CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 CONCLUSIONS

The comprehensive studies were carried out on characteristics of fly ash – gypsum flowable slurry to assess its suitability as a binder in the road pavement base/sub-base and also, the performance of the slurry bound macadam. Based on the results obtained, the following conclusions are drawn.

The relative ratios and successive relative ratios of flow are significantly higher than water requirement for both F-G slurry and FGQWS. It shows that even a small variation in water content drastically affect the flowability of slurry. Also, mixtures with higher flow are much more sensitive to even marginal variation in water content than the mixtures with low flowability. Further, it is noticed that minimum of 50% volume of water is required for both F-G slurry and FGQWS having flowability higher than 300 mm.

The water requirement of FGQWS is significantly less than that of F-G slurry without filler. The reduction in water content varies in the range of 5% to 30% depending on the filler content. It is due to the reduction in effective specific surface (ESS) of the blended solid phase.

The wet density of F-G slurry is varying from 1620 kg/m$^3$ to 1920 kg/m$^3$, whereas, the dry density is in the range of 1600 kg/m$^3$ to 1900 kg/m$^3$. However, the addition of quarry waste has increased the both wet and dry density of FGQWS. The wet and hardened density of FGQWS is in
the range of 1640 kg/m$^3$ to 2350 kg/m$^3$ and 1620 kg/m$^3$ to 2300 kg/m$^3$
depending on the quantity of solids respectively. It is due to higher specific
gravity of quarry waste than other ingredients in slurry. The marginal
reduction in density of wet slurry is noticed on hardening in both F-G slurry
and FGQWS. It is due to evaporation of water from slurry during hardening
process.

The compressive strength of F-G slurry is varying from 1.7 MPa to
5.61 MPa at the age of 28 days. It is noticed that compressive strength at all
ages improved with increase in volume of solids and reduction in flowability.
The rate of strength development is in the range of 45% to 86% in all
mixtures at the age of 7 days. Also, the rate of strength development increased
to 86% to 92% depending on the flowability of mixture at the age of 28 days
except the mixture with flowability of 425 mm. However, even this mixture
has shown higher compressive strength than the mixture with 500 mm
flowability at the age of 56 days.

The compressive strength of FGQWS mixtures reduced with
increase in flowability similar to that of F-G slurry mixtures. Also, it is found
that almost all FGQWS mixtures containing 10% of filler material have
shown higher compressive strength than F-G slurry mixtures. The
compressive strength varies from 2.74 MPa to 7.6 MPa at the age of 28 days
depending on flow of mixtures. Even the mixtures with 30% filler content
exhibited higher strength than the F-G slurry mixtures except the mixtures
having higher flow of 500 mm at the early age and also mixtures having the
flow of 150 mm.

The rate of strength development is more or less same in all the
mixtures irrespective of filler content. The rate of strength development varies
from 58% to 96% at the age of 7 days depending on the flowability of
mixture (assuming that the strength at 56 days is 100%). Also, it is noticed
that the rate of strength development increased to 80% to 100% at the age of 28 days depending on the flowability of mixture.

It is found that the both F-G slurry and FGQWS mixtures are free from bleed water except F-G slurry having flowability of 375 mm and above, that too during the first one hour period. Also, both the mixtures are free from shrinkage cracks and condition of set is considered to be hard. Further, it is noticed that the settlement in F-G slurry gradually reduced with age and decrease in flowability. However, FGQWS mixtures exhibited significantly less settlement due to the presence of quarry waste.

The characteristics of FGQWS mixtures have been compared with FGRSS mixtures. The increase in filler content reduced the water requirement irrespective of type of filler present in slurry. However, the water requirement for FGQWS mixtures is significantly less than FGRSS mixtures irrespective of filler content with same flowability. The FGRSS mixtures having 10% filler material require 43.4% and 51% more water than that of FGQWS mixtures having 425 mm and 300 mm flow values respectively. Since, the specific gravity of quarry waste is higher than the river sand, the FGQWS has showed higher flow at lower water content than FGRSS.

It is observed that the density of both FGQWS and FGRSS mixtures improved with increase in filler content. However, the density of FGQWS mixture is more than FGRSS mixture having same flowability and filler content. It is due to the higher volume of solids present in FGQWS mixtures and also higher specific gravity of fly ash – gypsum and quarry waste blend.

The compressive strength (at the of 28 days) of FGRSS having 300 mm flowability is less than FGQWS mixtures with same flowability by 9.2%, 4.3% and 21% respectively. Further, it is observed that both mixtures with 10% filler content show relatively higher strength than the mixtures with 30% and 50%.
The FGQWS mixtures are free from bleed water even during the first one hour period. However, the FGRSS mixtures exhibited bleed water during the first one hour period to a depth of 5 mm to 7 mm depending on flowability. The nail penetration result shows that the FGQWS mixtures exhibit faster setting than FGRSS mixtures due to less water demand. Further FGQWS shows significantly less settlement than FGRSS. However, both FGQWS and FGRSS mixtures are free from shrinkage cracks.

The loss in mass due to wetting and drying is significant over first two cycles and thereafter the rate of mass loss is very gradual. However, the mass loss during 5th and 6th cycle is quite insignificant. It is found that the wetting and drying reduced the compressive strength by only 11.2%. It shows that FGQWS exhibit reasonably good resistance against weathering. The loss in mass of cubes exposed to sulphate and chloride medium are 8.12% and 7.51% respectively. Also, the compressive strength of FGQWS cubes is decreased due to exposure in sulphate and chloride medium. However, the reduction in compressive strength is quite insignificant. It indicates that the FGQWS mixtures are resistant to sulphate and chloride attack. Further, the sulphate medium has showed relatively more effect on both of mass and compressive strength.

The micrographs indicate the presence of that dense formation of many complex compounds in the FGQWS. The needle shaped ettringite and mono-sulphate are absent in the slurry. The large quantity of water used could have made gypsum to leach in the initial 30 minutes. Hence, gypsum was not available to the system to initiate the formation of ettringite and tobermorite. Absence of ettringite and tobermorite resulted in poor strength of slurry. In addition, the pH of the system was reduced to less than 12. Hence, the initially formed hydrates of alumina and silicate in the system could not proceed further formation of secondary compounds like C-S-H.
Also, SEM micrographs show that partially hydrated as well as unhydrated fly ash particles are present in the slurry exposed to sulphate solution. The presence of partially hydrated particles is an indication of truncated hydration process in the slurry. Sulphate ingression also is seen in the matrix. EDAX analysis reveals that the silica is the dominant element present in the slurry followed by alumina, calcium, magnesium and iron. It is noticed that the sulphate environment has activated iron and magnesium to enter into the hydrated matrix. Iron and magnesium compounds also might have retarded the strength of the set matrix. However, the loss in strength is only marginal and insignificant as seen in durability. It can be stated that the durability of F-G slurry is not significantly affected in the sulphate environment.

Further the SEM micrographs showed that chloride seems to have initiated more crystalline compounds to form in the matrix. The chloride based crystalline compounds present in the mixture could not contribute to the strength. Instead, it might have contributed marginal reduction in strength.

It is observed that the depth of penetration of slurry found to increase with decrease in density and also increase in percentages of voids in pre-packed aggregate. Further, it is noticed that the slurry with 425 mm and 500 mm flowability exhibited full depth of penetration (100%). The compressive strength of slurry bound macadam is varying between 6.4 MPa to 13.85 MPa, at the age of 28 days, depending on the density of pre-packed aggregates. Also, that the compressive strength found to increase with decrease in the density of pre-packed aggregates. The decrease in the density increases the volume of voids and thereby, accommodates higher quantity of slurry in pre-packed aggregates. The higher quantity of slurry produces more amounts of cementitious compounds and thereby strengthens the interface between binder and aggregate.
The modulus of elasticity of F-G slurry bound macadam varying in the range of $1.00 \times 10^5$ MPa to $1.76 \times 10^5$ MPa depending on density of pre-packed aggregates. It is noticed that the modulus of elasticity of slurry bound macadam increase with decrease in the density of pre-packed aggregate. The behavior of modulus of elasticity is similar to that of compressive strength.

It is noticed that the F-G slurry bound macadam base exhibited modulus of sub-grade reaction of 1210 KPa/mm and 1550 KPa/mm for 100 mm and 200 mm thick layers respectively. The higher sub-grade reaction of FGSBM must be due to low water to binder ratio of FGQWS. Also, the base course layer was free from relative movement of aggregates during test. It is due to better bonding between the aggregate and hardened slurry in FGSBM. It is found that the load carrying capacity of FGSBM having 200 mm thickness is about 56.2% higher than WBM having same thickness at 1.25 mm settlement.

The FGSBM can be used in pavement as base/sub base course in the place of WBM to utilize the industrial waste material in large scale, reduce the cost and also improve the performance of pavement.

5.2 SCOPE FOR FUTURE STUDIES

The engineering properties of CLSM can be achieved satisfactorily using these materials. However, field studies should be conducted in order to investigate the effects of natural factors such as temperature and humidity on the potential use of flowable FGQWS in pavement applications. Also, the interfacial bond between FGSBM as a base course and asphalt / cement concrete as a surface course in pavement need to be studied. Further, performance of F-G slurry base with wearing course such as asphalt / cement concrete may be evaluated in future. Similar investigations may be carried out on dry lean concrete and fly ash lime concrete to compare with that of FGSBM base.