CHAPTER 9:
CONCLUSIONS,
RECOMMENDATIONS AND SCOPE FOR FUTURE RESEARCH

1.1 GENERAL

The objective of this work was to assess the possibility of utilizing RSA as a supplementary cementitious material in the construction of rigid pavements. To study the effects of RSA and MS as pozzolanic material, the investigations were divided into five sections; material properties, effect on properties of cement paste, effect on mechanical properties of mortar, effect on mechanical and durability properties of concrete and finally, structural analysis and cost comparison.

This chapter presents the conclusions from the current investigations despite the fact that the conclusions of the individual chapters have been incorporated independently in separate sections of each chapter. On the basis of the results of current investigation, few suggestions and scope for future research have also been provided, which may further improve the properties of concrete admixed with RSA and MS.

1.2 CONCLUSIONS

The conclusions drawn from this study are as follows:

1) Rice straw ash has a high amount of silica content (not as much as microsilica) even when it was produced by open air burning and without using any enhanced and sophisticated grinding technique. The specific surface area of rice straw ash (1.846 m^2/g) and microsilica (16.14 m^2/g) particles was higher than that of the OPC particles (0.3 m^2/g). They were 5 times and 28 times respectively, finer than the OPC particles. It was found from the TGA analysis that RSA has a high amount of unburned carbon, possibly because of burning rice straw in open air that may have

contributed to the higher normal consistency (28 to 109%) of cement paste admixed with RSA, as compared to the control paste apparently revealing its hydrophilic nature. Similar to the behaviour of RSA paste, cement paste admixed with MS also had higher normal consistency (16 to 38%) because of the high specific surface area of MS particles.

2) The admixing of MS did not affect the setting times of cement paste as much as the RSA did. The admixing of RSA remarkably increased the setting times of the cementitious paste (increment ranging between 3.9 to 82%). However, in the case of composite of RSA and MS, the results of setting times test were indistinct (initial setting time decreases while final setting time increases). The MgO content in RSA was very high; therefore, higher expansion (43 to 256%) was observed in cement paste admixed with RSA in comparison to the expansion observed in the control cement paste. The soundness of cement remained largely unaffected due to admixing of MS. The HRWR dosage for admixed mortar was proportional to the amount of RSA or MS in the admixed paste. It increased linearly with increase in the proportion of RSA or MS in the paste.

3) The compressive strength of the mortar hiked up to 5% replacement of OPC by RSA for all days of curing. At 10% replacement, the compressive strength was less than that of 5% replacement but was higher than the strength of the control mortar for all days of curing. Beyond 10% replacement by RSA, the compressive strength of the mortar began to fall significantly and was much lower than that of the control for all days of curing. In case of MS, up to 7.5% replacement of OPC was possible without any loss of compressive strength of mortar cubes at all the ages of curing. When replacement level of OPC by MS was increased beyond 7.5%, the compressive strength of admixed mortar cubes was significantly lower than that of

the control mortar cubes at early days of curing (3 and 7 days) and vice versa at later days of curing (28 days and beyond). This could be attributed to the dominance of dilution effect of OPC particles during early days of curing while at later days of curing, filler and pozzolanic effect of MS were more dominant.

4) The variation of compressive and flexural strength of concrete mix M10 was similar to that of its mortar counterpart at all days of curing. The admixing of RSA (mix R10) marginally increased the strengths of concrete (up to 2%) as compared to the control concrete. Amongst the concrete mixes of RSA-MS composite cured for 28 days, R5M7.5 had the maximum compressive strength (53.61 MPa), flexural strength (6.07 MPa) and split tensile strength (4.23 MPa) while the maximum strengths amongst all the concrete mixes investigated in the present study were observed in concrete mix M7.5 (7.5% MS) as compared to the control concrete for all days of curing. MS was more effective in improving the mechanical strengths of concrete as compared to RSA. It was found that the strength (compressive/flexural/split tensile) of concrete admixed with RSA and MS varies logarithmically with the curing age. The power equations between compressive and flexural strength ($f_r = 0.87 \times \sqrt{f_c}$ for 28 days of curing; and $f_r = 0.561 \times f_c^{0.615}$ for other days of curing) and compressive-split tensile strength (f_t= 0.137× $f_c^{0.873}$ for all days of curing) were more effective in predicting one parameter from another in comparison with equations prescribed by other researchers and standard specifications of different countries. Also, the relationship between flexural-split tensile strength was defined by a power equation ($f_r = 2.295 \times f_t^{0.6923}$).

5) In the mineralogical analysis of concrete samples at 28 days of curing, it was found that the peaks of alite and belite were prolonged due to admixing of RSA and MS especially in concrete mix R5M5 and R5M7.5 as compared to control concrete. It

signifies that the strength of concrete admixed with RSA and MS will continue to grow even at later days of curing. Anyway, these peaks were missing in XRD diffractogram of control concrete R0, which suggests that control concrete accomplishes the majority of its strength at 28 days of curing. The microstructure of selected concrete samples by SEM and petrography were analysed at various ages of curing. Mostly, it was observed that the admixing of RSA significantly reduces the number of voids in the concrete matrix by its pozzolanic effect. RSA also reduces the formation of ettringite in the concrete, thereby reducing the potential damage to the concrete due to delayed ettringite formation. Most of the voids present in concrete admixed with RSA and MS were being infilled with the additional C-S-H gel (formed due to consumption of portlandite by pozzolanic action of RSA and MS).

6) The replacement level of OPC beyond 15% by RSA and MS did not affect the air content of the fresh concrete as compared to the lower replacement levels (i.e. 12.5%, 10% and so on). The admixing of MS and RSA significantly improves the resistance of concrete to water absorption by reducing permeability as well as by reducing capillary action. It also increases the defense mechanism of concrete to chloride ion penetration. However, MS was more effective as compared to the RSA in improving the water absorption and chloride ion penetration of concrete. The saturated water absorption, rate and coefficient of water absorption and chloride ion penetration of different concrete mixes were dependent on the curing age. In order to facilitate their prediction, predictive graphs have been developed in the study.

7) The loss of mass and loss of compressive strength (due to immersion in acidic solutions) in concrete admixed with MS were lower than in concrete admixed with RSA. HCl solution was more abrasive to concrete admixed with RSA and MS as

compared to H_2SO_4 solution. The prolonged curing of concrete in water (before acidic immersion) hardened it to the extent that acid penetration was same irrespective of the type of acid solution. In the XRD analysis of the concrete samples subjected to acid attack, it was found that the damage due to HCl attack was mainly because of the formation of $CaCl_2$. It, being highly soluble in water, leaches out from the concrete, thereby creating a tenuous texture within the microstructure of concrete (confirmed from SEM analysis). The damage due to H_2SO_4 attack was because of the formation of gypsum. The presence of gypsum (which is expansive in nature) generates internal stresses, thereby leading to micro-cracks in the hardened cement paste. These microcracks were clearly observed in the SEM images of different concrete samples. In any case, the concrete admixed with RSA and MS demonstrated the best ability to opposing the propagation of micro-cracks. It was also concluded from the SEM analysis that when concrete containing MS was subjected to immersion in HCl solution, most of the formation of $CaCl_2$ was due to dissolution of C-S-H gel while in concrete containing composite of RSA and MS (mix R5M7.5 and R10M7.5), formation of $CaCl_2$ was due to dissolution of C-S-H gel as well as portlandite. In comparison to gypsum and ettringite, the dissolution of hydrated cement paste was higher by $CaCl_{2,}$ which consequently causes higher loss of mass and loss of compressive strength.

8) The depth of carbonation in concrete admixed with RSA was more than the carbonation depth in concrete admixed with MS and lesser than the control concrete. Unlike natural carbonation (where CO_2 reacts with hydration products), the CO_2 (from carbonation chamber) reacted directly with C_3S and C_2S to form $CaCO_3$ due to their incomplete transformation into hydration products (in the absence of sufficient amount of moisture). The carbonation depth in concrete at 28

days of combined curing (14 days water curing followed by 14 days ACC) decreases with an increase in its compressive strength. A mathematical relationship is developed between carbonation depth of different concrete mixes (‘d’) at 28 days of combined curing (ACC + water) and respective compressive strength (‘f_c’) at 28 days of water curing ($d = 5 \times 10^{13} \times 2.718^{(-0.568 \times f_c)}$).

9) Based on the structural design of the rigid pavement, it is evident that, in all likelihood, admixing of RSA and MS would reduce the slab thickness of the rigid pavement. The lowest slab thickness was found in case of mix M7.5 (20 to 23% lower than that of control concrete slab) due to its highest flexural strength amongst all the mixes. However, mix M7.5 was 10% costlier than mix R10 which had lowest cost amongst all mixes (for construction of 1 km of NH). The admixing of RSA reduced the slab thickness by 11%, cost of 1 m^3 of concrete by 3% and cost of constructing 1 km length of NH (two lanes, one way) by 14% as compared to the control concrete.

1.3 RECOMMENDATIONS

In view of the findings of current investigation, the following suggestions are being made for maximising the positive impacts of RSA without influencing the general expense of the development of rigid pavement:

1) Mix R10 is recommended for the construction of rigid pavements as it not only reduces the slab thickness by 11% but also the overall cost of construction by 14% as compared to the control mix. It is recommended, especially for cases where economic aspect of the rigid pavement is the governing factor.
2) Mix R5M7.5 is recommended when there is great concern about the durability of a rigid pavement. It is recommended, especially for cases where economic aspect of

the rigid pavement is not the governing factor as its usage may incur a marginal increase in the cost of construction. The cost difference is likely to be 6% as compared to the control mix.

3) RSA should be collected carefully (only after complete combustion) in order to avoid unwanted dirt particles which may affect the composition of RSA. It should always be kept in sealed bags as they tend to absorb moisture from the atmosphere due to their hydrophilic nature.
4) Proper mixing and compaction of concrete admixed with RSA are highly recommended as RSA (due to its lower specific gravity) tends to migrate along with water to the top surface of concrete if excessive vibrations are performed.

1.4 SCOPE FOR FUTURE RESEARCH

Following are the suggestions for the future research that are important to further reinforce the idea of RSA as a supplementary cementitious material:

1) A small stretch of a rigid pavement incorporating RSA should be constructed so as to approve the outcomes obtained in this study.
2) In the current study, w/b ratio was kept constant at 0.39 for all the tests. Varying w/b ratio may be adopted.
3) All the tests could also be performed without using HRWR. However, it will increase the water requirement of the concrete mix, which may affect the properties of concrete is a matter of future research.
4) Apart from XRD, SEM and petrography study, more analysis about the mineralogy and microstructure of concrete can be done for an in-depth study on the effects of RSA on various properties of concrete.

5) Apart from the experiments performed in this study, tests for analysing the freezing and thawing properties of concrete and abrasion resistance of concrete admixed with RSA and MS may be conducted.
6) Various experiments on DLC admixed with RSA and MS may be performed to analyse its usage as a sub-base layer.