of shortening the span, and adding the complementary supports [1]. In addition to the traditional strengthening methods, the performance of steel plates as external bond [2,3], strengthening with textile reinforced mortars (TRM)[4, 5], polyurethane cement composites (PUCs)[6], steel laminates, fibers reinforced polymer (FRP)[7,8], and the bonding techniques of these methods attracted many researchers’ attention. Although these methods have been used considerably, but the present disadvantages such as undesirable shear failure, corrosion of bonded steel plates [9,10] and heavy laminates, mismatch in tensile strength and stiffness of FRP sheets and costly FRP sheets have led many researchers to perform many studies during several recent years to use powerful materials with mechanical and behavioral properties similar to concrete instead of the conventional materials, one of which is (HPFRCC). Namman and Reinhardt (2003) introduced the materials as HPFRCC that had tensile strain hardening in strain stress curve. HPFRCC materials have been classified separate from fiber-reinforced concrete (FRC), so that HPFRCC are a particular type of composites which their notable sing is the strain hardening behavior in post-crack tension that are accompanied with multiple cracks until they reach relatively large strains [11]. The studies by Chanvillard and Rigaud (2003) concluded a tensile strength of 12 MPa and a tensile ductility of 0.02% - 0.06% [12]. Li’s studies (1993) and Fisher (2003) showed a tensile strength of 4 to 6 MPa and a tensile ductility of 3 to 5 % [13,14]. In 2006, the Technical committee of RILEM decided to emphasize the strain hardening properties of these materials, so the name of Strain Hardening Cementitious Composites (SHCC) was selected for it [15]. Also, CARDIFRC materials, developed at Cardiff University, Wales, are one of a variety of HPFRCCs innovated by Farhat, Nicolaides, Kanellopoulos and Karihalloo in 2006, and compressive strength was observed up to 200 MPa and a tensile strength up to 27 MPa [16] that main application of these materials is for repairing and improving the structural members. Habel And Gauvreau (2008) compounded concepts of ultra high performance concrete (UHPC) and fiber concrete and designed new materials named as ultra-high performance fiber reinforced concrete (UHPFRC) that tensile strength, compressive strength and ultimate tensile strain are higher than 10 MPa, 150 MPa and 0.005 respectively [17]. In 2009, Yoo et al. carried out some researches on improvement of the beam to concrete column connection behavior. The beam-to-column connection was strengthened with prefabricated fiber composite laminate. The results showed that the initial hardness of the strengthened sample was reduced, but its resistance increased by 15%. The amount of energy depletion has also increased [18]. In the 2015, Hemmati et al., performed experimental and parametric studies to
evaluate the effect of compressive strength, loading type and tensile reinforcement ratio on the characteristics of the final deformation of the reinforced HPFRCC beams, and showed that if the loading conditions is changed from concentrated to monotonic loading, the plastic hinge rotation capacity is increased [19, 20, 21]. In 2015, Behzad et al. carried out to investigate the effectiveness of a novel Near Surface Mounted (NSM) technique using innovative manually Made CFRP Rods (MMRs) and manually made CFRP strips (MMSs) for flexural strengthening of Reinforced Concrete (RC) two way slabs with low clear cover thickness. The test results confirmed the feasibility and efficacy of this technique in improving the behavior of the RC two- way slabs. Strengthened slabs showed an increase in flexural capacity between 279% and 394% over the control specimen [22]. In 2016, Khairaldin et al. have conducted some researches on increasing the capacity of reinforced concrete frame using HPFRCC materials in numerical way. In these models, the connecting span was replaced by HPFRCC materials with different tensile and compressive strengths then was compared with complete concrete frames and complete HPFRCC. The results indicated that the use of these high performance materials can increase the load-bearing capacity and ductility of these frames [23]. In 2017, Abasszade et al. arranged an experimental programs to investigate the effectiveness of using two innovative methods near surface mounted (NSM) techniques and HPFRCC Composites for improvement RC middle two-way slabs. The results confirmed the Strengthened slabs showed an increase in flexural capacity between 17.5% and 97% over the control specimen [24].

In recent years, investigations on the application of HPFRCC materials have been focused mostly on the cases such as the effects of bonding conditions between the substrate concrete and the laminate of HPFRCC [25], the layer thickness [26], the fiber volume percentage and the properties of the HPFRCC mix [27], crack growth and propagation [28], optimization and optimization and flexural performance [29, 30] and tensile strain hardening behavior [31]. Recently, the feasibility of using HPFRCC for the strengthening of deficient or damaged slab and beam has been investigated widely [26, 32, 33]. In this paper, the feasibility of using HPFRCC composites has been studied as a slab and various applications and settings for HPFRCC have been proposed. Then, the load-displacement curves obtained from the tested slabs and some of the parameters of the flexural performance of them, such as energy absorption capacity, ductility factors, initial stiffness and maximum resistance, were evaluated.

2. Experimental Plan

2.1 Materials Properties

The used gravel in the applied concrete had a fracture percentage of 47% located in the sieve range of 0.5 inches (12.5 mm) to the 4 (4.75 mm). The sand used in this test is also in the blow sieve range of 4 (4.75 mm). The sand and gravel grading curves is shown in Fig. 1. The cement used in this test is Portland type 2 cement.
Mixture design of conventional concrete used to cast reference and weak slabs need to be strengthened as well as the mixture of HPFRCC as prefabricated strengthening sheets is given in Table 1. The used sand and gravel were dry, therefore the extra water was considered. HPFRCC thin composites prefabricated sheets was installed with two-part special glue for flexural strengthening of the weak slabs. Since composite concrete with various fibers can used in different forms for the slabs [25], Poly propylene synthetic (PPS) fibers with 1 and 2% volume percentage were used in this study for HPFRCC composite fabrication. This fiber has a length to diameter ratio (L/D) equal to 47.62 (length 50 mm and diameter of 1.05 mm), which is shown in Fig. 2. The fibers were gradually added during the mixing process in order to prevent from balling phenomena. The distribution of fibers in HPFRCC mix is presented in Fig. 2.

Plastiment sica super lubricant has also been used in the ratio of HPFRCC mix.

In order to determine the compressive strength of two types of conventional and composite concrete, five cubic 10 × 10 cm were used. The average compressive strength

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**Table 1.** Ratio of conventional concrete and HPFRCC mortar mix (cubic meter).

<table>
<thead>
<tr>
<th>Material</th>
<th>Cement (kg)</th>
<th>Gravel (kg)</th>
<th>Sand (kg)</th>
<th>Water (kg)</th>
<th>Silica fume (kg)</th>
<th>Silica powder (kg)</th>
<th>Super plasticizer (kg)</th>
<th>PPS fiber (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>405</td>
<td>662</td>
<td>1222</td>
<td>211</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HPFRCC</td>
<td>846</td>
<td>422</td>
<td>716</td>
<td>254</td>
<td>84.60</td>
<td>25.40</td>
<td>8.50</td>
<td>8.46</td>
</tr>
</tbody>
</table>
of the cube samples of the conventional concrete and HPFRCC concrete were equal to 23.5 and 74.5 MPa, respectively and the equivalent value of cylindrical samples of these two types of concrete were approximately 19 and 59 MPa. Steel bars with a diameter of 10 mm were selected from the type of thread class of AII, which the yielding strength of the rebar obtained using uni-axial tension tests was equal to 366 MPa.

2.2 Experimental Specimens and Set-Up

Five simple-supported rectangular two-way RC slabs with a geometric dimension length of 1500mm, width 1500mm and depth 100mm were constructed and tested. Two-way slabs with a low ratio longitudinal bar were designed to achieve flexural dominate failure and preventing any possible punch shear failure, the two-way slabs with a reinforcement ratio of 1% and higher are prone to shear failure caused by punching [34], thus in order to ensure prediction of flexural failure mode in the slabs and to investigate the effects of the strengthening technique, the slabs were designed with a low reinforcement ratio about the minimum reinforcement ratio (0.2%) according to regulation of ACI 318-99 [33]. Therefore, 5 steel rebars with a diameter of 10 mm, at a distance of 130 mm on each side, with an average effective depth of 75 mm, have been placed in a layer near the slab tensile face. The anchorage of bars was provided by 180 degree hooks at both ends. The general layout of a test samples and steel reinforcement details are shown in Figure 3.

The specimen details are given in Table 2. One of these five specimens was as non-strengthened weak reference (control slab) named M and four other similar specimens were strengthened with different techniques. Two specimens of the second (MB1) and fourth (MA1) were strengthened with HPFRCC composites sheets contained 1% fibers and two specimens of the third (MB2) and fifth (MA2) specimen were fabricated with HPFRCC composites contained 2% fiber. In the second and third specimens, the composite cover was installed only on the lower tensile face of slab and in the fourth and fifth specimens simultaneously the composite sheets was installed on the tensile and compressive face of the slab, more complete details are shown in Figure 4. HPFRCC composites were individually fabricated in a mold with dimensions of 1000 x 1000 x 30 mm and, after reaching the age of 28 days, they were installed to the slabs faces with special two-component adhesives. In order to connect properly, firstly the slab surfaces are grinded and completely smoothed.

Fig. 3. General layout of a test specimen and details of steel reinforcements.
First, the considered strengthened and non-strengthened slabs are placed on four 1,350 mm steel rollers embedded on top of the supporting frame as a roller support along the edges. A 500 kN hydraulic jack was used to test the slab failure under monotonic loading. These loads were transmitted to the slab using a distributor steel beam, through four loading points shown in Figure 5. The loading points and supports were selected to provide an effective 1,350 mm span and a 300 mm slit opening in both directions, as shown in Figure 5. Vertical displacements of the each tested specimen were measured at

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### Table 2. The Details tested specimens and strengthening methods.

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Name of slab</th>
<th>Type of concrete slab</th>
<th>Upper layer</th>
<th>Lower layer</th>
<th>Fibre volume percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean composite laminate HPFRCC</td>
<td>composite laminate HPFRCC</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>M</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>MB1</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>3</td>
<td>MB2</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>MA1</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>5</td>
<td>MA2</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
</tr>
</tbody>
</table>

---

**Fig. 4.** Layout of strengthened forms.
different positions in two directions perpendicular to each other using the linear variable displacement transducer (LVDT) mounted on a rigid metal base placed individually below the slab, shown in Figure 6. One of the LVDTs is placed below the center of the slab and the four LVDTs were placed in the direction of the central lines of the slab to measure the raise at 300 and 550 mm from the center of the slab.

![Diagram of test setup](image1.png)
a) schematic  
b) real  

**Fig. 5.** Layout of general test setup.

![Diagram of LVDT locations](image2.png)  

**Fig. 6.** Location of LVDTs.

3. Results and Discussion

The results obtained from the experiments are presented in the later sections as the load-displacement curves, the comparison of the failure modes, the cracking pattern, values of strength loads, displacement and energy ductility, the excessive resistance and the maximum resistance.

3.1. Load Displacement Response

The load-displacement response curves of the control weak reference specimen in comparison with the other four slabs which have been strengthened with HPFRCC composites are illustrated in Figure 7. The maximum displacement recorded at the centre of the slab in each loading stage is used to draw the load-displacement curve.
A summary of the results from the experiments, including the cracking, yielding and ultimate load and their corresponding displacements (the centre) have been presented for all specimens in Tables 3 and 4. In the mentioned tables, $P_{cr}$ and $\Delta_{cr}$ respectively, load and displacement corresponding to the cracking load, and $P_y$ $\Delta_y$ determine the yielding load and the displacement corresponding to the yielding load, and $P_{max}$ and $\Delta_{max}$ are the maximum load and raise corresponding to it, $P_u$ and $\Delta_u$ ultimate loading capacity and displacement corresponding to the ultimate slab load. Indeed $\Delta_u$ indicates the slab load displacement in 20% load drop after the maximum load. In $P_y$ & $\Delta_y$ value the proposed method of Park Robert have been used, as shown in Figure 8. In general, the load-displacement response is divided into two stages before cracking and the post-cracking stage. The cracked stage can be divided into two stages such as before yield and after yield stages. The cracked stage before yield is from cracking load ($P_{cr}$) to yield load ($P_y$). The cracked stage, after yield, continues from the yield ($P_y$) to the ultimate load ($P_u$).
Table 3. Load-displacement response parameters of slabs in cracking and yielding resistances.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Cracking</th>
<th>Initial stiffness</th>
<th>Yield</th>
<th>Yield stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta_c$ (mm)</td>
<td>$P_c$ (kN)</td>
<td>$k_i$</td>
<td>$k_y$ (kN/mm)</td>
</tr>
<tr>
<td>Control(M)</td>
<td>0.8</td>
<td>21.60</td>
<td>27</td>
<td>1</td>
</tr>
<tr>
<td>MB1</td>
<td>1.14</td>
<td>67.17</td>
<td>58.92</td>
<td>2.18</td>
</tr>
<tr>
<td>MB2</td>
<td>1.33</td>
<td>73.16</td>
<td>55.01</td>
<td>2.04</td>
</tr>
<tr>
<td>MA1</td>
<td>1.72</td>
<td>85.83</td>
<td>49.90</td>
<td>1.85</td>
</tr>
<tr>
<td>MA2</td>
<td>1.88</td>
<td>80</td>
<td>42.55</td>
<td>1.58</td>
</tr>
</tbody>
</table>

Table 4. Load-displacement response parameters of slabs in maximum and ultimate resistances.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Maximum</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta_u$ (mm)</td>
<td>$P_u$ (kN)</td>
</tr>
<tr>
<td>Control(M)</td>
<td>33.47</td>
<td>180</td>
</tr>
<tr>
<td>MB1</td>
<td>27.18</td>
<td>182.3</td>
</tr>
<tr>
<td>MB2</td>
<td>18.45</td>
<td>199.5</td>
</tr>
<tr>
<td>MA1</td>
<td>36.30</td>
<td>210.6</td>
</tr>
<tr>
<td>MA2</td>
<td>32.42</td>
<td>220.3</td>
</tr>
</tbody>
</table>

Since the visual observation of the first cracking in the under face of the slab is not possible with sufficient precision, the first cracking load can be accepted as the point where the load-displacement response from the initial elastic response is diverted. Yielding load can be defined as the load that leads to strain in steel bars equal to the yield curve measured from the tension tests. Also, in the yield load, there is a significant change in the slope of the load-displacement curve. The ultimate load is the maximum tolerable load by the specimen (load bearing capacity of specimen). By observing the load-displacement response curves it can be seen that the strengthened slabs had the initial hardness far more than the reference slab from the first stage. Also, in all samples, the yield strength and maximum and finally the ductility and energy absorption rate have been improved significantly.

![Fig. 8. determiner Curve of the yield resistance by Park Robert method [35].](image-url)
3.2. Comparison of Failure Mode and Cracking Pattern

By comparing the failure patterns of the specimens in Figures 9 and 10, it was observed that the strengthened specimens showed a more ductility behaviour than the control specimen. All strengthened specimens had a lower crack width than the control specimen, the reason for this was the effect of strengthening HPFRCC in preventing the crack propagation. Also, by comparing the load-displacement response of the specimens in Figure 7 and the results presented in Table 3, it can be seen that resistance to cracking and initial stiffness of the specimens were increased by strengthening with HPFRCC. An increase in cracking load in the strengthened specimens compared with control slab is attributed to the role of strengthened with HPFRCC composites in limiting the growth of cracks.

Cracking patterns in the tensile face (lower) of the control specimen in the failure stage are shown in Figure 10. The first crack in the control slab, which is simulator of a weak slab behaviour in bending, occurred in the form of a shield (Y) (pre-cracking stage). After the first crack and the slope change of the load displacement curve, which represent the initial stiffness of the slab, the pre-yield cracking stage is begun, which continues until the yield of the tensile reinforcements. After yielding of steel bars, the slab is entered the third part of the behavioural curve which is strain hardening. In this area, with increasing the applied load, the length of the flexural cracks reaches the edges then it turns into shear cracks with a 45 degree angle at the sides. These cracks were expanded with increasing force and reach themselves to the pressure section of the slab. Also, by comparing the cracking patterns in this section and the load-displacement response in section 3.1, it can be seen that the behaviour of the MB1 and MB2 slabs in the pre-cracking stage was quite similar to that of the control slab. Due to the presence of composites, these slabs were flowed at higher yield load, but the behaviour of the MA1 and MA2 slabs in the pre-cracking stage was different from the control slab and showed a great stiffness at this stage.

Fig. 9. The expansion of the flexural cracks and their movement toward the edge of the control slab.
3.3. Comparison of the Loads and Stiffness

The comparison of the cracking load ($P_{cr}$), yielding load ($P_y$), ultimate load ($P_u$) and their corresponding displacements ($\Delta_{cr}$), ($\Delta_y$) and ($\Delta_u$) for all specimens are shown in Figures 11 and 12, respectively. Also, comparison of the stiffness of the specimens at three cases of ($k_{cr}$), ($k_y$) and ($k_u$) are shown in Figure 13. As expected, the initial stiffness ($k_i$), which was calculated through the load-displacement curve as the tangent stiffness of the un-cracked stage, all strengthened slabs had a higher value compared to the reference slab, and increase in the initial stiffness was due to increased cracking resistance and indicated the effect of HPFRCC composites.

The strengthened slabs also received higher cracking values from range of 67.17 kN in slab MB1 to 83.8 kN in slab MA1. A further increase in cracking load was observed in the strengthened slabs with a 1 and 2% fibre content was closed to each other and had a slight difference. This issue was also true for yield and maximum loads of the strengthened slabs, indicating that increasing the fibre higher than 1% in slab load bearing was not very effective, while the increase in load in two-way strengthened slabs is significant compared to one-way strengthened slabs. According to the diagrams in all samples, the amount of displacement was increased in cracking load and decreased in yield load. Decrease in the amount of displacement in
the strengthened specimen was due to the hardening effects of the HPFRCC composites.

Fig. 11. Comparison of loads ratio in cracking, yielding and ultimate modes.

Fig. 12. Comparison of displacement ratio in cracking, yielding and ultimate modes.

**3.4. Energy Absorption**

The energy absorption capacity of the slabs is evaluated by the area under the load-displacement curve. To compare the effect of different types of HPFRCC composites on increasing of weak slab strength, the tolerance values are calculated in Table 5 and are drawn in Figure (14). As can be seen, energy absorption capacity has been increased in all slabs. So that the energy absorption ratio was increased by 1 to 5 percent in slab strengthened only at the lower part and 23 to 50 percent in the slabs strengthen at the top and bottom.

**Table 5.** Energy absorption capacity, and ductility of the slabs.

<table>
<thead>
<tr>
<th>Strengthen specimens</th>
<th>Energy absorption (kN.mm)</th>
<th>Energy absorption of each specimen to reference</th>
<th>$\mu_E = \frac{E_{80%}}{E_y}$</th>
<th>$\mu_{E(80%)}$</th>
<th>$\mu_A = \frac{\Delta_{80%}}{\Delta_y}$</th>
<th>Excessive resistance factor $R = (P_{\text{max}}/P_y)$</th>
<th>$\frac{R}{R_w}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control(M)</td>
<td>6794.95</td>
<td>1</td>
<td>4.07</td>
<td>1</td>
<td>2.77</td>
<td>1</td>
<td>1.14</td>
</tr>
<tr>
<td>MB1</td>
<td>6859.26</td>
<td>1.01</td>
<td>4.25</td>
<td>1.04</td>
<td>3.74</td>
<td>1.35</td>
<td>1.22</td>
</tr>
<tr>
<td>MB2</td>
<td>7119.37</td>
<td>1.05</td>
<td>6.31</td>
<td>1.55</td>
<td>4.43</td>
<td>1.60</td>
<td>1.21</td>
</tr>
<tr>
<td>MA1</td>
<td>8327.61</td>
<td>1.23</td>
<td>6.11</td>
<td>1.50</td>
<td>4.16</td>
<td>1.50</td>
<td>1.18</td>
</tr>
<tr>
<td>MA2</td>
<td>10163.43</td>
<td>1.50</td>
<td>6.06</td>
<td>1.49</td>
<td>4.30</td>
<td>1.55</td>
<td>1.23</td>
</tr>
</tbody>
</table>
3.5. Displacement and Energy of Specimens Ductility

Ductility is defined as the ability of the structure to tolerate the non-elastic displacements after the displacement of the first yielding in steel rebar without decreasing the bearing capacity of the structure and is introduced by a relation called the index or ductility coefficient ($\mu$). Ductility index is usually defined as the ratio of displacement ($\Delta$) or absorbed energy ($E$) at 20% load loss after the ultimate load of the specimen to the corresponding values at the yield load of the sample according to equations 1, 2 and Figure 15.

\[ \mu_\Delta = \frac{\Delta_{80\%}}{\Delta_y} \]  
\[ \mu_E = \frac{E_{80\%}}{E_y} \]  

A comparison of the absorbed energy values and the displacement ductility of all five tested specimens is presented in Table 5. The column algorithm for comparing the displacement and energy ductility is shown in Figures 16 and 17, respectively. As it is shown, the displacement ductility of all samples was increased comparing to the control sample, as well as the MB2 sample had the highest displacement ductility of 4.43. A similar trend was observed in the graphs for energy ductility.
By comparing the ductility values of the samples in this section and the load-displacement response in section 3.1, it can be seen that in samples with higher ductility, the load bearing capacity decreased with a more moderate slope and was not accompanying with any sudden drop. Conversely, samples that had a lower degree of ductility exhibited a bitter behaviour, and the load bearing capacity was fell down suddenly in these samples.

3.6. Extensive Resistance Factor and Maximum Resistance

The coefficient of excessive resistance (R), which is influenced by factors such as the number of uncertain degrees of the structure, the strain hardening, the displacement constraints, the mechanical properties of the materials, and the strengthening pattern, is determined by an inelastic response curve, which is the ratio of maximum to yield loads of slabs specimens. The coefficient values of the excessive resistance are calculated for all samples and presented in Table 5. As shown in Figure 18, the maximum coefficient of excessive resistance of specimens has increased up to 23% in slab MA2.
4. Conclusion

The results of experimental research on application of HPFRCC composite pre-casted sheets for strengthening of deficient slabs are presented as following:

1. By comparing the specimen failure modes and the load-displacement response curves, it can be seen that the strengthened specimens exhibited a more ductility behaviour than the control specimen.

2. All strengthened specimens have a lower crack width than the control specimen.

3. The cracking strength and initial stiffness of the specimens strengthened with HPFRCC were increased due to limiting the expansion of the cracks, so that the initial stiffness ratios in the specimens strengthened only at tensile face were 2.18 and 2.04 times of that of control sample and this ratios at specimens strengthened at both tensile and compressive faces were 1.58 and 1.85.

4. The yield and maximum load were increased respectively up to 14 and 22% in all strengthened specimens compared to the control sample. There was no significant difference between loads of specimens strengthened only at tensile face at two cases of 1 and 2%, but there was difference at 1 and 2% fibre specimens strengthened at both tensile and compressive faces.

5. The energy absorption values of the slabs strengthened at both tensile and compressive faces were increased significantly up to 1.50 times of the energy value in the control slab.

6. The displacement ductility values in all strengthened specimens were increased up to 60% compared to the control sample.

7. Excessive resistance coefficients in all slabs were increased up to 23% compared to control un-strengthened specimen.

REFERENCES


