CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 GENERAL

The motivation for the present investigation has been presented in chapter 1. The need for conducting a feasibility study for producing of recycled coarse aggregate concrete slabs is identified. The need to understand the behavior of thus produced recycled coarse aggregate concrete slab elements in flexure and punching shear is identified. The aims and specific objectives are decided accordingly for the present investigation.

Once the aim and objectives are decided, the state of the art of the technology related to the present work is reviewed. From this review the aim and objectives of the present investigation have been validated.

The implementation strategy is then decided. Accordingly, experimentation in the laboratory is planned. A total number of 18 cubes of size 150 x 150 x 150 mm and 36 cylinders of size 150 mm dia and 300 mm long were cast and tested to arrive mechanical properties of RCAC. A total number of 32 slab specimens have been cast and tested to evaluate the behaviour under flexure. Another 32 number of slab specimens have been cast and tested to understand the behavior of RCAC slabs in punching shear. The results obtained from these tests have been analysed to understand the behaviour of RCAC slab elements. The bending moment coefficients have been obtained for RCAC slabs by using yield line analysis. The punching shear strength results are compared to provisions of codes IS 456, ACI 318, B.S 8110, Euro code 2 (CEB) codes and yield line analysis. Regression models have been developed from the experimental data obtained from the present study. It is concluded that
RCAC slabs exhibit moderate characteristics in flexure and shear when compared to NCAC slab elements.

6.2 CONCLUSIONS

Based on the results of the experimentation and the analysis of the results, the following conclusions seem to be valid.

1) The literature review carried out led to the identification of the need for conducting the feasibility study of producing recycled coarse aggregate concrete slab elements.

2) The cube and cylinder compressive strength decreases as the recycled coarse aggregate percentage increases. Similarly the split tensile strength also reduces.

3) The cube compressive strength of recycled coarse aggregate concrete (replacing of natural coarse aggregate with recycled coarse aggregate from 20% to 100%) is in the range of 42.52 to 33.48 MPa, where as natural coarse aggregate concrete is having a cube compressive strength of 43.33 MPa.

4) The cylinder compressive strength of recycled coarse aggregate concrete (replacing of natural coarse aggregate with recycled coarse aggregate from 20% to 100%) is in the range of 33.50 to 26.42 MPa, where as natural coarse aggregate concrete is having a cylinder compressive strength of 34.35 MPa.

5) The split tensile strength of recycled coarse aggregate concrete (replacing of natural coarse aggregate with recycled coarse aggregate from 20% to 100%) is in the range of 3.25 to 2.78 MPa, where as natural coarse aggregate concrete is having a tensile strength of 3.35 MPa.
6) The punching shear strength of slab specimen decreases as the percentage replacement of natural coarse aggregate with recycled coarse aggregate increases.

7) The Punching shear first crack load of simply supported natural coarse aggregate concrete slab specimen is 14.60 kN. The first crack load of simply supported recycled coarse aggregate concrete slab specimens by replacing natural coarse aggregate with recycled coarse aggregate from 20% to 100% is between 14.20kN to 12.20 kN. Therefore, first crack load of recycled coarse aggregate concrete slab specimen decreases by 2.74 to 16.44%, when compared with natural coarse aggregate concrete slab specimens.

8) The Ultimate load in punching of simply supported natural coarse aggregate concrete slab specimen is 48.20 kN. The ultimate load of simply supported recycled coarse aggregate concrete slab specimens by replacing natural coarse aggregate with recycled coarse aggregate from 20% to 100% is in the range of 47.20kN to 41.40kN. Therefore, ultimate load of recycled coarse aggregate concrete slab specimen decreases in the range of 2.07 to 14.11%, when compared with natural coarse aggregate concrete slab specimens.

9) The central deflections corresponding to punching shear first crack load of simply supported recycled coarse aggregate concrete slab specimen is decreases from 3 to 30% when compared with natural coarse aggregate concrete specimens. And the central deflections corresponding to ultimate load decrease from 3 to 15% when compared with natural coarse aggregate concrete specimens. It is clear that similar trend is observed at first crack and ultimate failure stages. But, rate of decrease of deflections at first crack stage is more when compared to that of ultimate stage.
10) The stiffness and stiffness degradation decrease as the percentage of recycled coarse aggregate increases in simply supported slab specimens under punching shear.

11) The energy absorption of simply supported recycled coarse aggregate concrete slab specimens under punching shear decrease from 4.17 to 27.5% when compared with natural coarse aggregate concrete specimens.

12) For the simply supported slab specimens under punching shear, the cracks on the bottom face are radial running predominantly between the loading point and the corners. A circular punching occurred on the top surface (surrounding the patch load), this was reflected on the bottom face with an enlarged area, clearly identifying the truncated cone. It is observed that the bottom perimeter of this truncated cone decreases as the replacement of natural coarse aggregate with recycled coarse aggregate increases, although the overall cracking pattern remains identical for all slab specimens.

13) The average critical section of simply supported recycled aggregate concrete slabs under punching shear is 2.05 times of thickness of the slab.

14) The ultimate punching loads of recycled coarse aggregate concrete slab specimens with simply supported edge condition are compared with codes of IS 456, ACI 318, BS 8110 and Euro code 2. The computed values of IS 456, ACI 318 and Euro code 2 give conservative predictions.

15) The regression models developed for predicting punching shear strength of simply supported recycled coarse aggregate slab specimens are presented below.
\[ \tau = (0.359 - 0.0067 \, r) \sqrt{f_c} \quad (f_c = \text{cube compressive strength}) \]

\[ \tau = (0.403 - 0.0091 \, r) \sqrt{f'_c} \quad (f'_c = \text{cylinder compressive strength}) \]

where \(r\) is replacement ratio of natural coarse aggregate with recycled coarse aggregate. Standard deviation of above equations is 0.0020 and 0.0025, respectively.

16) The punching shear first crack load of restrained natural coarse aggregate concrete slab specimen is 19.00kN. The first crack load of restrained recycled coarse aggregate concrete slab specimens by replacing natural coarse aggregate with recycled coarse aggregate from 20% to 100% is in the range of 18.20 to 15.80kN. Therefore first crack load of recycled coarse aggregate concrete slab specimen decreases in the range of 4.21 to 16.84%, when compared with natural coarse aggregate concrete slab specimens.

17) The ultimate load in punching of restrained natural coarse aggregate concrete slab specimen is 64.00kN. The ultimate load of restrained recycled coarse aggregate concrete slab specimens by replacing natural coarse aggregate with recycled coarse aggregate from 20% to 100% is in the range of 62.80kN to 56.00kN. Therefore, ultimate load of recycled coarse aggregate concrete slab specimen decreases in the range of 1.88 to 12.50%, when compared with natural coarse aggregate concrete slab specimens.

18) The central deflections corresponding to punching shear first crack load of restrained recycled coarse aggregate concrete slab specimen is decreases from 3 to 32% when compared with natural coarse aggregate concrete specimens. And the central deflections corresponding to ultimate load of restrained recycled coarse aggregate concrete slab specimen decreases from 2 to 9% when compared with natural coarse aggregate concrete specimens. It is clear
that similar trend is observed at first crack and ultimate failure stages. But, rate of decrease of deflections at first crack stage is more when compared to that of ultimate stage.

19) The stiffness and stiffness degradation decrease as the percentage of recycled coarse aggregate increases in restrained slab specimens under punching shear.

20) The energy absorption of restrained recycled coarse aggregate concrete slab specimen under punching shear decrease from 4.70 to 22.15% when compared with natural coarse aggregate concrete specimens.

21) For the restrained slab specimens under punching shear, the cracks on the bottom face are radial running predominantly between the loading point and the corners. A circular punching occurred on the top surface (surrounding the patch load), this was reflected on the bottom face with an enlarged area, clearly identifying the truncated cone. It is observed that the bottom perimeter of this truncated cone decreases as the replacement of natural coarse aggregate with recycled coarse aggregate increases, although the overall cracking pattern remains identical for all slab specimens.

22) The average critical section of restrained recycled aggregate concrete slabs under punching shear is 2.02 times of thickness of the slab.

23) The ultimate punching loads of recycled coarse aggregate concrete slab specimens with restrained edge condition are compared with codes of IS 456, ACI 318, BS 8110 and Euro code 2. The computed values of IS 456, ACI 318, BS 8110 and Euro code 2 highly conservative predictions.

24) The regression models developed for predicting punching shear strength of restrained recycled coarse aggregate slab specimens are presented below.
\[ \tau = (0.434 - 0.0014r) \sqrt{f_c} \quad (f_c = \text{cube compressive strength}) \]

\[ \tau = (0.488 - 0.0008r) \sqrt{f'_c} \quad (f'_c = \text{cylinder compressive strength}) \]

where \( r \) is replacement ratio of natural coarse aggregate with recycled coarse aggregate. Standard deviation of above equations is 0.0025 and 0.0030, respectively.

25) The first crack load of restrained recycled coarse aggregate concrete slab specimens is marginally higher than those corresponding to simply supported slabs.

26) The ultimate loads of restrained recycled coarse aggregate concrete slab specimens are higher in the range of 33.05 to 35.27% than those corresponding to simply supported slabs.

27) The flexural strength of recycled coarse aggregate concrete slab specimens decreases as the replacement of natural coarse aggregate with recycled coarse aggregate increases.

28) The first crack load of simply supported natural coarse aggregate concrete slab specimen under flexure is 26kN. The first crack load of simply supported recycled coarse aggregate concrete slab specimens by replacing natural coarse aggregate with recycled coarse aggregate from 20% to 100% under flexure is in the range of 26 to 21kN. Therefore, first crack load of recycled coarse aggregate concrete slab specimen decreases by 0.00 to 19.23%, when compared with natural coarse aggregate concrete slab specimen.

29) The flexural ultimate load of simply supported natural coarse aggregate concrete slab specimen under flexure is 186kN. The ultimate load of simply supported recycled coarse aggregate concrete slab specimens is in the range of 184 to 166kN. Therefore, ultimate loads of recycled coarse aggregate concrete
slab specimen decreases by 1.08 to 10.75%, when compared with natural coarse aggregate concrete slab specimens.

30) The central deflections in flexure corresponding to first crack load of simply supported recycled coarse aggregate concrete slab specimens decrease from 1 to 20% when compared with natural coarse aggregate concrete specimens respectively. The central deflections corresponding to ultimate load of simply supported recycled coarse aggregate concrete slab specimens is decreases from 1 to 8% when compared with natural coarse aggregate concrete specimens. It is clear that similar trend is observed at first crack and ultimate failure stages. At the first crack stage the variation in the deflections are more due to presence of old mortar over recycled coarse aggregate. But at the ultimate load stage rate of decrease of deflections is less due to the contribution of steel reinforcement.

31) The stiffness decreases as the recycled coarse aggregate increases in simply supported slab specimens under flexure.

32) The energy absorption of simply supported recycled coarse aggregate concrete slab specimens under flexure decreases from 2.00 to 24.67% when compared with natural coarse aggregate concrete specimens.

33) The first crack load of restrained natural coarse aggregate concrete slab specimen under flexure is 41kN. The first crack load of restrained recycled coarse aggregate concrete slab specimens by replacing natural coarse aggregate with recycled coarse aggregate from 20% to 100% under flexure is in the range of 40 to 31kN. Therefore, first crack load recycled coarse aggregate concrete slab specimen decreases by 2.44 to 24.39%, when compared with natural coarse aggregate concrete slab specimens.
34) The flexural ultimate load of restrained natural coarse aggregate concrete slab specimen under flexure is 218kN. The ultimate load of restrained recycled coarse aggregate concrete slab specimens is in the range of 216 to 193kN. Therefore, ultimate load recycled coarse aggregate concrete slab specimen decreases by 0.92 to 11.47%, when compared with natural coarse aggregate concrete slab specimens.

35) The central deflections in flexure corresponding to first crack load of restrained recycled coarse aggregate concrete slab specimen increases from 32 to 58% when compared with natural coarse aggregate concrete specimens respectively. The central deflections corresponding to ultimate load of restrained recycled coarse aggregate concrete slab specimens decreases from 1 to 21% when compared with natural coarse aggregate concrete specimens. The variation of deflections was more at first crack stage, where the variation is gradually decreases at ultimate stage. At the first cracking stage the variation in the deflections are more due to presence of old mortar over the RCA and end restraintment, but at ultimate stage rate of decrease of deflections are less due to the contribution of steel reinforcement.

36) The stiffness decreases as the recycled coarse aggregate increases in restrained slab specimens under flexure.

37) The energy absorption of restrained recycled coarse aggregate concrete slab specimens under flexure decreases from 6.47 to 43.53% when compared with natural coarse aggregate concrete specimens.

38) The Bending moment coefficients of recycled aggregate concrete slabs with different edge conditions and with different replacement ratios of natural
coarse aggregate with recycled coarse aggregate have been derived and are given below.

<table>
<thead>
<tr>
<th>Nomenclature of slab specimen</th>
<th>Edge condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All edges Simply supported</td>
</tr>
<tr>
<td></td>
<td>$\alpha_x$</td>
</tr>
<tr>
<td>NCAC</td>
<td>0.0409</td>
</tr>
<tr>
<td>RCAC-20</td>
<td>0.0408</td>
</tr>
<tr>
<td>RCAC-40</td>
<td>0.0406</td>
</tr>
<tr>
<td>RCAC-60</td>
<td>0.0403</td>
</tr>
<tr>
<td>RCAC-80</td>
<td>0.0396</td>
</tr>
<tr>
<td>RCAC-100</td>
<td>0.0394</td>
</tr>
<tr>
<td><strong>Average =</strong></td>
<td><strong>0.0401</strong></td>
</tr>
</tbody>
</table>

It is concluded that the natural coarse aggregate is replaced up to 40% with recycled coarse aggregate the resulting recycled aggregate concrete likely present same behavior than the natural coarse aggregate concrete in terms of the punching shear and flexural properties studied in this investigation. This fact justifies the efforts to use these concretes, which can contribute to the preservation of the environment.
6.3 SUGGESTIONS FOR FUTURE WORK

1) In the present investigation natural coarse aggregate is replaced by recycled coarse aggregate. Investigations may be carried out to conduct feasibility of using recycled fine aggregate in producing recycled fine aggregate concrete.

2) Investigations may be carried out to conduct feasibility of using both recycled fine and coarse aggregate in the production of recycled aggregate slabs.

3) Mineral admixtures like silica fume and metakaolinite can be used to improve the quality of matrix in recycled aggregate concrete.

4) The present investigation is carried out with simply supported and restrained edge conditions. However, the effect of other edge conditions can be investigated.

5) The present investigation has been carried out on square shape slab specimens. Experimentations may be carried out with slabs of different shapes and sizes.

6) Investigations may be carried out to study the influence of openings in recycled coarse aggregate concrete slabs.

7) Investigations may be carried out with different span-depth ratios for recycled coarse aggregate concrete slabs.

8) Finite element analysis may be carried out to find responses of RCAC slabs in shear and flexure.

9) The results of the present investigations may be synthesized for developing macro mechanical models for RCAC slabs using Neural Networks/Genetic Algorithms/Fuzzy logic.