Abstract

The consumption of cement at present in the construction industry has increased manifold as it is widely used in the production of concrete and mortar, which are the most common construction materials. This has therefore put an immense pressure on the cement industry. This has led to environmental problems and ecological imbalances due to the extensive mining of limestone that has to be used in the production of cement. The engineers and scientists are therefore looking for alternative materials, which may ease the pressure on cement industry. The production of polymer concrete (PC) using plastic waste is one such material, which besides being cost effective would also greatly solve the environmental problem arising from the disposal of plastic waste.

The environmental catastrophe that erupted in the last few decades in the urban regions of India and spread into rural areas is primarily caused due to boom in the production of plastic products. No aspect of human life is untouched by plastics, as these are used in cars, computers, telephones, clothing, packaging etc. The packaging industry is the biggest consumer of plastics. Of various plastics that are being used in packaging, polyethylene terephthalate (PET), thermoplastic polyester is widely used in the manufacture of soft drink and mineral water bottles. These bottles are not reused by the manufactures and thus generate plastic waste, which is a serious environmental problem. Thus an effort is being made herein to propose an effective solution of waste disposal by recycling these PET bottles to produce the unsaturated polyester resin, which can be used as a binder in the production of polymer concrete. The use of plastic waste in its production will not only lowers the cost of polymer concrete it will also enable engineers to take advantage of its inherent structural properties. This will greatly encourage the use of polymer concrete which is most neglected in our country because of being expensive.

Most of the studies carried out for the depolymerization of PET have discussed the role of various types of glycols and metal acetates to be used as catalyst in the process. The investigations carried out by some researchers to determine the load
deflection and moment curvature responses, modes of failure, strength properties etc. of polymer concrete by using recycled polymer resin obtained from PET. The effects of PET glycol ratio, use of dibasic acids, and the type of initiator promoter combination on the strength of PC have not yet been investigated. Moreover the literature reveals that not a single study has been undertaken for the microscopic analysis of the hardened resin and hardened polymer mortar composite material.

The moment of resistance determined by various researchers have not considered the tensile strength of polymer concrete and also have not given a rational procedure for the analysis and design of PC sections. The studies on the behaviour of PC under multi-axial state of stress have also not been reported in the literature. The researchers in the past have not studied the post cracking behaviour and the bond of PC made with recycled resin with reinforcing steel.

The purpose of the present investigation was to develop an alternative binding material from waste polyethylene terephthalate (PET) bottles, which can be used in place of ordinary Portland cement in the production of concrete to be used as a construction material. The recycled PET plastic waste was depolymerized through glycolysis to produce unsaturated polyester resin (UPER). The UPER so produced was then used as a binding agent to produce polymer mortar (PM) and polymer concrete (PC). Nine different sets of PC were produced with PET to glycol ratio of 1:1 and 2:1. The initiator promoter combinations taken were Methyl ethyl ketone peroxide (MEKP) and cobalt naphthanate (CoNp) in one group of sets while Benzoil per oxide (BPO) and N, N-diethyl aniline (NNDA) in other group of sets.

For studying the behaviour of the material under load, various properties of polymer mortar and concrete such as compressive strength, split tensile strength, modulus of elasticity, flexural strength, shear strength and bond with reinforcing steel were investigated experimentally. The behaviour of the material under multi-axial state of stresses was also investigated both experimentally and analytically. A rational design procedure has been developed for reinforced and un-reinforced polymer concrete beams.
The polymer resin may be produced by proper glycolysis of PET waste. The optimum conditions for the glycolysis of PET were observed at 190°C temperature, 8 hours of glycolysis time and 0.25% zinc acetate used as catalyst by weight of PET. The dibasic acids (malic and phthalic anhydride) were added in the resin and the mixture was heated for eight hours at 190°C to obtain unsaturated polyester resin (UPER). The hardening of UPER may be achieved by adding initiators (MEKP and BPO) and promoters (NNDA and CoNp).

In order to reduce the viscosity of the UPER and to facilitate the formation of cross linkages, styrene is mixed in the UPER. The resulting mixture may then be added in the inorganic aggregates along with initiator and promoter so as to produce polymer mortar or concrete. The polymer mortar and concrete composite was formed by the cross linking of styrene with the UPER in the presence of free radicals. The free radicals were provided by initiator benzoil per oxide (BPO) with N, N-diethyl aniline (NNDA) acting as promoter in group I and II. In the other groups i.e. (groups III and IV), the free radicals were provided by methyl ethyl ketone per oxide (MEKP) as initiator and cobalt naphthanate (CoNp) as promoter.

The SEM picture of the polymer mortar matrix shows that it has a very low porosity in comparison to the cement mortar of even rich grade. The X-ray diffraction pattern of hardened polymer mortar composite material for different sets indicates the crystalline nature of the material, whereas the nature of hardened polymer resin is amorphous. This change of nature from amorphous to crystalline is due to the presence of aggregate (coarse sand). The weight loss of hardened polymer mortar is less than 0.5% at 200°C indicating thermal stability up to 200°C. After 700°C almost 80% of the resin component of the polymer mortar composite material is decomposed.

Out of the nine sets taken up in the present study, four were short listed based on compression characteristics of polymer mortar, which were taken for investigations polymer concrete. These four sets were made of two types of initiator and promoter combinations with PET to glycol ratios of 1:1 and 2:1. The initiators considered were...
methyl ethyl ketone per oxide (MEKP) and benzoil per oxide (BPO), while promoter were N, N-diethyl aniline (NNDA) and cobalt naphthanate (CoNp). The compressive strength of polymer mortar for the four sets was found to vary from 18 to 28 MPa. The microscopic studies were also conducted on hardened polymer mortar to determine the thermal resistance by thermo-gravimetric analysis, the morphology of the material through SEM photographs and the nature of material by X-ray diffraction.

The detailed investigations carried out on polymer concrete include compression testing of cubes, split tension test, flexure test, bond test and determination of shear strength. Based on the analysis of the experimental results, two types of polymer concrete were found to be the best – one comprising of MEKP and CoNp as initiator promoter combination with PET to glycol ratio of 1:1 and the other produce with BPO as initiator and NNDA as promoter with PET to glycol ratio of 2:1. The compressive strength of the former was 42 MPa while that of the latter was 30 MPa. The flexural strength and shear strength of the two types of PC were more than the corresponding values of cement concrete of equivalent grade.

The ultimate deflection of reinforced PC beams is 4 to 6 times that of the ultimate deflection of un-reinforced PC beams, thus indicating the ductile nature of reinforced PC beams. The failure of reinforced PC beams is through the development of distributed cracks in the middle third portion of the beam. The final failure of the beam is by widening of one of these cracks.

The flexural analysis procedure has been developed for plain and reinforced (singly and doubly) PC sections. An exhaustive methodology for its design of PC sections has been developed. The design is based on the behaviour of material as observed through experiments. The limit state approach of design has been adopted. The ultimate tensile strain of all sets of PC being more than the yield strain of HYSD steel bars of Fe 415 grade steel, the PC will not fracture at the initiation of the yielding of steel, which is contrary to the ordinary cement concrete, whose ultimate tensile strain is much lower than the yield strain of steel. Thus the ordinary cement concrete gets cracked much before the initiation of the yielding of steel due to which the contribution of tensile
strength of concrete is ignored in flexural analysis. It is due to this reason that the
tensile strength of PC has been considered in the proposed flexural analysis. The
tensile strength of PC in the cover portion of tension steel has been ignored for the
simplicity of the analysis. However, flexural analysis by ignoring tensile strength of
PC is also developed. The stress blocks to be used in flexural analysis have been
proposed for compression as well as tension.

The results of flexural analysis of plain and reinforced PC sections have been
validated with the experimental results of plain and reinforced PC beams. The
validation is good and acceptable. The moment curvatures relation of plain and
reinforced PC beams is linear in the beginning followed by a flat curve. The value of
ultimate strain for reinforced PC beams is 10 to 20 times that of yield strain, which
shows that there is sufficient rotation capacity in the section thus permitting the
application of limit state design of reinforced PC cross sections.

The failure criteria for polymer concrete under combined states of stress have been
developed. Two failure surfaces, namely Mohr-Coulomb and Drucker-Prager are
suggested for failure modeling of PC. The model parameters of the two failure
surfaces have been obtained from experimental results. The uni-axial compressive
strength and uni-axial tensile strength of PC predicted from Mohr-Coulomb criteria
developed from tri-axial testing of the material compare well with the uni-axial
compressive and tensile strength determined independently. The inherent advantage
of smoothness and continuity of flow direction makes the Drucker-Prager failure
surface as a better choice than Mohr-coulomb surface for its adoption in practice. On
the basis of the tri-axial test results, PC produced with MEKP as initiator is better than
PC produce with BPO as initiator.

On the basis of the results pertaining to the behaviour of polymer concrete of all the
nine sets considered in the study, some of the sets are good in flexural response and
some other are good in shear and bond behaviour. The best would be one, whose
behaviour is good or at least acceptable for some of the parameters. The PC produced
with MEKP as initiator with PET to glycol ratio of 1:1 and BPO as initiator with PET
to glycol ratio of 2:1 is thus the best among all.
ACKNOWLEDGEMENT

It is to the glory of Almighty Who showered His choicest blessings upon us and made our dreams culminate into reality. I bow down before the Almighty who is most merciful and benevolent to me due to whom I am in a position to submit this thesis for the award of Ph. D. degree of Aligarh Muslim University, Aligarh. A few persons deserve special mention and all praise, without whom this effort would not have seen the light of the day.

I pay all my thanks to the Almighty Allah who enabled me to complete this difficult task and it gives me great pleasure to take this opportunity of acknowledging my deep sense of gratitude and obligation to my esteemed supervisors, Dr. Husain Abbas, Professor, Department of Civil Engineering, Z.H. College of Engineering and Technology Aligarh Muslim University, Aligarh (India) and Dr. Asif Ali Khan, Reader, Department of Applied Chemistry, Z.H. College of Engineering and Technology Aligarh Muslim University, Aligarh (India), for their able guidance and constant encouragement. This task would never have been completed without their active involvement, support, favour and guidance. Their dynamism and foresightedness helped me in a big way in the completion of this work. I really feel privileged to have worked under their supervision.

With deep sense of respect and regard, I acknowledge the very best support from Prof. Mohd. Jamil, the former Chairman, Department of Civil Engineering, Z.H. College of Engineering and Technology Aligarh Muslim University, Aligarh. He has been a constant source of moral support and inspiration for undertaking this study. Thanks are also due to him for making available all the facilities available in the department and allowing me to visit Indian Institute of Technology, Roorkee, for carrying out the experimental work. I am also thankful to Prof. Razaullah Khan, of the Department of Civil Engineering, AMU, Aligarh, for constant encouragement and support.

Useful discussions with Prof. Ramakrishnan of Indian Institute of Science (IISC) Bangalore, which helped greatly in the progress of this work, are also gratefully acknowledged.
I am greatly thankful to the Head and faculty members of the Department of Civil Engineering, Indian Institute of Technology (IIT), Roorkee, for extending all the help and making available the testing facilities of the department. I am thankful to the staff of the Concrete Laboratory, Test Hall and Geo-Tech. Laboratory of the Department of Civil Engineering, IIT. Roorkee for their help during the testing of the specimens. Special thanks go to Mr. J.S. Saini, Institute Instrumentation Centre, IIT, Roorkee for his very kind help during the testing of the specimens.

I also sincerely acknowledge the financial support provided by All India Council for Technical Education (AICTE) vide grant No. 8021/RID/PROJ/TAP-36/2002-03

I sincerely thank Mr. Mohd. Shariq, who was then the research scholar at IIT Roorkee, for providing all the possible help at IIT, Roorkee.

I sincerely acknowledge the cooperation and advice of all my colleagues and friends, especially Prof. M.M. Ashhar, Mr. S.A. Khan, Mr. F. Ghani, Dr. Amjad Masood, Dr. Sabih Akhtar, Mr. M.A Ansari, Mr. M.S. Ahmad and Mr. Anis Khan.

I sincerely acknowledge the help provided by Mr. Khadim Abbas, Mr. Muzaffar Ali Khan and Mr. Rafiq Ahmad during the progress of the work. I am also indebted to Mr. Majid Khan who helped in the preparation of the specimens in the Polymer Concrete Laboratory, Department of Civil Engineering, Aligarh Muslim University, Aligarh.

Special regards to my parents, elders and other members in the family whose blessings and wishes helped me to reach this end.

Finally, I owe present work much to my wife and son Hammad who despite their personal sufferings continued to extend their moral support and cooperation and helped me reach the target for which I shall ever remain indebted.

 Fareed Mahdi