A STUDY ON STRENGTH CHARACTERISATION OF SOILS MIXED WITH FLY ASH, SCRAP TYRE MATERIALS AND CEMENT

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DOCTOR OF PHILOSOPHY

By

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Dedicated to my parents

STATEMENT

I do hereby declare that the matter embodied in this thesis is the result of investigations carried out by me in the Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati, Assam, India.

In keeping with the general practice of reporting scientific observations, due acknowledgements have been made wherever the work described is based on findings of other investigators.

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CERTIFICATE

This is to certify that the thesis entitled **"A Study on Strength Characterisation of Soils Mixed with Fly Ash, Scrap Tyre Materials and Cement"** submitted by Pranjal Barman (Roll No. 09610403), to the Indian Institute of Technology Guwahati, for the award of degree of Doctor of Philosophy in Civil Engineering, is a record of bonafide research work carried out by him under my supervision and guidance. The thesis work, in my opinion, has reached the requisite standard fulfilling the requirement for the degree of Doctor of Philosophy. The results contained in this thesis have not been submitted in part or full to any other University or Institute for award of any degree or diploma.

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ABSTRACT

The globalisation of economy has triggered an increased demand for electricity and automobiles in many countries around the world. This has resulted in the generation of large quantities of fly ash and scrap tyres, and there are problem associated with the safe disposal of these materials. Fly ash and tyre fibres, with typical inherent properties, can be utilised for modification of various engineering properties of soil. There is enough scope for the bulk utilization of fly ash and scrap tyre materials in soil mixes for geotechnical applications such as in the construction of roads, embankments and backfilling behind retaining structures. The present research work focuses mainly on the strength behaviour of soil modified with fly ash, tyre fibre and cement, with respect to their geotechnical performance.

In this study, the individual or combined effect of fly ash and tyre fibre on geotechnical characteristics of two soils, a fine-grained residual lateritic soil (red soil) and granular riverbank sand (Brahmaputra sand), with or without ordinary Portland cement was investigated through a systematic series of compaction tests, unconfined compression tests and consolidated drained triaxial tests. Shear strength is a fundamental property of any soil that governs the stability of earth structures. Therefore, in this research work variation of shear strength of different mixes has been given main importance. The fly ash content used in this study varies from 20% to 50% content by weight. Tyre buffings and tyre crumb which were used as scrap tyre materials were added to the soil mix varying from 5% to 10% content by weight. The amount of cement added ranges from 1% to 2% by weight of the various soil mixes. This provided a wide range of gradation and texture of the mixes. Compacted specimens of the mixes were prepared based on the maximum dry unit weight obtained from the compaction tests and cured up to 28 days. The strength tests were conducted on the as-compacted specimens without saturating them to understand the strength characteristics.

The geotechnical characteristics were examined by analysing the results obtained from various tests to investigate the application of fly ash, tyre fibre and cement. Moisture-density relationships were established and examined for effect of additive ratios. Stress-strain-strength characteristics were analysed through unconfined compressive test and triaxial compression tests. A range of curing periods was adopted for these tests to understand the short-term and long-term changes on strength behaviour of the modified material.

Results from compaction tests show that inclusion of fly ash and tyre buffings to both the soil types reduces the dry unit weight. Improvement in unconfined compressive strength has been observed with the addition of fly ash to the sand and also with curing period which does not occur in case of the red soil mixes. Addition of tyre buffings to red soil-fly ash mixes reduces the strength, but increases the strength of sand-fly ash mixes especially in higher confining pressure. However, addition of cement to soil-fly ash-tyre fibre mixes can lead to considerable improvement of shear strength of the soil. Improvement in strength of different soil mixes is seen with the increase in curing period. Stiffness of soil-fly ash mixes is also affected by the addition of tyre fibers and cement to mixes. Moreover, soil-fly ash-tyre buffing mixes containing 35% or 50% fly ash and 5% tyre buffing content along with cement have been found to have some potential for use in the construction of roads.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

LL	Liquid Limit
PI	Plasticity Index
PL	Plastic Limit
MDU	Maximum Dry Unit weight
MDU_{RS}	Maximum Dry Unit weight of different RS specimens
MDU_{BS}	Maximum Dry Unit weight of different BS specimens
OMC	Optimum Moisture Content
UC	Unconfined Compression
UCS	Unconfined Compressive Strength
UCS*	Gain in UCS
UCS_{soil}	Average UCS of the untreated soil
UCS_{mix}	UCS of the mixture
CBR	California Bearing Ratio
EAC	Energy Absorption Capacity
DR	Ductility Ratio
DR_{RS}	Ductility Ratio of red soil mixes
DR_{BS}	Ductility Ratio of sand mixes
SR	Strength Ratio
SR_{RS}	Strength Ratio of red soil mixes
SR_{BS}	Strength Ratio of sand mixes

NOTATIONS

c	Cohesion intercept
G_s	Specific gravity
p	Stress path parameter $(\sigma_1+\sigma_3)/2$
q	Stress path parameter $(\sigma_1-\sigma_3)/2$
σ_1	Major principal stress
σ_3	Minor principal stress
$(\sigma_d)_f$	peak deviator stress from triaxial compression test
$(\sigma_d)_{res}$	residual deviator stress triaxial compression test
ϕ	Angle of shearing resistance
I_B	Brittleness Index
E_s	Secant elastic modulus
M_r	Resilient modulus
q_{100}	100% of the peak stress i.e. the compressive strength from UC test
ϵ_{100}	Axial strain corresponding to q_{100}
ϵ_{soil}	Average axial strain at failure of the untreated soil from UC test
ϵ_{mix}	Average axial strain at failure of soil-fly ash-tyre buffing mixes from UC test
q_{50}	50% of the peak deviator stress from triaxial compression test
ϵ_{50}	Axial strain corresponding to q_{50}

CHAPTER - 1
INTRODUCTION

1.1 INTRODUCTION

The rapid growth in industrialisation and urbanisation leads to an increasing demand for energy and increasing number of vehicles. This results in generation of large quantity of fly ash and scrap tyres all over the world. Fly ash, which is an industrial by-product, requires alternative solution for disposal in many parts of the world. Scrap tyres can also be considered as a waste material if they are not effectively reused or recycled for other application. These two waste materials will cause a great deal of problems to the environment and human health if they are not properly disposed. The development of sustainable methods for their disposal has become a major challenge for the waste management personnel. Moreover conventional building materials like clay, sand, gravel, aggregates are fast depleting with the increase in construction activities in the country and a ban on new quarries due to environmental concerns (Rao and Dutta, 2006). It necessitates the use of substitute materials for the natural construction materials which are non-renewable.

In the field of geotechnical engineering, soils are often found in such a condition that may create problem to the structures. In that case they have to be either discarded in total or have to be treated for the modification of their unfavourable characteristics (e.g. low strength, excessive swelling, brittleness etc.) so as to suit the field requirements. Soil can be amended with other selected materials in different proportions with or without a binder so as to obtain an improved soil mix by using mechanical or chemical means. The added material can be coal ash. During investigations it was found that by mixing fly ash with fine grained soil, the geotechnical properties of the soil could be modified (Cokca, 2001; Parsons and Kneebone, 2005; Edil et al., 2006; Sezer et al., 2006; Phanikumar and

Sharma, 2007). Of course some cementing agent (e.g. cement, lime) can be added to the mixture as a binder.

Another technique is in which various kinds of reinforcing materials have been used to improve the engineering performance of the soil. There have been many experimental researches on the reinforcement of soils with scrap tyre derived rubber fibres (Edil and Bosscher, 1994; Akbulat et al.; 2007, Ozkul and Baykal, 2006 & 2007; and Guleria et al., 2011). These previous investigations indicate that these fibres can effectively be used in the modification of soil properties e.g. compaction, compressibility, strength, deformability, and hydraulic conductivity with or without cementing agent.

Residual lateritic soils are those that form from rock and remain at the place where they were formed. This kind of soil is mainly found in the humid tropical regions where high temperature and abundant rainfall are responsible for their formation. Residual lateritic soil exhibits their strength through cohesion and frictional resistance among soil particles. On the other hand, coarse to fine fractions of sand together constitute the major portion of the total sand. Therefore the strength of sand is mainly derived from frictional resistance of sand.

This thesis examines the strength characteristics of a fine grained residual lateritic soil and granular riverbank sand modified with fly ash, scrap tyre materials and cement through several series of compaction tests and unconfined compression tests followed by triaxial compression tests**.**

1.2 FLY ASH

Fly ash is an industrial by-product generated as a result of burning of coal in thermal power plants. The fly ash is composed of hollow and spherical particles commonly known as cenospheres. The particles have large surface areas with no plasticity and they generally fall into silt size category. Based on the chemical composition, fly ash is classified into two categories: Class F and Class C (ASTM C 618). Class F fly ash is normally produced from burning anthracite or bituminous coal and contains a small amount of lime (CaO). Class F fly ash has siliceous and aluminous oxides, which give its pozzolanic property. These oxides react with added lime in the presence of moisture at ordinary temperature to form cementitious compounds. Class C fly ash is produced from burning of lignite and sub-bituminous coal, and usually contains a significant amount of calcium oxide (CaO). Class C fly ash has both pozzolanic and cementitious properties. In previous investigations, researchers have found that coal ashes have many advantageous properties. Pandian (2004) carried out study to characterize fly ash with reference to geotechnical applications and it was reported that fly ash has low specific gravity, lower compressibility, high California Bearing Ratio, water insensitiveness to compaction, pozzolanic reactivity and good frictional properties. It was also reported that the coefficients of permeability and consolidation of the compacted fly ash were comparable to those of nonplastic silts. As such fly ash has also higher rate of consolidation (Kaniraj and Gayathri, 2004 and Pandian, 2004). Due to these properties coal ash can be utilized in bulk only in geotechnical engineering applications.

1.3 SCRAP TYRE DERIVED MATERIAL

Scrap tyre derived materials are obtained by two ways: with and without shredding or cutting into small pieces of similar smaller size. The main components of tyres are vulcanized rubber, rubberized fabric containing reinforcing textile cords, steel or fabric belts, and steel wire-reinforced rubber beads.

The manufacturing process for tyres combines raw materials into a special form that yields unique properties such as flexibility, strength, resiliency and high-frictional resistance (Edil and Bosscher, 1994). The frictional resistance is the main component of strength of these scrap tyre derived material. Wu et al. (1997) and Yang et al. (2002), in their study found high value of internal friction angle of tyre derived material. Due to these unique properties of tyres, scrap tyre derived fibres can extensively be used in the field of geotechnical engineering such as light weight fill materials in highway construction, as drainage material in highway and landfill construction, and for other similar applications.

1.4 PROBLEM ASSOCIATED WITH DISPOSAL

The main problem associated with disposal of these two materials is requirement of huge disposal area. This poses a serious problem in terms of both land use and potential environmental pollution. Generation of large quantity of fly ash also causes threat to public health and ecology. The dumps of scrap tyres can be serious fire hazards, a breeding ground for rodents and mosquitoes, and an unpleasant sight. Because rubber tyres do not easily decompose, economically feasible and environmentally sound alternatives for scrap tyre disposal must be found. One effective way for proper utilization of these two materials is to find out the ways to use them in many civil engineering applications.

1.5 CIVIL ENGINEERING APPLICATIONS

Coal ash can be used in many geotechnical applications such as construction of embankments, as a backfill material, as a sub-base material, as filter material etc (Pandian, 2004). Fly ash has been used in earth work application to improve the mechanical properties of soils (Kaniraj and Gayathri, 2004). Due to its pozzolanic character, fly ash is found to be effective in stabilization of many soils and it contributes to soil stabilization in the following manner:

1. Filling the voids left by the soil particles and thus giving a more compact structure to the soil
2. Acting as fine aggregate, when used with other cementing material such as cement, lime etc.
3. By participating in chemical reaction with soil particles and soil moisture thus acting as cementing material.

Scrap tyre derived fibres can be used by using two techniques-mixing with soil and without mixing with soil. While using tyre chips only their inherent engineering properties are responsible for geotechnical applications. Again by mixing tyre chips with soil the various geotechnical properties of soil e.g. compaction, ductility, compressibility, permeability, shear strength can be modified for utilization in the field (Tiwari et al., 2012, Sheikh et al., 2013 and Tiwari et al., 2014). There are a number of ways in which tyres can be used for lightweight fill material in highway construction, as drainage material in highway and landfill construction, and for daily cover materials and construction of sorption barriers for liquid and vapour organic chemicals in waste landfills (Edil and Bosscher, 1994). It has also been found that the tyre chips reinforced composite backfill results in good performance of the soil-structure system during earthquake loading (Hazarika et al., 2010).

1.6 OBJECTIVE AND SCOPE OF THE PRESENT STUDY

In India fly ash and scrap tyre disposal problem has become a matter of great concern. The use of fly ash in combination with abundantly available local soils would facilitate its mass utilization. Keeping view of the above, the present research work is aimed at developing an understanding of the behaviour of a locally available residual lateritic soil and sand mixed with fly ash and scrap tyre materials in different proportions or in combination with cement by means of laboratory tests. The scope of the present work can be summarized as follows:

1. To investigate the compaction characteristics of various mixes consisting of the soils and their mixes with varying contents of fly ash and rubber materials.
2. To study the unconfined strength characteristics of the soil mixes by means of unconfined compression tests, particularly to identify:
    a) the individual and combined effects of the addition of different proportions of fly ash and tyre materials and
    b) the effect of curing.
3. To investigate the shear strength behaviour of the mixes through triaxial compression tests to understand:
    a) the effects of fly ash, tyre materials and cement contents, and
    b) the influence of curing.
4. To compare the strength characteristics of the two modified soils, due to the application of fly ash, tyre materials and cement.

1.7 ORGANISATION OF THE THESIS

The thesis is divided in seven chapters. Chapter 1 presents introduction of the work, motivation for the work, need for bulk utilization of fly ash and scrap tyre materials, and the objectives of the present study. A comprehensive literature review relevant to the present study is undertaken and reported in Chapter 2, summarizing the works carried out by various researchers based on the materials used and experimental methods adopted. Chapter 3 describes the physical properties of the experimental materials, types of laboratory tests, and specimen preparation procedure. Chapter 4 presents and discusses the details of results obtained from compaction tests. Chapters 5 and 6 deal with the testing programme, experimental details and results of unconfined compression tests and triaxial compression tests, respectively. Finally the summary and major conclusions of the study are presented in Chapter 7.

CHAPTER - 2
OVERVIEW OF THE LITERATURE

2.1 INTRODUCTION

A brief review of the literature is presented in this chapter. The available literature is itemised in seven groups, namely, studies on fly ash, studies on soil-fly ash mixes, studies on fly ash-cement mixes, studies on soil-cement mixes, studies on soil-fly ash-cement mixes, studies on scrap tyre derived materials, studies on soil-scrap tyre derived materials and studies on soil-cement-scrap tyre derived materials.

2.2 STUDIES ON FLY ASH

Various studies were carried out to investigate the different engineering properties of fly ashes and their application in the field of geotechnical engineering. Table 1 provides a brief description of various experimental works done during last few years and findings were mentioned in a concise form. It was reported that fly ash has many advantageous properties due to which it can be used in the construction of many geotechnical structures.

2.3 STUDIES ON SOIL-FLY ASH MIXES

Many researchers investigated the potentiality of using fly ash with soils and their application in the field of geotechnical engineering. Table 2 depicts various experimental works done on different soil-fly ash mixes during last few years. It was reported that fly ash can effectively be used with soils and these soil-fly ash mixes can be utilized in many geotechnical engineering works.

Table 1 Review on fly ash

Author	Objectives of the study	Concluding remarks
Prashanth et al. (1999)	Studied the compaction behaviour of fly ashes along with the mechanisms controlling their behaviour obtained on a volume basis, which eliminates the effect of variation in specific gravity.	• In order to obtain good strength, fly ashes can be compacted in the fully dry state or at the optimum water volume content. • To prevent dusting and to enhance the strength of self-pozzolanic fly ashes with time, it is desirable to compact fly ashes at the optimum water volume content.
Kaniraj and Gayathri (2004)	The influence of the head loss across the specimen, the effective stress and the void ratio on the permeability was studied.	• It was found that the coefficient of permeability and consolidation of the compacted fly ash were comparable to those of non-plastic silts. • Even at a high effective stress there was no appreciable reduction in the coefficient of permeability.
Pandian (2004)	Studied the characterization of fly ash with reference to geotechnical applications.	• Fly ash has low specific gravity, freely draining nature, ease of compaction, insensitiveness to changes in

		moisture content, good frictional properties. • Fly ash can be used in the construction of embankments, roads, reclamation of low-lying areas, fill behind retaining structures.
Ugurlu (2004)	Investigated the leaching behaviour of fly ashes disposed in ash pond and also the potential influence from the ash disposal on ground water quality.	• The conductivity (EC) values decreased with the number of extractions at all temperatures applied and the highest EC values were observed in the first extraction. • Ca, Na, K, Mn, Fe, S and Pb showed maximum leachability, whereas Cd, Mg, Cu, Cr, Zn and Co showed minimum leachability.
Kim et al. (2005)	Evaluated the suitability of Class F fly/bottom ash mixtures with high fly ash contents as construction materials for highway embankments.	• Fly/bottom ash mixtures (with mixture ratios ranging from 50% to 100% fly ash contents) were found to exhibit relatively well-defined moisture density relationships. • The hydraulic conductivity of compacted ash

		mixtures were found to decrease slightly with increasing fly ash content. • Increasing bottom ash content also tended to decrease dilatancy, primarily due to crushing of bottom ash particles during shearing.

Table 2 Review on soil-fly ash mixes

Author	Objectives of the study	Concluding remarks
Cokca (2001)	Studied the effect of class C fly ash for stabilization of an expansive soil.	• Plasticity index, activity, and swelling potential of the samples decreased with increasing percent stabilizer and curing time. • Swelling potential values of each sample were highest for those without curing and lowest for 28 day curing.
Prabhakar et al. (2004)	Investigated the behavioural aspect of soils mixed with fly ash to improve the load bearing capacity of the soil.	• Addition of fly ash reduces the dry density of the soil. • CBR value of soil can be improved by the addition of fly ash as compared to the pure soil which would be beneficial especially for pavement etc.

		• Soil admixed with fly ash gives a better strength.
Parsons et al. (2005)	Conducted a series of tests in the laboratory and on existing subgrades to evaluate the performance of fly ash stabilised subgrades.	• Incorporation of Class C fly ash into subgrade soils significantly improved the strength and stiffness of the pavement section very quickly. • Incorporation of Class C fly ash reduced soil plasticity and reduced the potential for swelling.
Edil et al. (2006)	Conducted a laboratory study to evaluate the improvement in mechanical properties relevant to highway design and construction that can be obtained when soft fine-grained subgrade soils are stabilized with fly ash.	• CBR of soil–fly ash mixtures generally increased with fly ash content and decreased with increasing compaction water content. • Addition of 18% fly ash to a soft and wet subgrade soil resulted in comparable or higher resilient modulus than the same subgrade soil dried and compacted at optimum water content. • Fly ash stabilized subgrades should stiffen over

		time, resulting in increased pavement support.
Sezer et al. (2006)	Presented an investigation into the stabilization of a soft clay subgrade with a very high lime fly ash.	• Fly ash addition increased the unconfined compressive strength of the soil. • Beyond 28 days, there was no appreciable increase in unconfined compressive strength. • Internal friction angle increased considerably with increasing fly ash inclusion level. There was a considerable increase in cohesion intercept at later ages in samples containing high percentage of fly ash.
Lin et al. (2007)	Performed various tests such as pH value, compaction, California bearing ratio, unconfined compressive strength (UCS), and triaxial compression to understand soil strength improvement because of the addition of both	• The strength of soil were improved on addition of both the sewage sludge ash and fly ashes. • However, compressive strength of sludge ash-soil was found lower than fly ash-soil mixes.

	sewage sludge ash and fly ashes.	
Phanikumar et al. (2007)	Presented the effect of fly ash on the volume change of two different types of high plastic clay.	• Swell potential and swelling pressure also decreased significantly with increasing fly ash content. • Maximum dry unit weight increased and optimum moisture content decreased with increasing fly ash content. • Addition of fly ash improves compressibility and Secondary consolidation characteristics of both expansive and non-expansive clays.
Chauhan et al. (2008)	Studied the influence of fly ash on compaction behaviour and compressive strength characteristics of silty sand.	• On addition of fly ash, maximum dry density value decreases but optimum moisture content of soil increases.. • The fly ash added soil improves the unconfined compressive strength of the mixes up to 30% fly

		ash content and then the strength decreases.
Mir and Sridharan (2013)	Performed laboratory tests which involved determination of physical properties, compaction characteristics and swell potential of a highly expansive soil mixed with Class C and Class F fly ashes.	• With the addition of fly ash to the soil the maximum dry unit weight of the soil-fly ash mixtures decreases with increase in optimum moisture content. • It is also observed that addition of fly ash to soil minimized the swell potential.
Yilmaz (2015)	To investigate the effects of Class C fly ash on the compaction and strength behaviour of clayey soil.	• As the fly ash content in the mixture increases, maximum dry unit weight of the fly ash–clay mixtures increases but optimum water content of the fly ash-clay mixtures tends to decrease. • As a general tendency, increasing fly ash content and curing period causes an increase in UCS of the fly ash–clay mixtures. • The increase of fly ash content and curing time

		changes failure pattern of the mixes from ductile to brittle.

2.4 STUDIES ON FLY ASH-CEMENT MIXES

Cement was used as an adhesive material to enhance the strength of class F type of fly ash which has no or very little cementing property. It was reported that fly ash-cement mixes can be used in the pavement construction. Table 3 provides a brief description of experimental works done on different fly ash-cement mixes.

2.5 STUDIES ON SOIL-CEMENT MIXES

Table 4 depicts some experimental works done on different soil-cement mixes. Unconfined compression tests, triaxial compression tests were carried out to investigate the strength of cemented soil. It was reported that soil-cement mixes can be used in the construction of roads.

2.6 STUDIES ON SOIL-FLY ASH-CEMENT MIXES

Table 5 provides a brief description of experimental works done on different soil-fly ash-cement mixes. Unconfined compression tests, triaxial compression tests were carried out to investigate the strength of cemented soil-fly ash mixes. Previously many studies were conducted to know the scope of utilization of soil-cement mixes. After that, fly ash was introduced in the soil-cement mixes to minimize the cement content without compromising the gain in strength of mixes.

Table 3 Review on fly ash-cement mixes

Author	Objectives of the study	Concluding remarks
Kaniraj and Gayathri (2003)	Conducted a laboratory study to investigate the effect of cement content, curing period, controlled and uncontrolled ambient conditions of curing, unit weight, and water content on the development of the strength of cement stabilized Class F fly ashes with reference to their use as pavement base courses.	• By appropriate selection of dry unit weight and degree of saturation of the mixes, it might be possible to achieve the required strength by providing adequate water for hydration of cement. • For any cement content, the rate of change in strength decreased as the curing period increased. • The increase in strength upon curing was more during summer than the monsoon season because of the higher temperature during these seasons.

Mishra and Ravindra (2015)	To evaluate the suitability of various mixtures of fly ash and cement for the landfill liner application by conducting various tests.	• Hydraulic conductivity of 90 % fly ash+10 % cement mixture was satisfied the hydraulic conductivity criteria for a landfill liner material. • 90% fly ash + 10% cement mixture compacted at 5 % wet of OMC-MDD can be used as a landfill liner material.

Table 4 Review on soil-cement mixes

Authors	Objectives of the study	Concluding remarks
Baghdadi and Shihata (1999)	Presented an experience with soil-cement in a research project to investigate alternative pavement systems.	• The weight loss of mixes decreases with increasing cement content and compressive strength increases with increasing cement content.
Schnaid et al. (2001)	Studied the stress-strain-strength behaviour of an artificially cemented sandy soil produced through the addition of Portland cement.	• The unconfined compressive strength seems to be a direct measure of the degree of cementation in triaxial compression. • The shear strength of the cemented soil measured in conventional triaxial tests can be determined as a function of the unconfined compressive strength and the uncemented friction angle.
Consoli et al. (2007)	Investigated the influence of the amount of cement,	• The unconfined compression strength

	the porosity and the moisture content on the strength of a sandy soil artificially cemented.	increases approximately linearly with an increase in the cement content and exponentially with the reduction in porosity of the compacted mixture. • An increase in strength is observed with the moisture content increase, until a maximum value, after which the strength reduces again. • The voids/cement ratio has been shown to be a more appropriate parameter to evaluate the unconfined compression strength of the soil-cement mixture studied.

Table 5 Review on soil-fly ash-cement mixes

Authors	Objectives of the study	Concluding remarks
Kaniraj and Havanagi (1999)	Conducted a laboratory study to determine the unconfined compressive strength of locally available soils mixed with fly ash and ordinary Portland cement in different proportions.	• The gain in unconfined compressive strength and secant modulus of the mixtures decreased as fly ash content increased, but increased as cement content increased. • The influence of cement content was more pronounced than that of the curing time.
Pandian and Krishna (2002)	Studied the effect of the addition of ordinary Portland cement on the CBR of black cotton soil-fly ash mixes.	• The variation of CBR with the addition of fly ash showed two optimum levels, one at 20% fly ash and the other at 70% fly ash addition. • The variation of unconsolidated undrained shear strength parameters resulted in the friction angle (ϕ_{uu}) following the trend of two

		optimum levels similar to CBR variation.
Lo and Wardani (2002)	Conducted an experimental work to study the strength and dilatancy of a silt stabilized with the addition of a cement and fly ash mixture in a slurry form.	• The cementing agent contributed to both stiffness and strength via two mechanisms, namely bonding between grains and additional dilation. • The UC strength for a slow loading rate was consistently higher than that for a fast loading rate.
Kolias et al. (2005)	Conducted a laboratory study to evaluate the effectiveness of using high calcium fly ash and cement in stabilising fine-grained clayey soils.	• The mechanical and strength properties of the mixes were found to be considerably enhanced.

2.7 STUDIES ON SCRAP TYRE DERIVED MATERIALS

Table 6 provides some experimental works done on scrap tyre derived materials. Various tests were carried out to investigate the geotechnical properties of scrap tyre derived materials. It was reported that scrap tyre derived materials have some inherent engineering properties which can be useful in the field of civil engineering.

2.8 STUDIES ON SOIL-SCRAP TYRE DERIVED MATERIAL MIXES

Use of reinforcing materials is one of the effective ground improvement or soil properties modification techniques. Various tests were carried out to investigate the geotechnical properties of soil mixed with scrap tyre derived materials. Table 7 provides a brief description of experimental works done on soil-scrap tyre derived materials.

2.9 STUDIES ON SOIL-CEMENT-SCRAP TYRE DERIVED MATERIAL MIXES

Many researchers investigated the potential use of scrap tyres in modification of different geotechnical properties of cemented soils. Tests were carried out to investigate the strength, drainage, compressibility and ductility characteristics of different tyre added soil-cement mixes. Table 8 depicts various experimental works done on soil-cement-scrap tyre derived materials.

2.10 STUDIES ON SOIL-FLY ASH-CEMENT-SCRAP TYRE DERIVED MATERIAL MIXES

Table 9 provides a brief description of experimental works done on soil-fly ash-cement-scrap tyre derived materials. Various tests were carried out to investigate the geotechnical properties of different soil mixes.

Table 6 Review on scrap tyre derived materials

Author	Objectives of the study	Concluding remarks
Eldin et al. (1992)	Presented the results of an investigation into the potential of shredded tyres as fill material in road construction.	• Use of shredded tyres in road construction poses no major handling or placement problems. • The road showed acceptable performance under freeze-thaw conditions and under service loads with moderate maintenance requirements and minimum undesirable effects on ground water quality under the tested conditions.
Cecich et al. (1996)	Showed the feasibility of using shredded tyres as a lightweight backfill material for retaining walls.	• Using shredded tyres as an alternative backfill material is quite economically advantageous. • The sliding and overturning factors of safety for the retaining walls with shredded

		tyre as backfill were significantly greater than that for the retaining walls with sand as the backfill material.
Wu et al. (1997)	Conducted triaxial compression tests to determine the shear strength of five processed scrap tyre products having different gradation and particle shapes.	• The inter particle frictional component of shear strength was fully mobilized and nearly reached a constant value after approximately 5% axial strain.
Yang et al. (2002)	Evaluated the mechanical characteristics of tyre chips by conducting confined compression, direct shear, and triaxial tests.	• The stress-displacement curves from direct shear tests were nonlinear with no well-defined peak stress for most tests. • Both confined compression and isotropic compression tests showed that the tested tyre chips exhibited strain hardening but the strains in isotropic compression were larger than those from confined compression.

		• For triaxial tests, the stress-strain response was linear up to 15% strain but exhibited strain softening beyond 15% strain. • The initial stress strain modulus increased with increasing confining pressure according to a quadratic function.
Young et al. (2003)	Determined the physical properties of tyre shreds for use in engineering construction as a replacement for aggregates in embankments or as backfill.	• Specific gravity and water adsorption exhibited no change with increase in shred size. • The hydraulic conductivity showed an increase as tyre shreds size increased. • Direct shear results showed an increase in shear strength as the particle size and density of tyre shreds increases.

Table 7 Review on soil-scrap tyre derived materials

Author	Objectives of the study	Concluding remarks
Edil et al. (1994)	Assessed the pertinent engineering properties of shredded scrap tyres for use as a light-weight fill material in highway construction, as drainage material in highway and landfill construction, and for other similar applications.	• Clay mixtures exhibited lower deformation modulus than sand mixtures at the same mixing ratios. • Tyre chips showed improvement in frictional resistance when mixed with sand. • Hydraulic conductivity and compressibility could be reduced by mixing sand with tyre chips.

Foose et al. (1996)	Investigated the feasibility of using shredded waste tyres to reinforce sand.	• Three significant factors affecting shear strength were identified: normal stress, shred content and sand matrix unit weight. • Shred content and sand matrix unit weight were the most significant characteristics of the mixes influencing shear strength.
Lee et al. (1999)	Conducted triaxial tests to investigate the stress-strain relationship and strength of tyre chips and a mixture of sand and tyre chips.	• Mixtures of sand and tyre chips presented a response intermediate between those of pure sand and pure tyre chips. • The results from numerical modelling suggested that the performance of rubber-sand, being both lightweight and reasonably strong, compared well with that of sandy gravel, as a backfill material.

Youwai et al. (2003)	Presented the results of triaxial tests on compacted shredded rubber tyre – sand mixtures.	• A proposed constitutive model broadly captured the strength and deformation characteristics of a shredded rubber tyre – sand mixture at different mixing ratios. • The strength of the shredded rubber tyre – sand mixture increased linearly with increasing confining pressure and amounts of sand in the mix. • With an increasing proportion of sand in the mix, deformation due to isotropic compression decreased. • This type of mixture can be used as lightweight backfill for embankment on soft gorund foundation.
Zornberg et al. (2004)	Evaluate the optimum dosage and aspect ratio of	• As the tyre shred content in the tyre

	tyre shreds within granular fills. The effects on shear strength of varying confining pressure and sand matrix relative density were also evaluated.	shred-sand mixes increased the axial strain at failure also increased. • For a given tyre shred content, increasing the tyre shred aspect ratio led to increasing overall shear strength. • The gain in shear strength induced by tyre shred inclusions was found to be sensitive to the applied confining pressure, with larger shear strength gains obtained under comparatively low confinement.
Bergado et al. (2005)	Conducted triaxial tests to investigate the strength and deformation characteristics of flat rubber tyre chips with and without sand mixes.	• Flat tyre chips yielded more compressibility than cubical chips. Adding flat tyre chips tended to transform the mixed material to be ductile. • With higher sand content, the flat tyre

		chips acted as reinforcement and increased the shear strength of tyre chip–sand mixtures.
Ghazavi and Sakhi (2005)	Reported the usefulness of optimizing the size of waste tire shreds on shear strength parameters of sand reinforced with shredded waste tires.	• The friction angle of mixtures increased with shred contents and mixture compaction. • For a given width, there is only a certain length that gives the greatest value of friction angle irrespective of compaction level and shred contents in the mixtures.
Ozkul et al. (2006)	Studied the compaction and shear strength behaviour of clay with tyre buffing inclusions.	• Drained shear strength of the clay was essentially unchanged by the introduction of rubber buffings or by an increase in the level of compaction energy employed. • Its undrained strength was also not

		changed when standard compaction energy was used, but decreased slightly.
Cetin et al. (2006)	Investigated the geotechnical properties of pure fine and coarse grained tyre-chips and their mixtures with a cohesive clayey soil.	• The shear strengths increased up to 30%for fine and 20% for coarse tyre chip mixtures. • As the percent tyre-chips increased, the fine and coarse tyre-chips mixtures under lower normal pressures did not show considerable vertical strains or volume change during shear. • The permeability increased as the normal pressure decreases and the % tyre-chips increased.

Rao and Dutta (2006)	Triaxial compression tests to investigate the possibility of using tyre chips with sand.	• The strength of the sand-tyre chip mixtures showed a marginal improvement as compared to sand alone. • As the compressibility was found to be excessive for a chip content of more than 20%, therefore the use of tyre chips and sand mixture is advantageous in construction of highway embankments up to a maximum height of 10 m.
Ozkul et al. (2007)	Evaluated the drained and undrained shear strength of mixtures of clay and tyre buffings.	• The contribution of rubber fibres to the strength of clay decreased with increasing levels of confinement. • The hydraulic conductivity of clay did not change significantly due to the inclusion of rubber fibres.

		• Shearing to large strains increased the hydraulic conductivity of clay and composite soil if paths of lower flow resistance, such as slip planes or zones of strain localization, developed.
Akbulat et al. (2007)	Investigated the influence of randomly oriented inclusion of scrap tyre rubber fibres and synthetic fibres on the geotechnical behaviour of clayey soils.	• The UCS values increased with increasing tyre rubber fibre contents up to 2% and then decreased. The optimum tyre rubber fibre length was 10 mm and optimum tyre rubber fibre content was 2%. • The maximum cohesion values were observed for 10 mm long fibres. The internal friction angle value of each reinforced sample increased in a non-linear way.

		• Issues related to dynamic properties of earth structures can be solved using scrap tyres with soils.
Tabbaa et al. (2010)	Investigated the potential of using waste shredded tyre in 2% to 20% by weight in soil-tyre mixtures for specific engineering applications.	• Inclusion of tyres decreased the compacted dry density, strength and permeability. • The use of lime in the soil-tyre mixes minimized the leaching of iron and zinc metals.
Edincliler et al. (2012)	Performed triaxial tests to analyse the effects of tyre content, tyre shape, and tyre aspect ratio on the shear strength of sand.	• The shear strength decreased with increase in tyre content in the sand-tyre mixes. However inclusion of fibre shaped tyre buffings gave higher strength parameters compared to addition of granular

		shaped tyre crumbs.
Sheikh et al. (2013)	Investigated the shear and compressibility behaviour of sand-tyre crumb mixtures.	• The shear strength was found to decrease with the increase in the amount of tyre crumbs in the mixtures. • Due to the ductile behaviour of tyre crumb, significant increase in the axial strain was observed corresponding to peak deviator stress which is helpful in geotechnical seismic isolation of infrastructure.
Cabalar et al., (2014)	Investigated the influences of both tyre buffings and lime in clay by conducting CBR and unconfined compression tests.	• Addition of tyre buffings only reduced the CBR and compression values of clay, while addition of small amount of lime to the clay with the tyre buffing increased the stnegth values of the specimens.

Shrivastava et al. (2014)	Carried out a study to obtain the geotechnical properties of black cotton soil by partially replacing it with shredded waste tyres.	• Addition of shredded tyres reduced the swelling potential and shrinkage characteristics of the black cotton soil. • Addition of 5% shredded tyres provided a mix having a lighter weight and marginally improved shear strength.
Mahiri et al. (2015)	Carried out a series of triaxial tests on sand mixed with various tyre chips content.	• Tyre chips significantly influenced the shear strength and dilatancy behaviour of sand-tyre chips mixtures in addition to the confining pressure and relative density.
Anbazhagan et al. (2016)	Assessed the influence of granulated rubber and tyre chips size and the gradation of sand on the strength behaviour of sand-rubber mixtures.	• The peak strength was significantly increased with increasing granulated rubber size up to a rubber size passing 12.5 mm and retained on 9.5 mm, and by adding granulated rubber up to 30%.

		• More uniformly graded sand gave an improved value of shear strength with the inclusion of granulated rubber when compared to poorly graded sand.
Ajmera et al. (2017)	Investigated the compaction, unconfined compressive strength and permeability characteristics of soils mixed with crumb rubber.	• The maximum dry unit weight increased with the addition of crumb rubber regardless of the size of the crumb rubbers. • The unconfined compressive strength of different mixes also showed similar trends as in the case of maximum dry unit weight. The unconfined compressive strength of mixes increased with the increase in the size of the crumb rubber in the soils with kaolinite, but decreased in soils where montmorillonite presents.

		• The permeability increases as the tyre crumb content in the mixes increases.

Table 8 Review on soil-cement-scrap tyre derived materials

Author	Objectives of the study	Concluding remarks
Mitrai et al. (2008)	Evaluated the failure properties of cement stabilized soil containing tyre chips under unconfined and triaxial compression using X-ray CT scanner.	• Addition of tyre chips improved the ductile behaviour of cement treated soil. However, stress-strain curve of triaxial test did not show large strain softening such as in the case of unconfined compression test. • The lateral confining stress is effective in improving ductility of cement treated clay, more so by adding of tyre chips.
Hazarika et al. (2010)	Presented the drainage, compressibility, vibration absorbing capability and ductility characteristics of scrap tyre derived materials.	• Mixing of tyre chips with cement-treated clay added a useful characteristic (ductility) to cement-treated clay. • Cement treated clay mixed with tyre chips can successfully be applied as a sealing

		material to protect against leakage of contaminated materials.
Promputthangkoon and Karnchanachetancee (2013)	Investigated the sustainable utilisation of used tyres as geomaterials by mixing them with low-strength soil and stabilised by cement for road and embankment construction.	• The low strength soil mixed with up to 15 % of recycled tyre chips and stabilised by cement could be used for road construction.

Table 9 Review on soil-fly ash-cement-scrap tyre derived materials

Author	Objectives of the study	Concluding remarks
Tsoi and Lee (2011)	Investigated the stress-strain-strength behaviour of lightly cemented scrap rubber tyre chips.	• Despite the high flexibility of the rubber chips and hence their higher ductility, the material behaviour was found to be generally similar to that of typical cemented soils. • In an unloading–reloading stress–strain curve the unloading path was practically identical to the reloading path in a constant-p' test, but more curved in a consolidated drained test.

Kim and Kang (2013)	Performed unconfined compression, elastic wave and California bearing ratio (CBR) tests to investigate the stiffness, small strain properties and CBR values of composites consisting of soils, crumb rubber, bottom ash and cement.	• Addition of bottom ash to the soil mixture increased the unit weight, unconfined compressive strength, secant modulus, shear modulus and CBR at a given rubber content. • Increase in rubber content resulted in reduction in bulk unit weight, unconfined compressive strength and CBR values.

2.11 STUDIES ON FLY ASH-LIME-SCRAP TYRE DERIVED MATERIAL MIXES

Guleria and Dutta (2011) presented the potential and effect of treated tyre chips on the unconfined compressive strength in a reference mix containing fly ash, lime, and gypsum. Tyre chips were treated with dry, sodium hydroxide and carbon tetrachloride. The tyre chip content varied from 5 to 15% of 5mm strip size approximately. The specimens were cured for 7, 28, 90, and 180 days with three different curing methods (in a dessicator, burlap, and water-filled container). It was found that the unconfined compressive strength of the reference mix with dry tyre chips could be increased by treatment with carbon tetrachloride and sodium hydroxide. The increase in unconfined compressive strength was highest with carbon tetrachloride treatment. The results further revealed that the increase in unconfined compressive strength was highest when cured in water-filled container, followed by burlap and dessicator. The unconfined compressive strength increased with curing period, and the increase was significant up to a curing period of 90 days. With the increase in tyre chip content (5–5%) in the reference mix, there was a decrease in the unconfined compressive strength. This decrease in the unconfined compressive strength was highest when cured in water filled container, followed by burlap and desiccator. The reference mix with treated tyre chips may be used for road sub base with light traffic.

2.12 SUMMARY AND CRITICAL APPRAISAL OF LITERATURE REVIEW

With the rapid generation of fly ash and waste tyres, it has become a great concern of disposal of these waste materials. So there is need to find the reuse of those materials in various applications. The individual effect of addition of either fly ash or scrap tyre derived material to soil with or without cement on different engineering properties such as compaction, strength, deformability and permeability etc. has already been studied. Substantial literature is also available on modification of various types of soils using fly ash and many other additives. Investigation has also been done to study the effect of confining pressure, effects of delay in compaction, influence of cement, lime and other additives, pozzolanic activity, on different properties of soil modified by either fly ash or scrap tyre by a large number of researchers.

However only a limited number of studies are available in the literature regarding use of both scrap tyre derived materials and fly ash with soil with or without cementing agent. There is a need of a detailed investigation of strength and deformation behaviour of these mixes. Large deposits of residual lateritic soils and riverbank sand are available in the northeastern part of India. There is a need to understand the characteristics of mixtures made with these locally available soils, fly ash and scrap tyre derived material along with cement. This is the motivation behind the present study.

CHAPTER - 3
MATERIALS AND METHODS

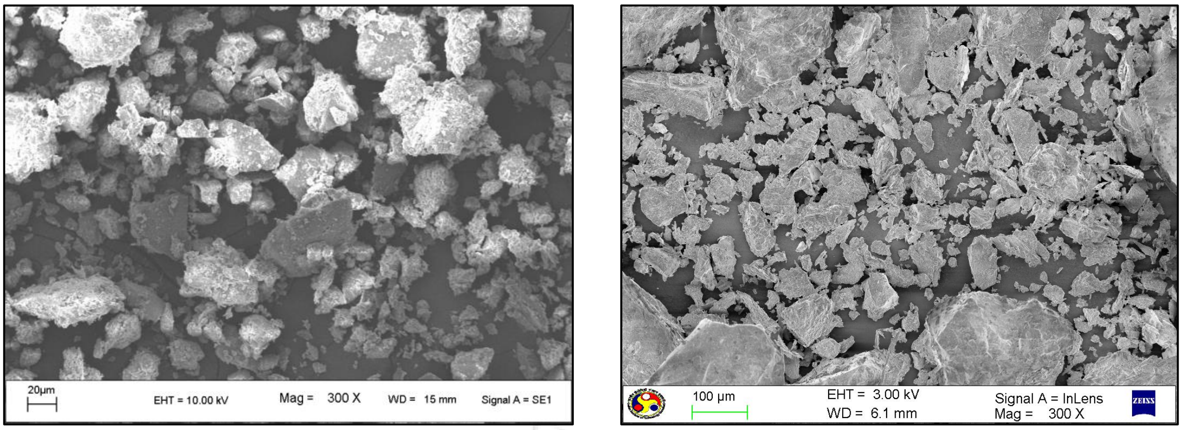
3.1 INTRODUCTION

This chapter contains details of the materials as well as various methods used in the investigation. The properties of different materials, the laboratory test procedures and the preparation of test specimens are dealt in different sections of the chapter.

3.2 MATERIALS AND INDEX PROPERTY TESTING

3.2.1 Soils

The soils used in the present study were both locally available in the state of Assam, India: a fine-grained residual lateritic soil (red soil or RS) and granular riverbank sand (Brahmaputra sand or BS). The lateritic soil was reddish in colour and was procured from nearby hills. The sand was sampled from a nearby bank of Brahmaputra River. According to the Indian Standard Soil Classification System the lateritic and granular soils are classified as MI (silt of intermediate plasticity) and SP (poorly graded fine sand) respectively. The red soil and sand particles have flaky and angular shapes respectively as shown in Figs. 3.1(a) and 3.1(b). The gradation curves of the red soil and sand are obtained using IS 2720 Part IV code and depicted in Fig. 3.2. The specific gravity values of the red soil and sand are 2.60 and 2.71 respectively. The results of geotechnical characterization tests of both the soil type are summarized in Table 3.1. The relationship between moisture content and dry unit weight of RS and BS mixes are shown in Figs. 3.3 and 3.4 respectively.



(a) (b)

Fig. 3.1 SEM images of (a) Red soil and (b) Sand

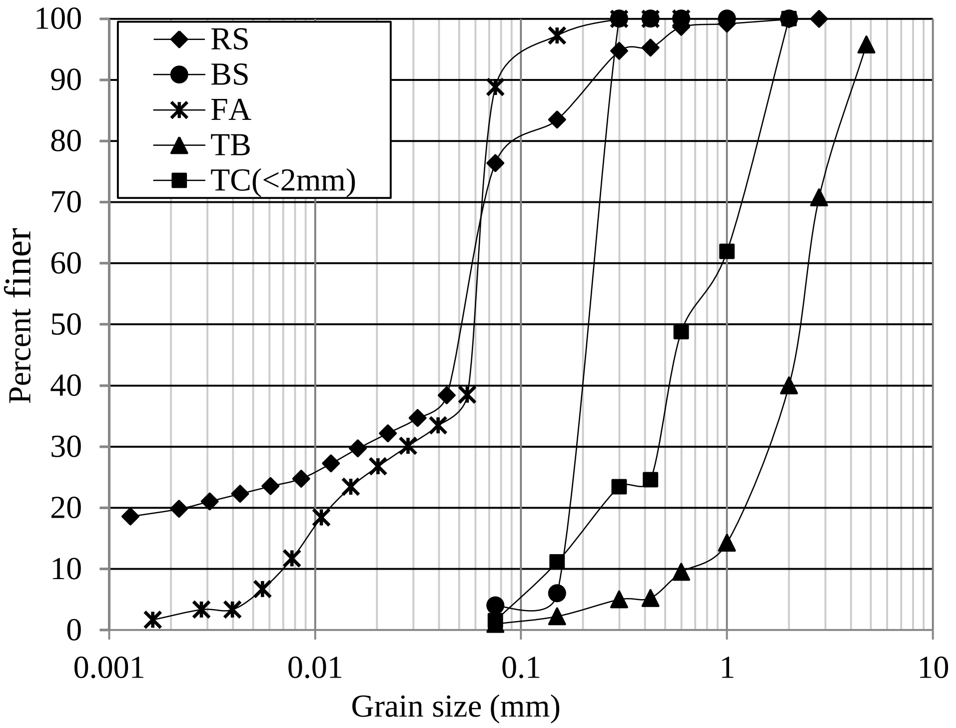


Fig. 3.2 Grain size distribution curves of red roil, Brahmaputra sand, fly ash, tyre buffings and tyre crumbs

Table 3.1 Geotechnical characterization of various materials

Property	Materials				
	Soil		Fly ash	Tyre buffing	Tyre crumb
	RS	BS	FA	TB	TC
Specific gravity, G_s	2.60	2.71	2.13	1.05	1.05
Grain size					
Gravel (> 4.75 mm) (%)	0.0	0.0	0.0	0.0	0.0
Sand (0.075 – 4.75 mm) (%)	23.6	96	11.2	99	98.5
Coarse sand (2.0-4.75 mm) (%)	0.1	0	0.0	60	0
Medium sand (0.425 – 2.0 mm) (%)	4.7	0	0.1	34.7	75.4
Fine sand (0.075 – 0.425 mm) (%)	18.8	96	11.1	4.3	23.1
Silt (0.002 – 0.075 mm) (%)	56.6		87.1		
Clay (< 0.002 mm) (%)	19.8		1.7		
Plasticity	Plastic	Non-plastic	Non-plastic		
Atterberg limits					
Liquid limit, LL (%)	46		29		
Plastic limit, PL (%)	28				
Plasticity index, PI	18				
Compaction parameters					
Optimum Moisture Content (%)	20.6	16.38	19.3	Air Dried	
Maximum Dry Unit Weight (kN/m^3)	16.7	15.69	13.6	5.8	
Soil classification					
Indian Standard Soil Classification System (*ISSCS*)	MI	SP	MS		
Description	Silt of intermediate plasticity	Poorly graded fine sand	Sandy silt		
Particle shape	Flaky	Granular	Spherical	Fibrous	Granular

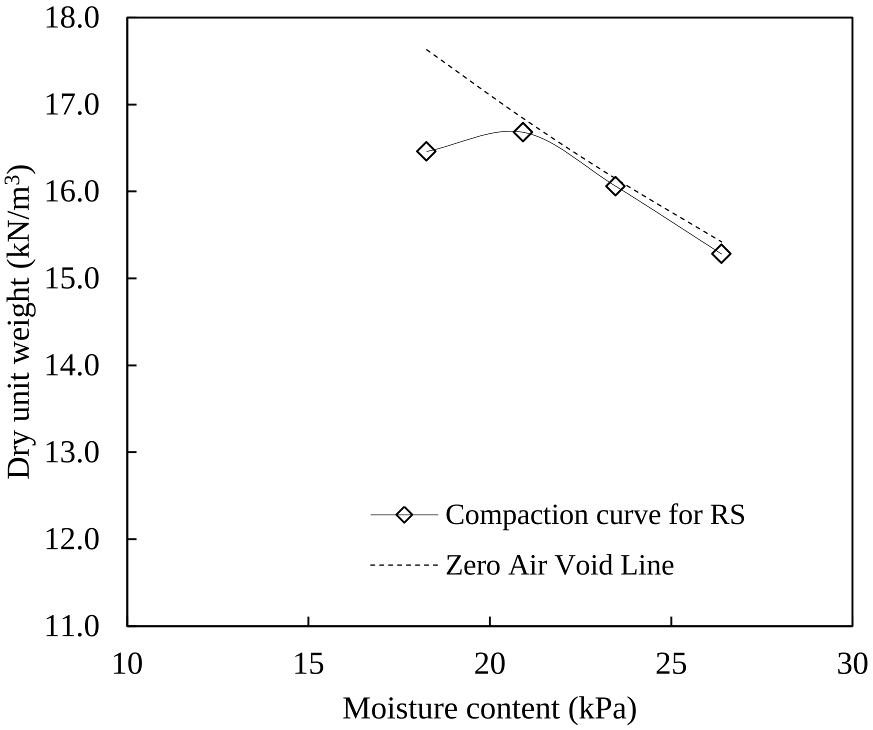


Fig. 3.3 Dry unit weight and moisture content relationships of RS mix

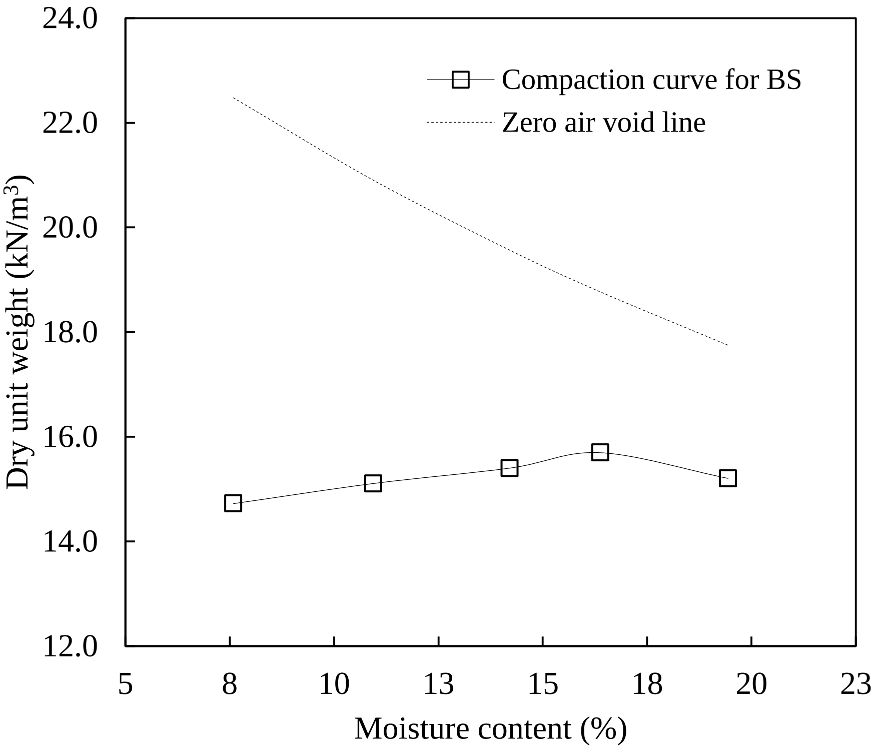
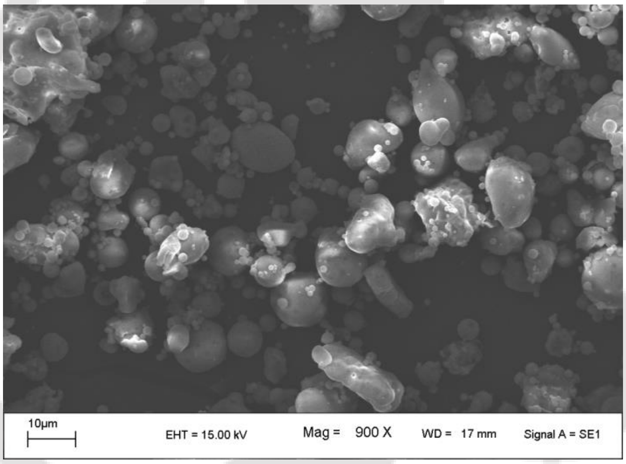


Fig. 3.4 Dry unit weight and moisture content relationships of BS mix

3.2.2 Fly Ash

Fly ash of Class F type was procured from the Farakka thermal power plant located in the adjoining state of West Bengal. The fly ash can be classified as MS-type soil belonging to the Sandy silt category (Table 3.1). The chemical composition of the fly ash is presented in Table 3.2. It can be seen that the CaO content is only 0.9%. The specific gravity value of fly ash is 2.13, which is lower than the specific gravity values of red soil and sand. Fly ash particles have spherical shape as shown in Fig. 3.5.The gradation curve of fly ash is also depicted in Fig. 3.2. The relationship between dry unit weight and moisture content of fly ash has been shown in Fig. 3.6.



(c)

Fig. 3.5 SEM image of Fly ash

Table 3.2 Chemical composition of fly ash

Element	Value (%)	Element	Value (%)
Silica (SiO_2)	60.238	Manganese oxide (MnO)	0.038
Alumina (Al_2O_3)	22.895	Titanium oxide (TiO_2)	1.234
Iron oxide (Fe_2O_3)	6.350	Phosphorus oxide (P_2O_5)	0.566
Lime (CaO)	0.854	Barium oxide (BaO)	0.085
Magnesia (MgO)	1.239	Strontium oxide (SrO)	0.056
Soda (Na_2O)	0.037	Sulphur oxide (SO_3)	0.090
Potash (K_2O)	1.648		

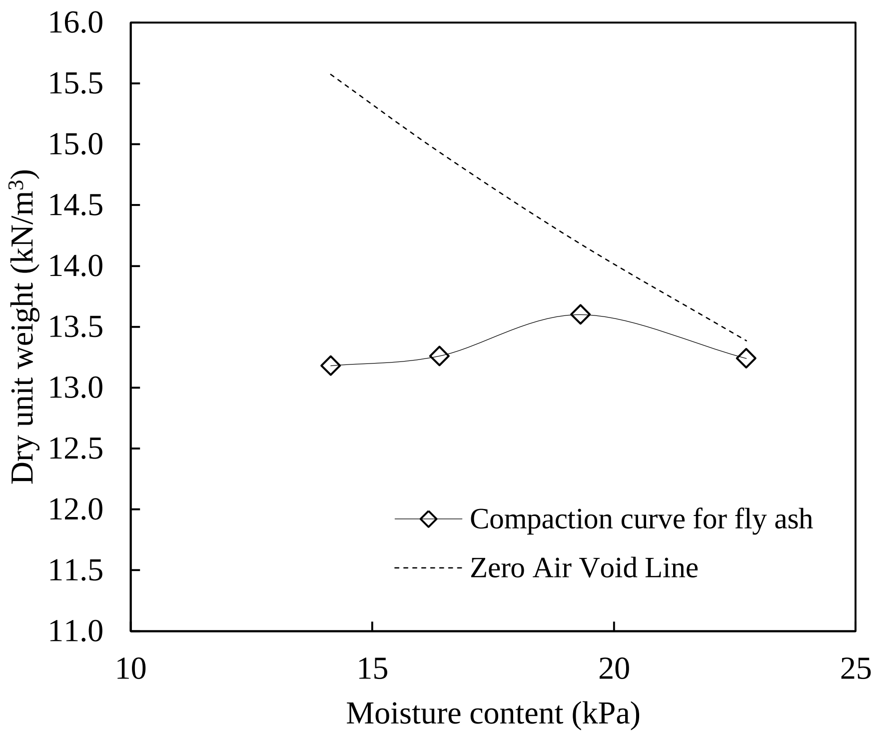


Fig. 3.6 Dry unit weight and moisture content relationships of FA mix

3.2.3 Scrap Tyre Derived Materials

Scrap tyre derived materials can be of various forms: tyre shreds, tyre chips and granulated rubber etc. According to ASTM code D 6270-98 (2004) tyre shreds resulting from mechanical processing of scrap tyres have a basic geometrical shape and are generally between 50 mm and 305 mm in size, tyre chips also derived from mechanical processing are generally between 12 mm and 50 mm in size and have most of the wire removed, finally granulated rubber composed of mainly nonspherical particles that span a broad range of particle size, from below 0.425 mm to 12 mm. Tyre buffings (TB) used in this study are a by-product of the tyre retread process, and have an elongated fibrous shape with variable length. They were found in many dimensional forms and were obtained from a commercial scrap tyre supplier. Grading of tire buffing was necessary in order to reduce the size effect. Tyre buffings used in this study consist of particles passing through 4.75 mm sieve and retained on 2 mm sieve. The specific gravity and maximum dry unit weight of tyre buffings at air dried condition were found to be 1.05 and 5.8 kN/m^3 respectively. Another form of scrap tyre derived material named as tyre crumb (TC) comprising of particles finer than 2mm have also been used in this study. The images of tyre buffings and tyre crumb are shown in Figs. 3.7 (a) and 3.7(b) respectively, and their gradation curves are depicted in Fig. 3.2.

(a)

(b)

Fig. 3.7 Images of (a) Tyre buffings and (b) Tyre crumb

3.2.4 Cement

Ordinary Portland Cement of 43 Grade was used as a cementitous material. The chemical composition of cement is tabulated in Table 3.3.

Table 3.3: Chemical composition of the cement

Major Oxides	Value (%)
Silica (SiO_2)	23.09
Alumina (Al_2O_3)	3.80
Iron oxide (Fe_2O_3)	2.31
Lime (CaO)	59.90
Magnesia (MgO)	1.32
Soda (Na_2O)	0.21
Potash (K_2O)	0.37
Manganese oxide (MnO)	0.05
Titanium oxide (TiO_2)	0.23
Phosphorus oxide (P_2O_5)	0.05

3.3 COMPACTION TESTS

Compaction tests were performed to determine the maximum dry unit weight (MDU) and optimum moisture content (OMC) for the soil, fly ash, soil-fly ash and soil-fly ash-tyre buffing mixes according to the guidelines of IS: 2720 (Part 7)-1980. The MDU and OMC values are then used to prepare specimens for other tests, viz. triaxial compression test and unconfined compression test to determine the strength properties of different mixes.

3.4 UNCONFINED COMPRESSION TESTS

Unconfined compression (UC) tests were performed to determine the unconfined compressive strength of the specimens. Tests were conducted as per the guidelines given in IS 2720 (Part 10)-1990. A minimum of three specimens were prepared for each combination of variables and tested at a deformation rate of 1.25 mm/min. The average cross-sectional area at each measured strain is determined. Each specimen is compressed until a definite failure surface developed, or the stress-strain curve passes its peak. The unconfined compressive strength (UCS) is taken as the average of the three specimens. Failure strain reported is also the average of the three specimens.

3.5 TRIAXIAL COMPRESSION TESTS

The shear strength parameters of prepared specimens were determined from the triaxial compression tests. During the entire test drainage valve was kept open. Since the specimen was at MDD-OMC state, it was unsaturated. Because of the low degree of saturation of the compacted specimen, it was difficult to saturate it by applying backpressure. So the specimen was consolidated at as compacted condition prior to shearing. Ranjan et al. (1996) also conducted triaxial compression tests on partially saturated reinforced specimens. The tests were performed at confining pressures of 100, 200, 300 and 400 kPa. The specimens were sheared at a constant deformation rate of

0.24 mm/min until the peak value of the stress well passed or until an axial strain of 20% was reached. The electronic triaxial set-up used in this study is shown in Fig. 3.8. The setup uses a pneumatic system for application of confining pressure. Axial load and axial deformation were measured with an electronic load cell and a linear variable displacement transducer (LVDT), respectively. The values were recorded through an electronic data acquisition system connected to a computer. The volume change and pore water pressure measurements were not made during the experiments. The tests were carried out according to the guidelines given in ASTM D 7181 (2011).

Fig. 3.8 Electronic triaxial set-up

The failure criteria used for any specimen in the triaxial compression tests is the maximum deviator stress observed within 20% axial strain or the deviator stress at 20% axial strain if the peak is not attained within 20% axial strain.

3.6 PREPARATION OF TEST SPECIMENS

The required amounts of soil, fly ash, tyre buffing and water were measured to start the procedure. The soil-fly ash, soil-tyre buffing and soil-fly ash- tyre buffing mixes were first mixed together in the dry state and the dry mixes was mixed with optimum water amount. All mixing was done by mixing tool and proper care was taken to prepare homogeneous mixes. To prepare the specimens, a 38 mm inner diameter and 76 mm long mould with detachable collars at both ends was used (Fig. 3.9). To ensure uniform compaction, the entire quantity of the mixture was placed inside the mould-collars assembly and compressed alternately from the two ends until the specimen reached the dimensions of the mould. Specimens for compression tests were prepared to achieve their respective maximum dry densities.

The specimens were extruded from the mould immediately and were cured at room temperature, inside desiccators at constant relative humidity of 100%. Four specimens for each curing time were prepared in order to provide an indication of the reproducibility as well as to provide sufficient data for accurate interpolation of the results. Specimens were cured for the periods of 0, 3, 7, 14 and 28 days. Table 3.4 shows the details of different soil mixes used in the present study and their designations.

Fig. 3.9 Fabricated miniature static compaction tool

Table 3.4 Designations of mixes used in the present investigation

Designation	Type of mix
RS	Red soil only
BS	Sand only
FA	Fly ash only
TB	Tyre buffing
RS+FA	Red soil-fly ash mix
BS+FA	Brahmaputra sand-fly ash mix
RS+C	Red soil-cement mix
BS+C	Brahmaputra sand-cement mix
RS+TB	Red soil-tyre buffing
BS+TB	Brahmaputra sand-tyre buffing
RS+FA+TB	Red soil-fly ash-tyre buffing mix
BS+FA+TB	Brahmaputra sand-fly ash-tyre buffing mix
BS+FA+TB+2C	Brahmaputra sand-fly ash-tyre buffing -2% cement mix
RS+FA+TB+2C	Red soil -fly ash- tyre buffing-2% cement mix
BS+20FA	80% Brahmaputra sand-20% fly ash
BS+20FA+5TB	75% Brahmaputra sand-20% fly ash-5% tyre buffing
BS+20FA+5TB+2C	75% Brahmaputra sand -20% fly ash-5% tyre buffing-2% cement
RS+20FA+5TB+2C	75% red soil-20% fly ash-5% tyre buffing-2% cement
RS+20FA+5TC+2C	80% red soil-20% fly ash-5% tyre crumb-2% cement

CHAPTER - 4
COMPACTION TESTS

4.1 INTRODUCTION

Mixing and compaction are important steps for construction processes involving the use of admixtures. It was considered essential to examine the resulting changes of fly ash and tyre fibre addition on the compaction behaviour of the soil and its mixes. Investigation on compaction characteristics of fly ash admixed soils had been done by many early researchers (Prabhakar et al., 2004; Parsons and Kneebone, 2005; Sezer et al., 2006; Lin et al., 2007; Phanikumar and Sharma, 2007; Chauhan et al., 2008; Mir and Sridharan, 2013; Yilmaz, 2015) on fly ash admixed soil. Compaction studies on soil-scrap tyre derived fibre mixes were also carried out by many researchers (Edil and Bosscher, 1994; Ozkul and Baykal, 2006; Cetin et al., 2006; Tabbaa et al., 2010; Cabalar et al., 2014; Srivastava et al., 2014). Compaction tests were performed to determine the maximum dry unit weight (MDU) and optimum moisture content (OMC) of the soil, fly ash, soil-fly ash mixes, soil-tyre buffing mixes and soil-fly ash-tyre buffing mixes. The MDU and OMC values are then used to prepare specimens for unconfined compression and triaxial compression tests to determine the strength characteristics of the mixes.

4.2 TEST PROGRAMME

Table 4.1 summarizes the composition of the various mixes used. The compaction properties of the soil-fly ash, soil-tyre buffing and soil-fly ash-tyre buffing mixes were investigated by conducting standard proctor tests. Two series of tests were conducted. In the first series**,** compaction properties of all the red soil mixes were investigated as per IS: 2720 Part 7 (1980). In the second series, tests were conducted to investigate the compaction behaviour of sand mixes.

Table 4.1 Composition of various mixes for compaction tests

Soil	Fly ash	Red soil-fly ash mixes	Red soil-tyre buffing mixes	Red soil-fly ash-tyre buffing mixes
RS	FA	RS+20FA	RS+5TB	RS+20FA+5TB
		RS+35FA	RS+10TB	RS+20FA+10TB
		RS+50FA		
				RS+35FA+5TB
				RS+35FA+10TB
				RS+50FA+5TB
				RS+50FA+10TB
		BS+20FA	BS+5TB	BS+20FA+5TB
		BS+35FA	BS+10TB	BS+20FA+10TB
		BS+50FA		
				BS+35FA+5TB
				BS+35FA+10TB
				BS+50FA+5TB
				BS+50FA+10TB

4.3 RESULTS AND DISCUSSION

Results obtained from compaction tests for RS and BS mixes are discussed here. The values of the MDU and OMC of the soil, fly ash, soil-fly ash mixes, soil-tyre buffings mixes, soil-fly ash-tyre buffings mixes are summarized in Tables 4.2 and 4.3.

4.3.1 Compaction Behaviour of Red Soil-Fly Ash Mixes

Fig. 4.1 shows the compaction curves of the red soil, fly ash and red soil-fly ash mixtures. As the fly ash content increases, MDU of the mixes is noted to decrease gradually. The specific gravity values of the fly ash and red soil are 2.13and 2.60 respectively. The fly ash has MDU of 13.6 kN/m^3, which is lower than that of the red soil (16.7 kN/m^3). Thus, MDU is the highest for the RS+20FA mix and the least for the RS+50FA mix as shown Fig. 4.2(a). The decrease in MDU is attributed to the lower specific gravity of the ash particles, and change in the texture within the mix. Prabhakar et al. (2004), Lin et al. (2007) and Mir and Sridharan (2013) also reported the same kind of observation. On the contrary to that Phanikumar and Sharma (2007) and Yilmaz (2015) found that replacement of a clay soil by a class C fly ash increases the MDU of the mixes.

Fig. 4.2(b) depicts that as the fly ash content in the red soil-fly ash mixes increases the OMC of the mixes tends to decrease from 21% to 19.40%, which resemble the findings of Phanikumar and Sharma (2007), and Yilmaz (2015). The fly ash has OMC of 19.30%, which is marginally lower than that of the red soil (20.60%). Replacement of soil by fly ash causes reduction of the repulsive forces due to the double layer of adsorbed water present in the surface of the clay particles and it helps in a closer packing more easily. This may be the cause of reduction of OMC on addition of fly ash to soil.

4.3.2 Compaction Behaviour of Red Soil-Tyre Buffing Mixes

As tyre buffings are lighter, inclusion of tyre buffing causes a drop in the dry unit weight of the mixes and it is depicted in Figs. 4.3 and 4.4(a). Increase in tyre buffing content reduces the MDU of red soil from 16.70 kN/m^3 to 15.40 kN/m^3. Presence of tyre buffings has an influence on the effectiveness of compaction. It is possible that a portion of the energy is absorbed because of the flexible nature of tyre buffing. Edil and

Bosscher (1994) studied the compaction chracteristics of clay mixed with tyre chips of size 50 mm by 75 mm. It was reported that the unit weight increased with increasing clay: tyre chips ratio. Cetin et al. (2006) reported that dry unit weights for cohesive soil-tyre chip mixtures decreased as the percentage of tyre chips increased. They used tyre chips free of steel belts and size ranging from 2 mm to 4.75 mm. Reductions in dry unit weight due to inclusion of tyre buffing to clay was also observed by Ozkul et al. (2006). In this study tyre buffings retained between the sieve sizes of 2.36 mm and 2 mm were used. Ajmera et al. (2017) reported that addition of tyre crumb beyond 4% reduces the maximum dry unit weight of tyre crumb added soils.

Figs. 4.3 and 4.4(b) reveal that addition of 5% tyre buffings to red soil mixes decreases the OMC of the mixes. Due to the low absorption capacity of tyre buffing increase in TB content increases the OMC of the RS+TB mixes (Cetin et al., 2006; Cabalar et al., 2014; Srivastava et al., 2014).

4.3.3 Compaction Behaviour of Red Soil-Fly Ash-Tyre Buffing Mixes

The presence of tyre buffings in soil-fly ash mixes causes a change in the moisture-unit weight relationship. Due to lower specific gravity of tyre buffings, addition of tyre buffings to red soil-fly ash mixes decreases the dry unit weight. It is depicted in Figs.4.5 to 4.7 and Fig. 4.8(a). It is also seen that as the fly ash content in the RS+FA+TB mixes increases the MDU of the mixes decreases. Fig. 4.8(b) depicts that increase in fly ash content in RS+FA+TB mixes decreases the OMC of the mixes. This kind of behaviour may be due to the lower water absorption capacity of tyre buffings (Cabalar et al., 2014).

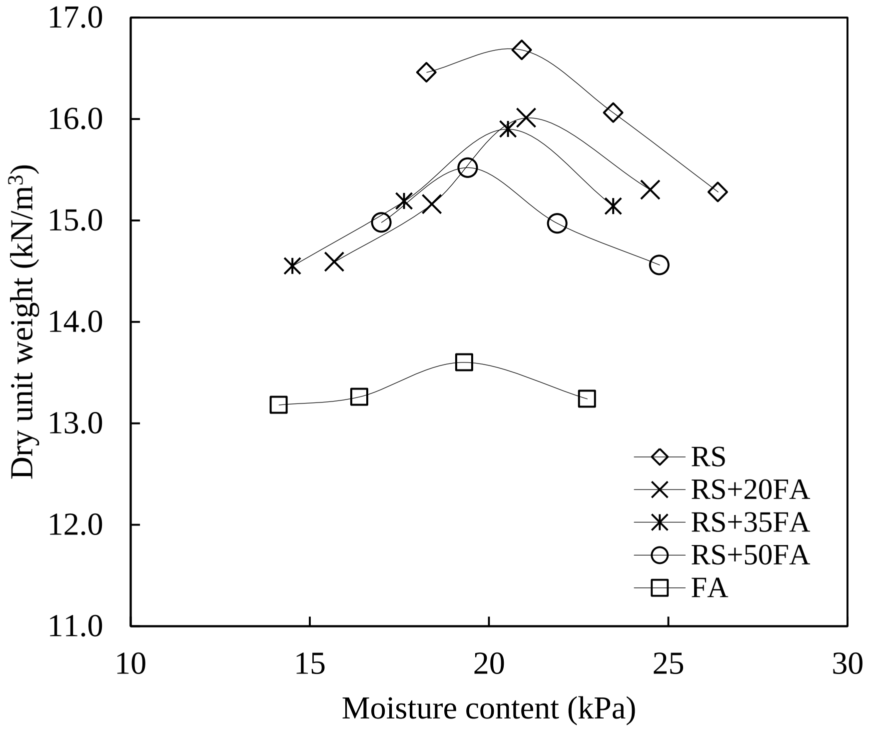


Fig. 4.1 Compaction curves of red soil, fly ash and red soil-fly ash mixes

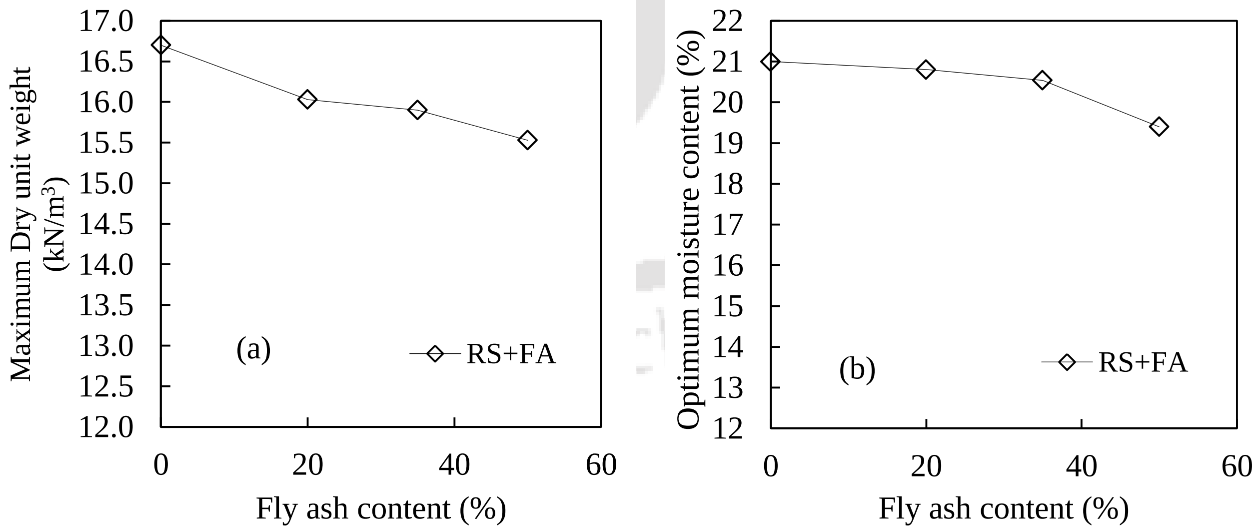


Fig. 4.2 Effect of fly ash on (a) maximum dry unit weight and (b) optimum moisture content of RS+FA mixes

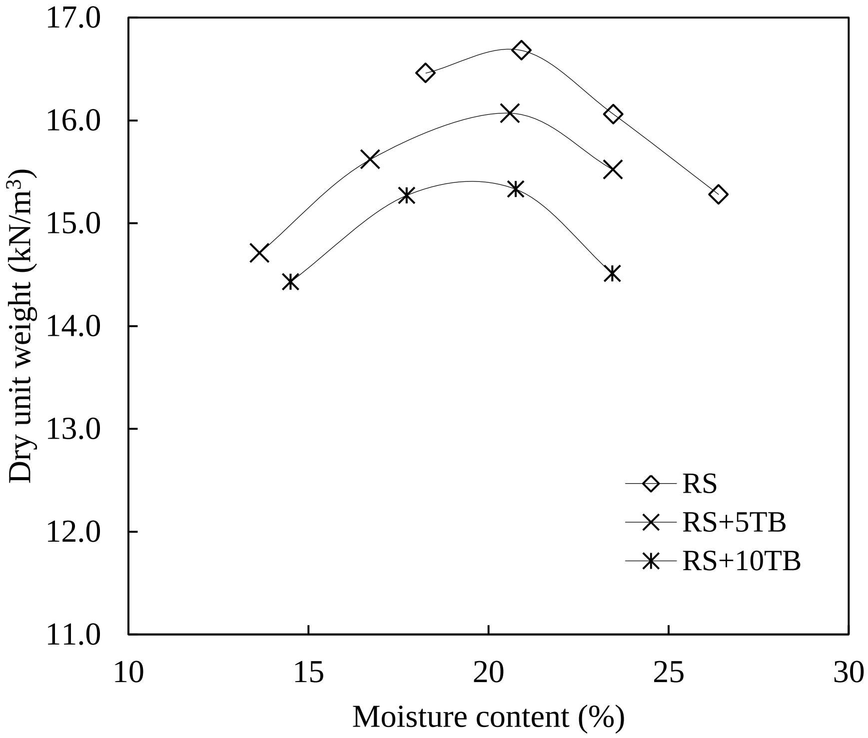


Fig. 4.3 Compaction curves of red soil-tyre buffing mixes

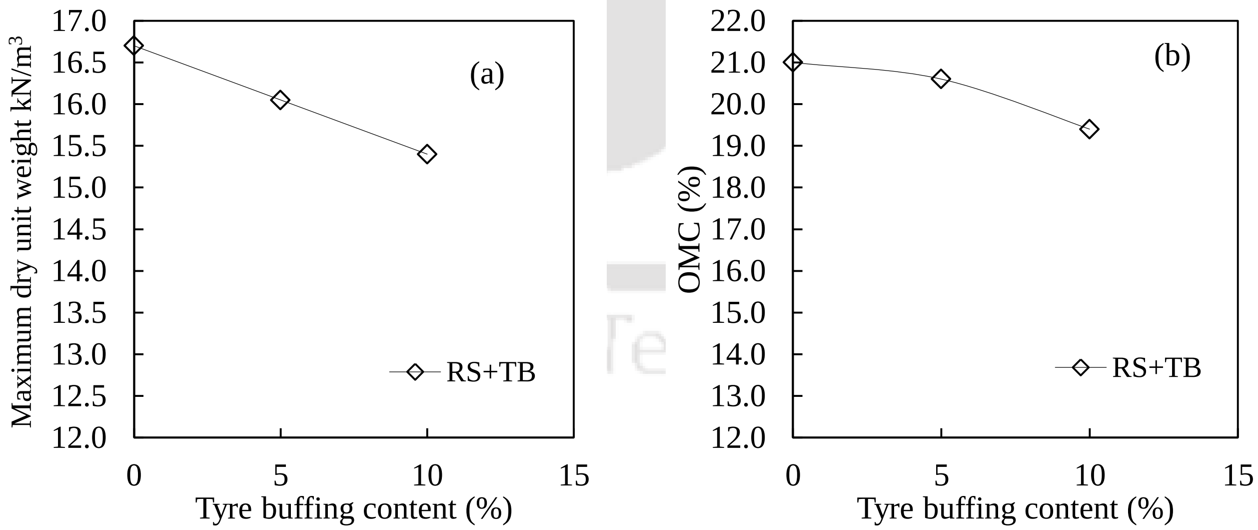


Fig. 4.4 Effect of fly ash on (a) maximum dry unit weight and (b) optimum moisture content of RS+TB mixes

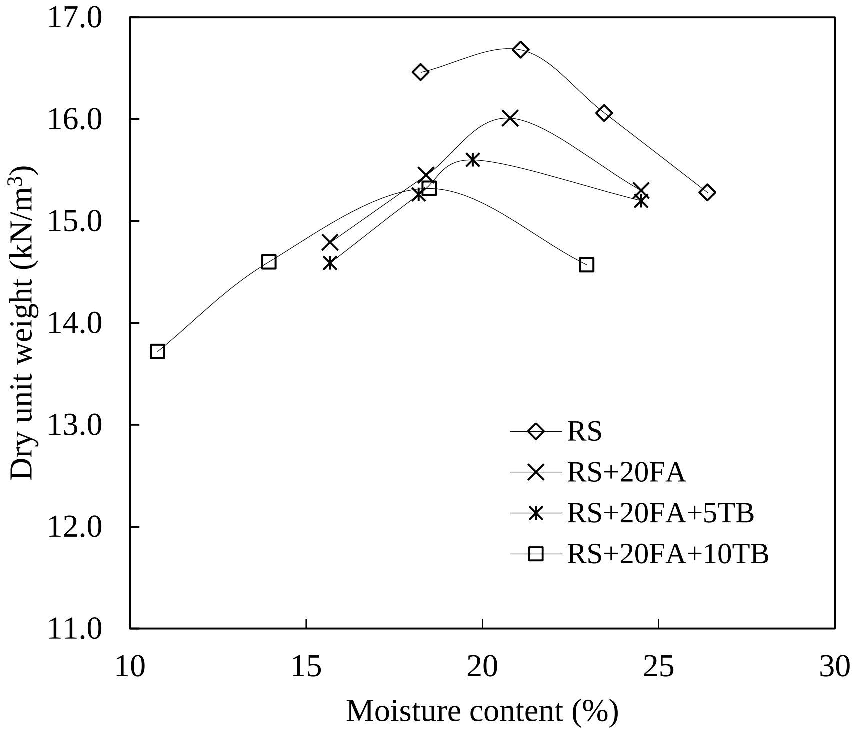


Fig. 4.5 Compaction curves of RS and RS+20FA+TB mixes

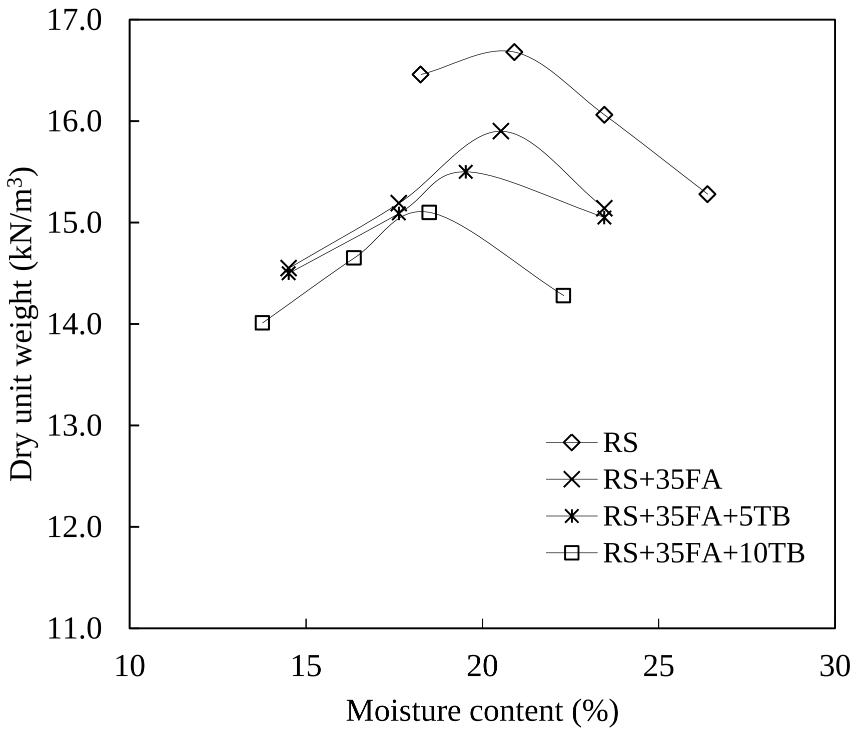


Fig. 4.6 Compaction curves of RS and RS+35FA+TB mixes

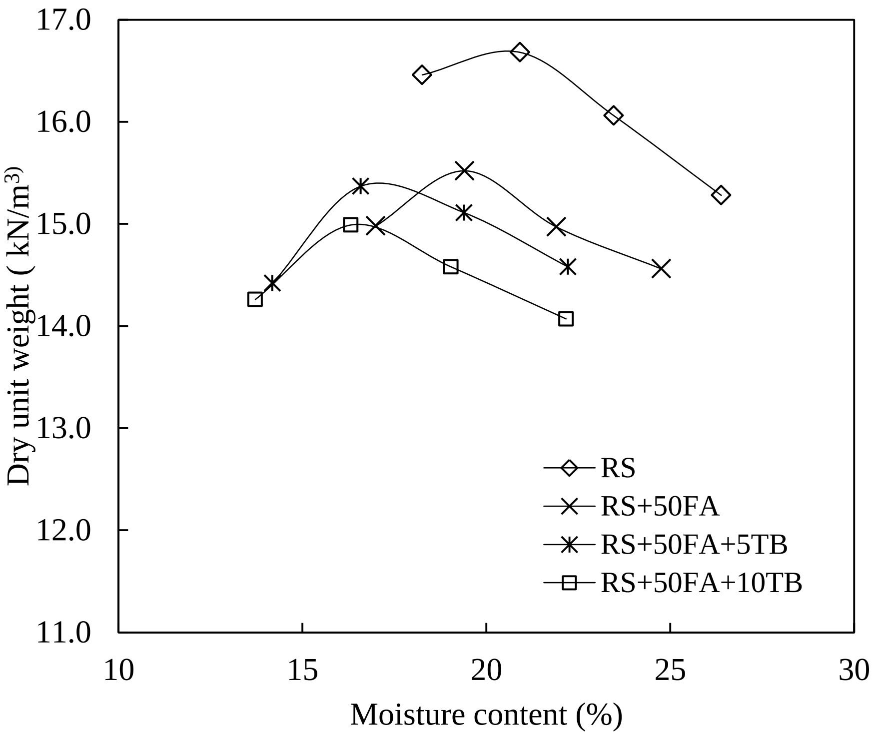


Fig. 4.7 Compaction curves of RS+50FA+TB mixes

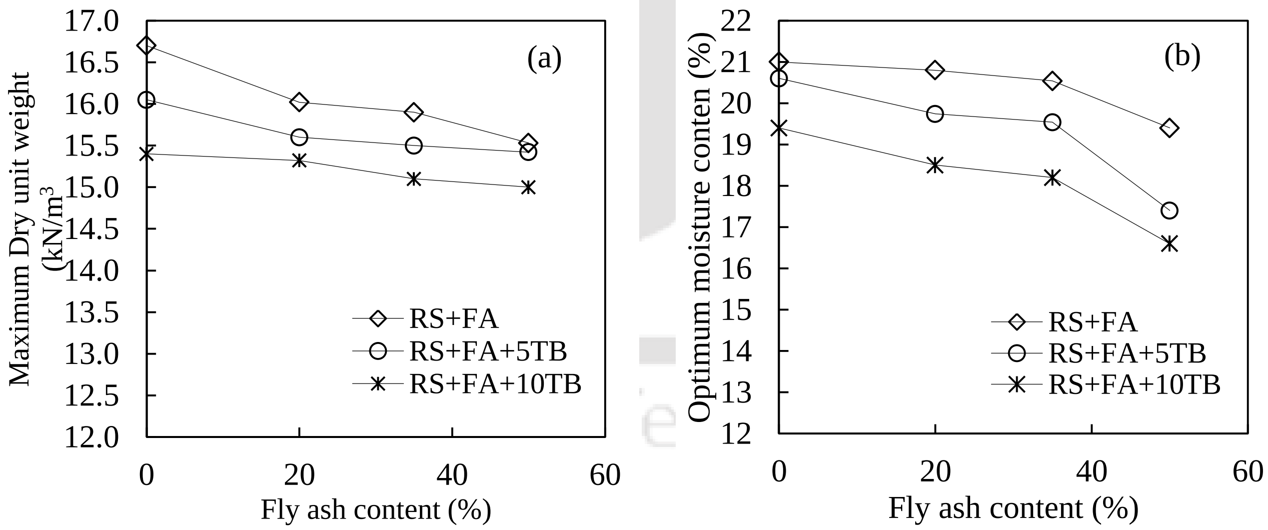


Fig. 4.8 Effect of fly ash and tyre buffing content on (a) maximum dry unit weight and (b) OMC of various RS+FA+TB mixes

Table 4.2 Experimental compaction results of various red soil mixes

Mix	MDU (kN/m^3)	OMC (%)
RS	16.70	21.00
FA	13.60	19.30
RS+20FA	16.10	20.80
RS+35FA	15.90	20.54
RS+50FA	15.53	19.40
RS+5TB	16.05	20.60
RS+10TB	15.40	19.40
RS+20FA+5TB	15.60	19.74
RS+20FA+10TB	15.32	18.50
RS+35FA+5TB	15.50	19.54
RS+35FA+10TB	15.10	18.20
RS+50FA+5TB	15.42	17.40
RS+50FA+10TB	15.00	16.60

4.3.4 Compaction Behaviour of Sand-Fly Ash Mixes

From Fig. 4.9, it is observed that addition of 20% fly ash content in sand increases the MDU of the mixes. But beyond 20%, further addition of fly ash to sand decreases the MDU values of the sand-fly ash mixes. The fly ash has MDU (13.60 kN/m^3) which is lower than that of the sand (15.69 kN/m^3). Again as the fly ash is finer than sand, addition of fly ash to sand initially fills up the voids between the sand particles which results in greater value of MDU than the BS mix. Beyond 20% fly ash content, increase in fly ash content decreases the MDU of BS+FA mixes as seen in the Fig. 4.10(a). The decrease in MDU is attributed to the lower specific gravity of the ash particles. Chauhan et al. (2008), Mir and Sridharan (2013) and Yilmiz (2015) reported that addition of fly ash in soil reduced the MDU values of the mixes. It is also observed that the MDU values of sand-fly ash mixes are higher than the corresponding MDU values of red soil -fly ash mixes.

From Fig. 4.10(b) it is seen that the OMC values of sand-fly ash mixes initially decreases at 20% fly ash content due to the fact that being finer particle, voids between the sand particles are filled up with fly ash which could have been filled up with water. Again fly ash has higher water holding capacity, therefore beyond 20% addition of fly ash increases the OMC of BS+FA mixes. Increase in OMC due to an increase in fly ash content in BS+FA mixes were also reported by other researchers (Chauhan et al., 2008; Mir and Sridharan, 2013; Priyadarshee et al., 2018).

4.3.5 Compaction Behaviour of Sand-Tyre Buffing Mixes

From Fig. 4.11, it is found that increase in percentage of tyre buffings to sand mixes decreases the MDU and also decreases the OMC of BS+TB mixes. Figs. 4.12(a) and (b) also depict the same findings. As tyre buffings are lighter, addition of TB to sand causes a drop in the dry unit weight of the mixes, which resembles the findings by Edil et al. (1994), Youwai et al. (2003), Cetin et al. (2006) and Mukherjee and Mishra (2017). They reported that with decreasing proportion of sand in the sand-tyre mixture, the dry unit weight decreased.

4.3.6 Compaction Behaviour of Sand-Fly Ash-Tyre Buffing Mixes

Figs. 4.13 to 4.15 show the relation between dry unit weight and moisture content after addition of tyre buffing to BS+FA mixes. Further addition of tyre buffing to sand-fly ash mixes decreases the MDU and it is also evident from Fig. 4.16(a). This kind of behaviour is attributed to the lower specific gravity of the ash particles as compared to sand and fly ash particles, and it resembles with earlier finding by Priyadarshee et al.

(2018). It is also seen that 20% fly ash addition in BS+FA+TB mixes reaches highest MDU, beyond that MDU decreases.

Fig. 4.16(b) shows that increase in tyre buffing content in BS+FA mixes decreases the OMC values of the mixes. Addition of tyre buffing decreases the OMC values of BS+20FA mixes from 13.81% to 13.50% .The presence of tyre buffings in soil-fly ash mixes causes a change in the moisture-unit weight relationship. Lower water absorption capacity as compared to sand and fly ash particles is responsible for this reduction. It is also observed that for 20% FA content in BS+FA+TB mixes initially reduces the OMC of the mixes, but further increase in fly ash content in BS+FA+TB mixes increase the OMC values of the mixes. The reason behind this kind of behaviour can be explained as the same manner as in the case of BS+FA mixes.

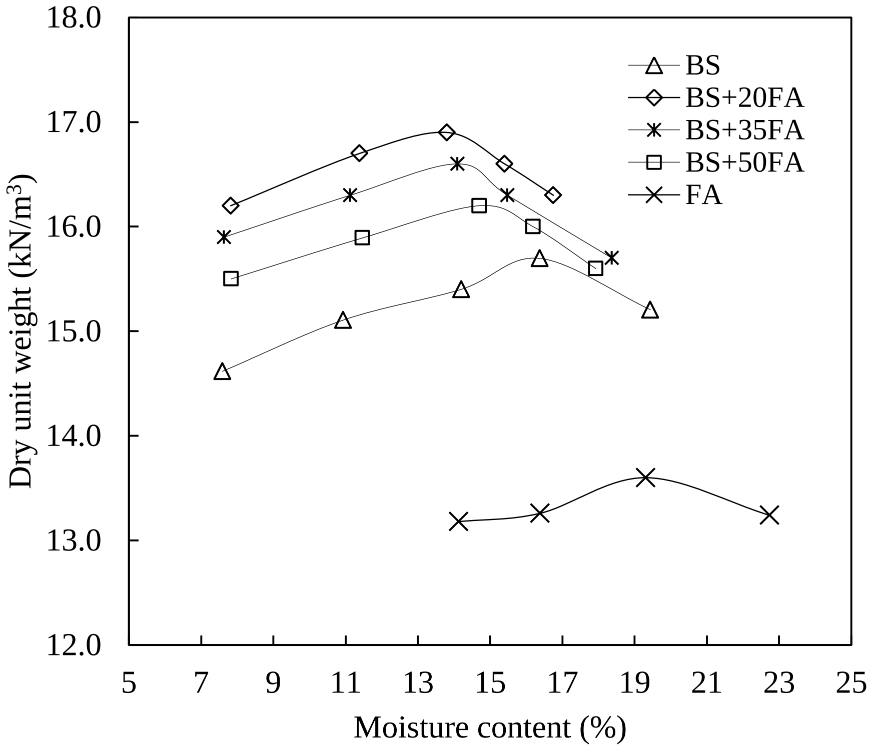


Fig. 4.9 Compaction curves of BS alone and BS+FA mixes

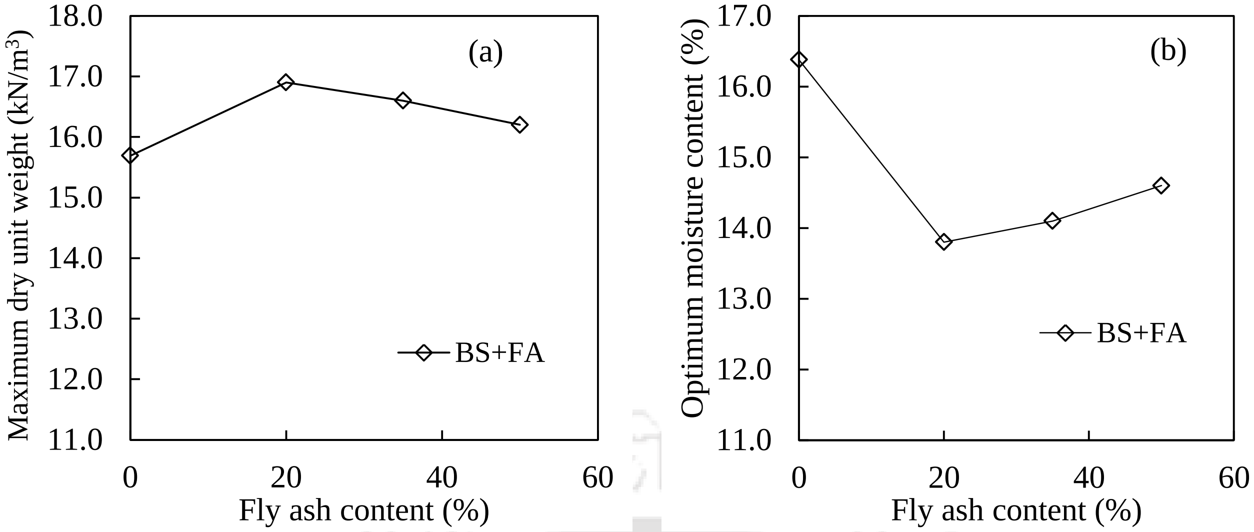


Fig. 4.10 Effect of fly ash on (a) MDU and (b) OMC of various BS mixes

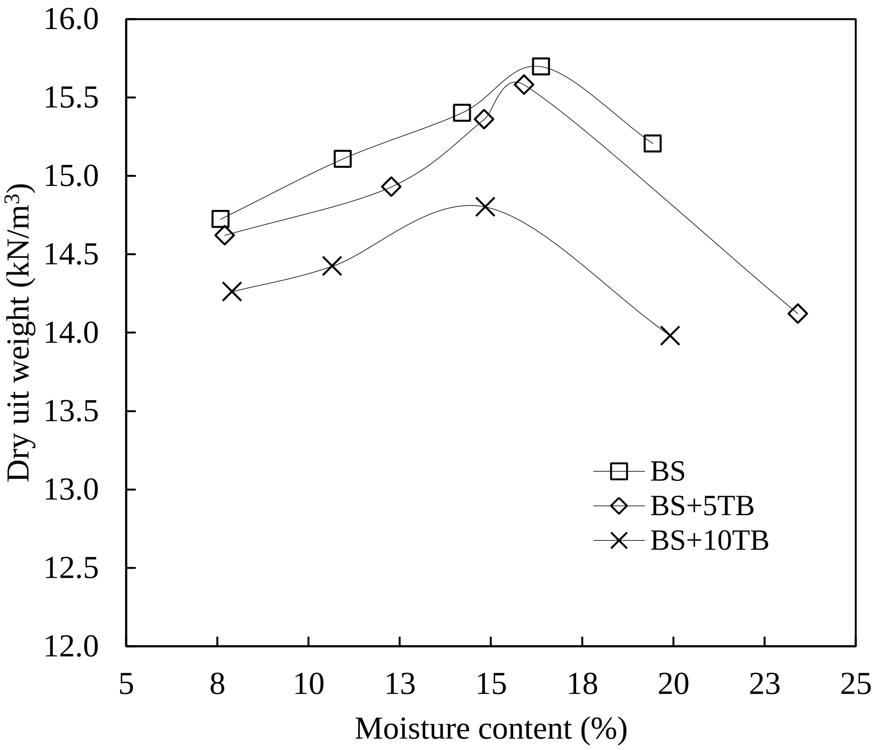


Fig. 4.11 Compaction curves of BS+TB mixes

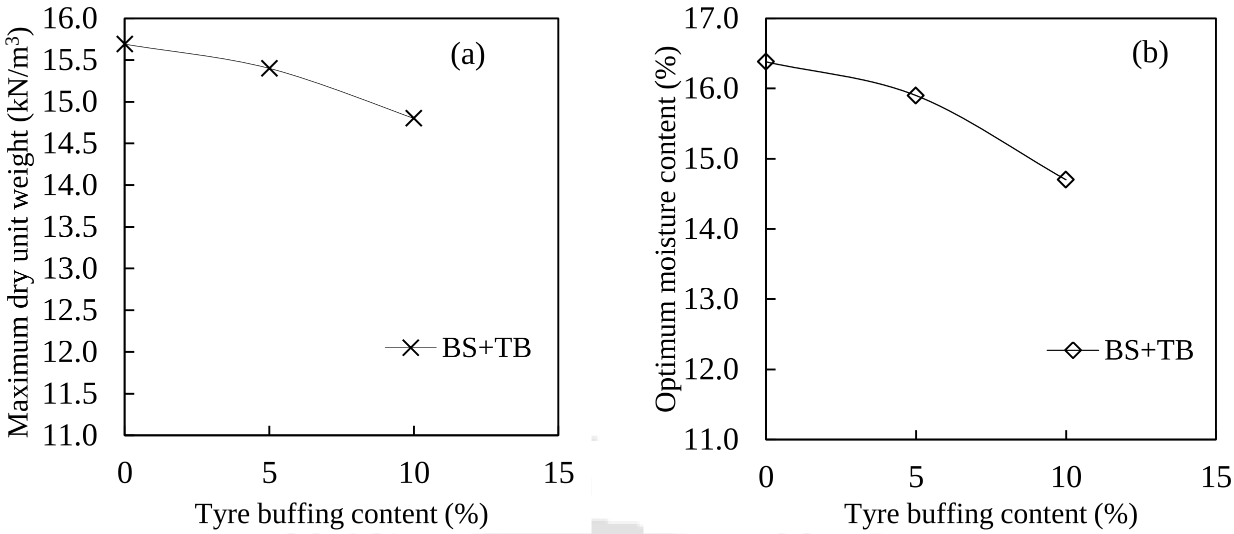


Fig. 4.12 Effect of tyre buffing on (a) MDU and (b) OMC of various BS+FA mixes

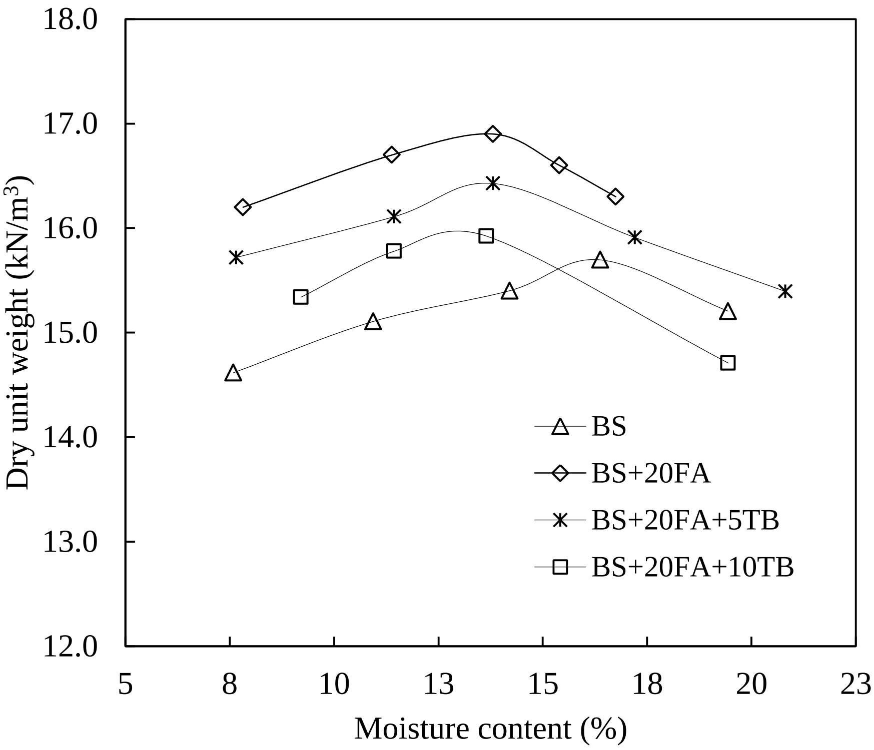


Fig. 4.13 Compaction curves of BS+20FA+TB mixes

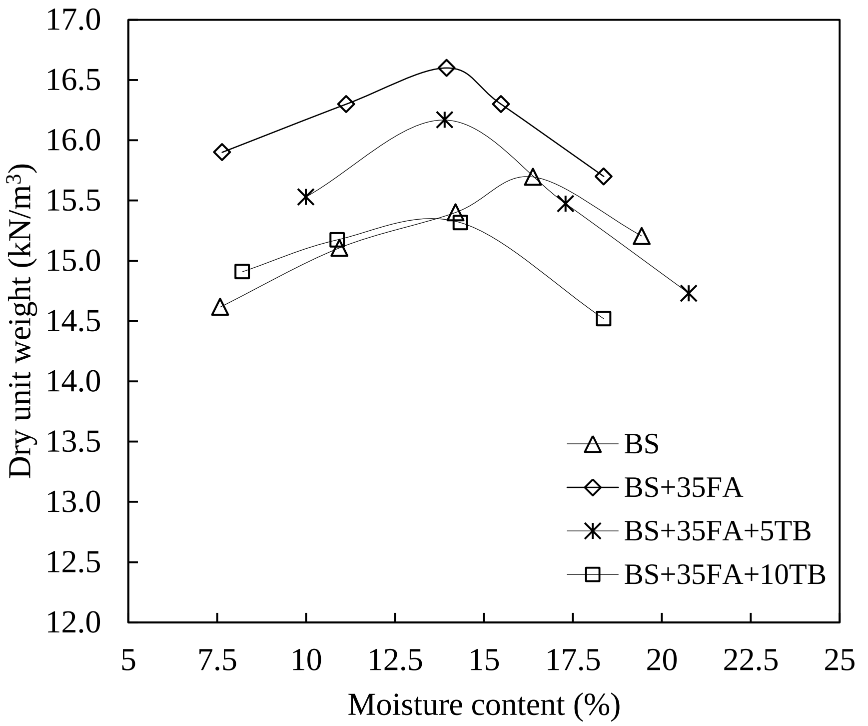


Fig. 4.14 Compaction curves of BS+35FA+TB mixes

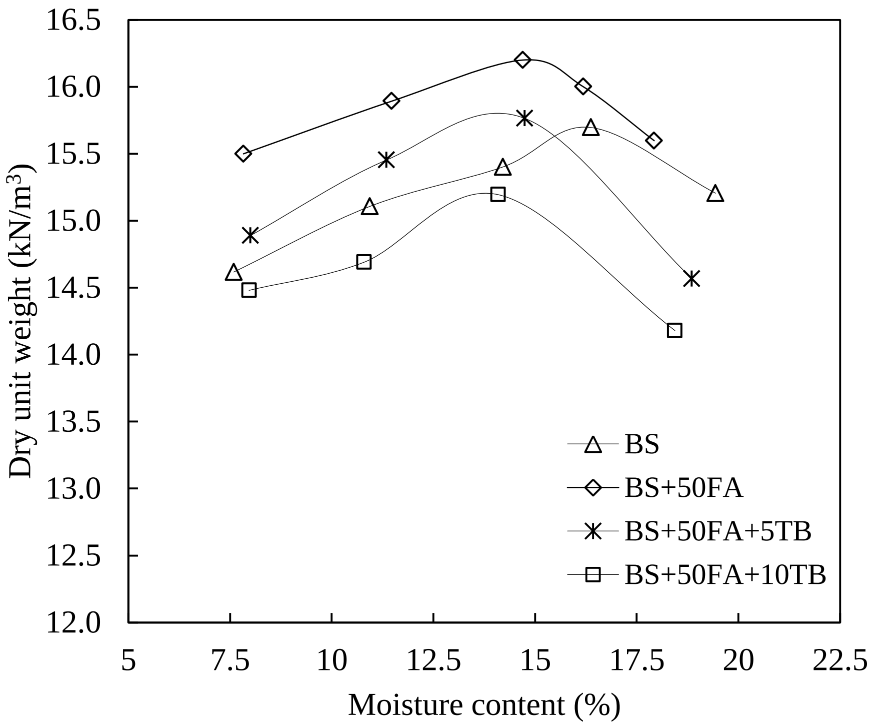


Fig. 4.15 Compaction curves of BS+50FA+TB mixes

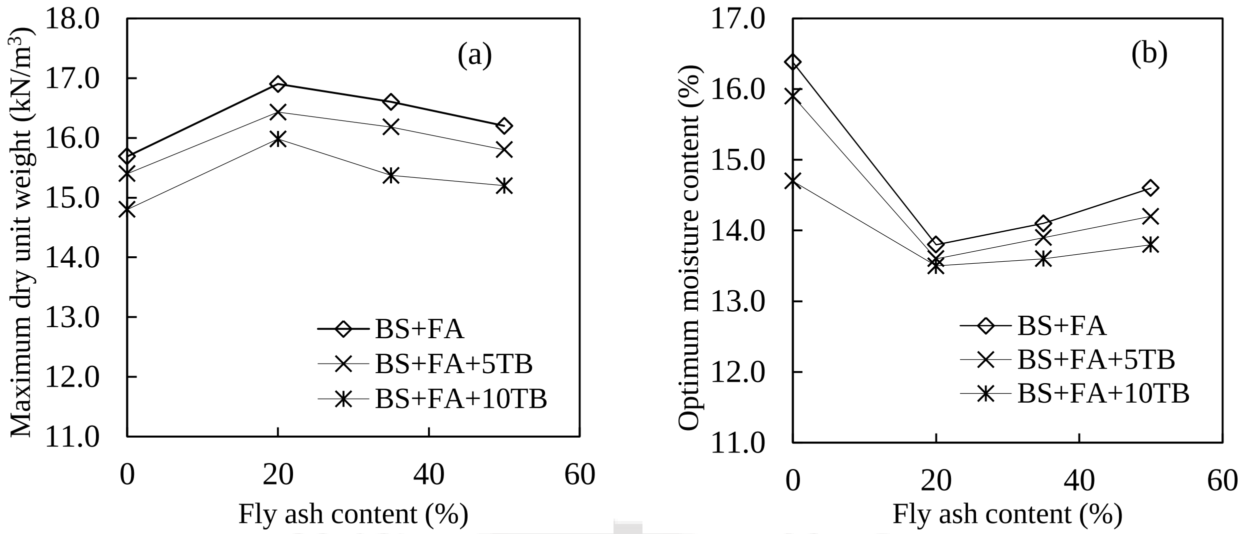


Fig. 4.16 Effect of fly ash and tyre buffing on (a) MDU and (b) OMC of various BS+FA mixes

Table 4.3: Experimental compaction results of various sand mixes

Mix	**MDU (kN/m^3)**	**OMC (%)**
BS	15.69	16.38
FA	13.60	19.30
BS+20FA	16.90	13.81
BS+35FA	16.60	14.10
BS+50FA	16.20	14.60
BS+5TB	15.40	15.90
BS+10TB	14.80	14.70
BS+20FA+5TB	16.43	13.60
BS+20FA+10TB	15.98	13.50
BS+35FA+5TB	16.18	13.90
BS+35FA+10TB	15.37	13.60
BS+50FA+5TB	15.80	14.20
BS+50FA+10TB	15.20	13.80

4.4 REGRESSION ANALYSIS

To investigate the effect of addition of fly ash and tyre buffings on compaction characteristics of soil specimens, multiple-regression statistical analysis was conducted based on the experimental results. In multiple regression analysis, the relationship between dependent and independent variables is presented as follows:

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_k x_{ik} \qquad \text{......(4.1)}$$

where,

$i = 1, 2, 3\ldots, n$ is the number of observations;

y_i = dependent variable;

$x_{i1}, x_{i2,\ldots,}x_{ik}$ = independent variables and

$\beta_0, \beta_1, \beta_2, \ldots, \beta_k$ = regression coefficients.

The different influencing parameters identified as independent variables in the model are fly ash content (FA) and tyre buffing content (TB). The effect of these parameters on MDU of different RS specimens (MDU_{RS}) have been evaluated by the following regression model,

$$MDU_{RS} = 16.44 - 0.014(FA) - 0.085(TB) \qquad \text{......(4.2)}$$

The model developed to investigate the effects of different parameters as mentioned above on MDU different BS specimens (MDU_{BS}) is as follows:

$$MDU_{BS} = 15.81 + 0.072(FA) - 0.057(TB) - 0.0013(FA)^2 - 0.0044\,(TB)^2 \qquad \text{......(4.3)}$$

The respective values of R^2 for equations 4.2 and 4.3 are 0.9227 and 0.9301 respectively. It is observed that the equations 4.2 and 4.3 obtained by regression analysis indicate the goodness of fit to the data. Hence, it can be stated that the relationship between the MDU and other influencing parameters can be well explained by those regression equations and prediction of MDU can be made.

4.5 CONCLUDING REMARKS

It is evident that when fly ash is added to red soil, the MDU decreases with increase in fly ash content in the mixes due to the lower specific gravity of the fly ash particles. Addition of fly ash to sand initially fills up the voids between the sand particles which results in greater value of MDU than the BS mix and hence addition of 20% fly ash to sand increases the MDU values of the mixes. Further increase in fly ash content reduces the MDU values of the sand-fly ash mixes, which is attributed to the lower specific gravity of the ash particles. The MDU values of red soil-fly ash mixes are lower than the corresponding MDU values of sand-fly ash mixes. However, the OMC values of red soil-fly ash mixes are higher than that of sand-fly ash mixes at the same fly ash content. Addition of tyre buffings to soil alone or soil-fly ash mixes reduces the MDU of the mixes. This is due to the lower specific gravity of tyre buffings compared to soil and fly ash. As the fly ash content of RS+FA+TB increases, the MDU of the mixes decreases. But increase in MDU of BS+FA+TB mixes is observed up to 20% fly ash addition, further addition of fly ash to BS+FA+TB reduces the MDU. The variation of particle size distribution in the fine grained and sand influences the maximum dry unit weight of different soil mixes. The water absorption capacity of tyre buffings is lower as compared to soil and fly ash particles, which results in reduction in OMC of soil alone and soil-fly ash mixes with the addition of tyre buffings to the mix.

CHAPTER - 5
UNCONFINED COMPRESSION CHERACTERISTICS

5.1 INTRODUCTION

The compressive strength of a soil is an important factor in evaluating the suitability criteria for use as a construction material. Although the test conditions do not simulate actual field conditions, the test results can be used for cases of low confinement. Many early researchers (Sezer et al., 2006; Akbulut et al., 2007; Hazarika et al., 2010; Tabbaa et al., 2010; Guleria and Dutta, 2011; Promputthangkoon and Karnchanachetanee, 2013) have studied the compressive strength of soil or fly ash treated soils with or without scrap tyre derived material using unconfined compression tests and have found the method to be quick and convenient for studying the strength of these materials.

The literature review indicates that the variation of strength development of amended and tyre added soils depends on several factors including: type of soil, type of fly ash, amount of replacement of soil with fly ash, amount and size of scrap tyre derived material added to soil mix and curing environment etc. Several series of unconfined compression tests were carried out on the soil, fly ash and their various mix proportions with and without tyre buffing in order to examine the effect of different fractions on the material behaviour particularly the stress-strain response, stiffness, ductility, and peak strength with curing.

5.2 TEST PROGRAMME

Table 5.1 summarizes the unconfined compression test programme to study the compressive strength of the soil, fly ash and different soil-fly ash-tyre buffing mixes. Due to some practical problem, specimens of BS alone and BS+TB mixes could not be prepared for curing periods of 3, 7, 14 and 28 days. A total of 195 compression tests were performed in the first test series for RS mixes only. In the second test series, BS mixes were subjected to 144 no of compression tests. Specimens were compressed until cracks have definitely developed or the stress-strain curve is well past its peak.

Table 5.1 Composition of various soil mixes for unconfined compression test

Soil	Fly ash	Soil-fly ash mixes	Soil-tyre buffing mixes	Soil-fly ash-cement mixes
RS	FA	RS+20FA	RS+5TB	RS+20FA+5TB
		RS+35FA	RS+10TB	RS+20FA+10TB
		RS+50FA		
				RS+35FA+5TB
				RS+35FA+10TB
				RS+50FA+5TB
				RS+50FA+10TB
BS		BS+20FA	BS+5TB	BS+20FA+5TB
		BS+35FA	BS+10TB	BS+20FA+10TB
		BS+50FA		
				BS+35FA+5TB
				BS+35FA+10TB
				BS+50FA+5TB
				BS+50FA+10TB

5.3 RESULTS AND DISCUSSION

In the first test series, compression tests were performed on red soil and different red soil-fly ash mixes. Tyre buffings were added to these mixes. Similarly 2nd series of compression tests were conducted on sand and sand-fly ash mixes initially after which tyre buffings were then added.

5.3.1 Compressive Strength of Red Soil-Fly Ash Mixes

Fig. 5.1 depicts the stress-strain behaviour of red soil and red soil-fly ash mixes for no curing and for 28 days curing, respectively. It is observed that addition of fly ash decreases the peak compressive stress as well as the stiffness of the mix. The influences of fly ash content and curing period on the unconfined compressive strength of red soil mixes are shown in Fig. 5.2(a). For any curing period, it is observed that addition of fly ash leads to decrease in compressive strength. It is due to the increase in non-cohesive fraction in the red soil-fly ash mixes. Lower maximum dry unit weight of red soil-fly ash mixes as compared to red soil alone mixes also contributes the reduction in compressive strength of RS+FA mixes. In all cases it is observed that as the curing period increases the UCS of mixes also increases. Investigations carried out by some earlier researchers also depict the same findings (Tonsend, 1985; Pandian, 2004; Kaniraj and Havanagi, 1999). RS+35FA mix shows an increase in compressive strength from 184 kPa to 368 kPa over a curing of 28 days. From Table 5.2, it is seen that for the same set of curing periods varied from 0 day to 28 days, the red soil and fly ash specimens show variation of UCS from 178 to 368 kPa and from 35 to 65 kPa, respectively. It is evident that as the fly ash content in mix increases, the non-cohesive fraction in the mix increases which reduces both the compressive strength of the mixes and the stiffness as well.

Fig. 5.2(b) shows the effect of fly ash addition on compressive strain at failure of red soil specimens. It is seen that as the fly ash content in RS+FA mixes increases the failure strain deceases; it is also evident from Table 5.2. Curing periods also influences the failure strain of different specimens. Clear crack patterns at failure are observed in RS+FA mixes as shown in Table 5.3.

Sezer et al. (2006) investigated the strength characteristics of soil-fly ash mixtures. A clayey soil of high plasticity was used in their study, and 0%, 5%, 10%, 15%

and 20% by weight of the soil was replaced with high lime fly ash. They found that addition of fly ash content up to 15% significantly increased the unconfined compressive strength of the soil. Increasing fly ash substitution level to 20% has a negligible effect on UCS as compared to that of the 15% fly ash content. Increase in unconfined compressive strength is observed up to 28 days curing, beyond that there is no appreciable increase in strength. They attributed this effect to the increase in cohesion of the soil upon pozzolanic action of very fine fly ash particles and its self-hardening effect related to the presence of free lime.

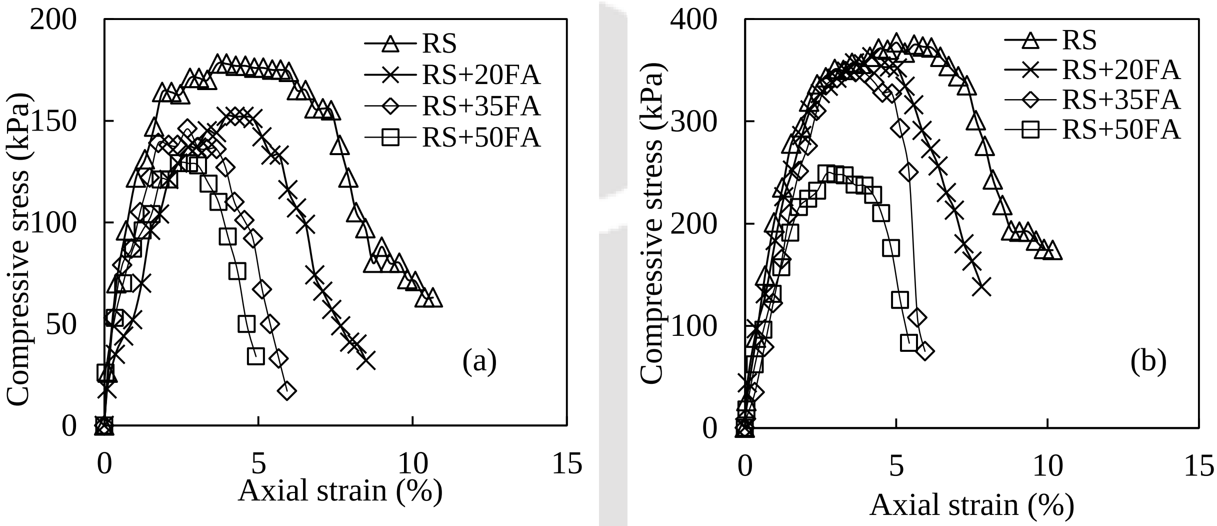


Fig. 5.1 Stress-strain behaviour of RS+FA for (a) 0 Day and (b) 28 days curing period

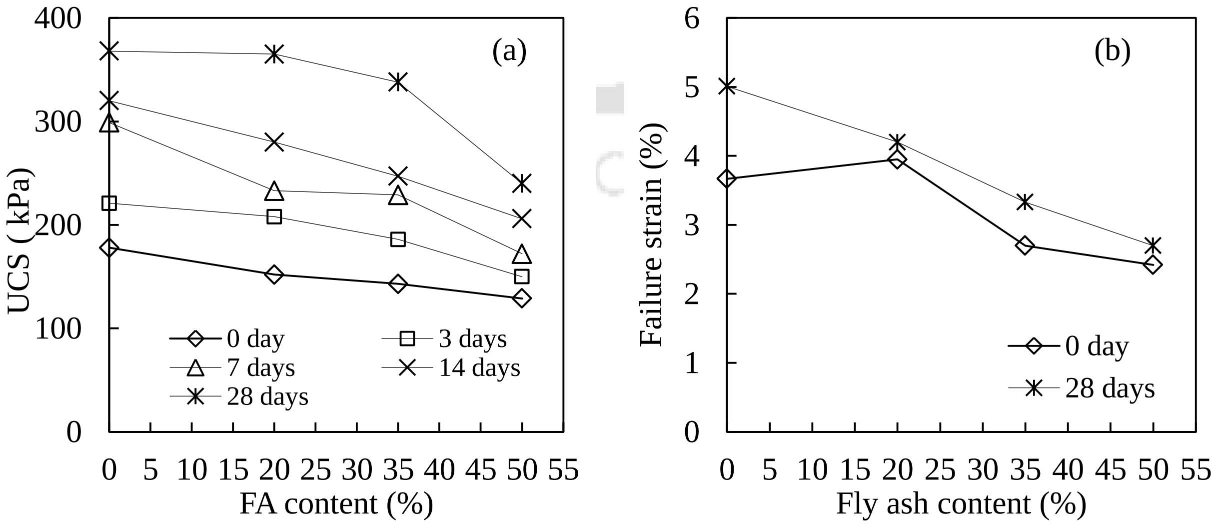


Fig. 5.2 Effect of fly ash content on (a) UCS and (b) failure strain of red soil mixes at

different curing periods

5.3.2 Compressive Strength of Red Soil-Tyre Buffing Mixes

The stress-strain plots of RS+TB mixes have been shown in Fig. 5.3. Addition of tyre buffing to red soil leads to decrease in both the compressive strength and stiffness. The influences of tyre buffing content and curing period on the unconfined compressive strength of red soil mixes are shown in Figs. 5.4(a). It can be seen that addition of tyre buffings to red soil decreases the compressive strength. However increase in curing period increases the UCS of RS+TB mixes. Fig. 5.4(b) shows that addition of tyre buffing content generally increases the failure strain. This kind of behaviour is attributed to the flexible nature of tyre buffings.

Reduction of unconfined compressive strength of a clayey soil due to inclusion of tyres is also observed by Tabba et al. (2010). Ajmera et al. (2017) also reported that unconfined compressive strength of soil decreased when more than 4% tyre crumb was added to fine-grained soil. The shredded tyre used in their study was sieved into three groups: 1-4 mm, 4-8 mm and 8-12 mm and mixed with the soil in the percentages ranging from 2% to 20% by weight. Stiffness of the mixes also decreases with the inclusion of tyre buffings. Red soil-tyre buffing specimens fail at larger strain than red soil alone specimen and it is evident from Table 5.2. Table 5.3 shows the failure patterns of RS+TB mixes. Irregular crack patterns are observed in specimens. Before the test, the surface of the specimens is almost smooth.

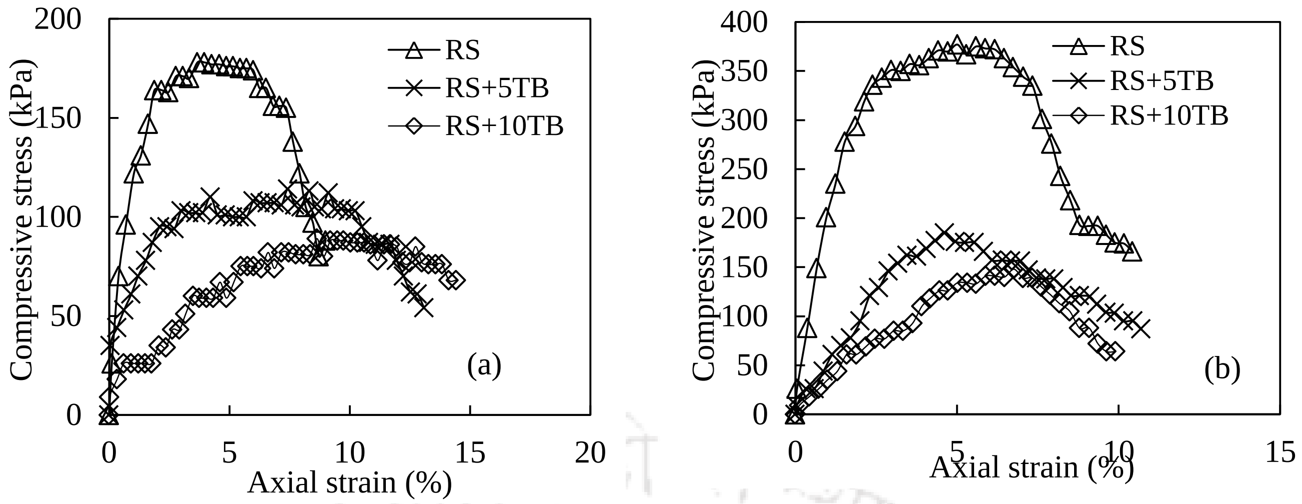


Fig. 5.3 Stress-strain plots of RS+TB mixes for (a) 0 Day and (b) 28 days curing periods

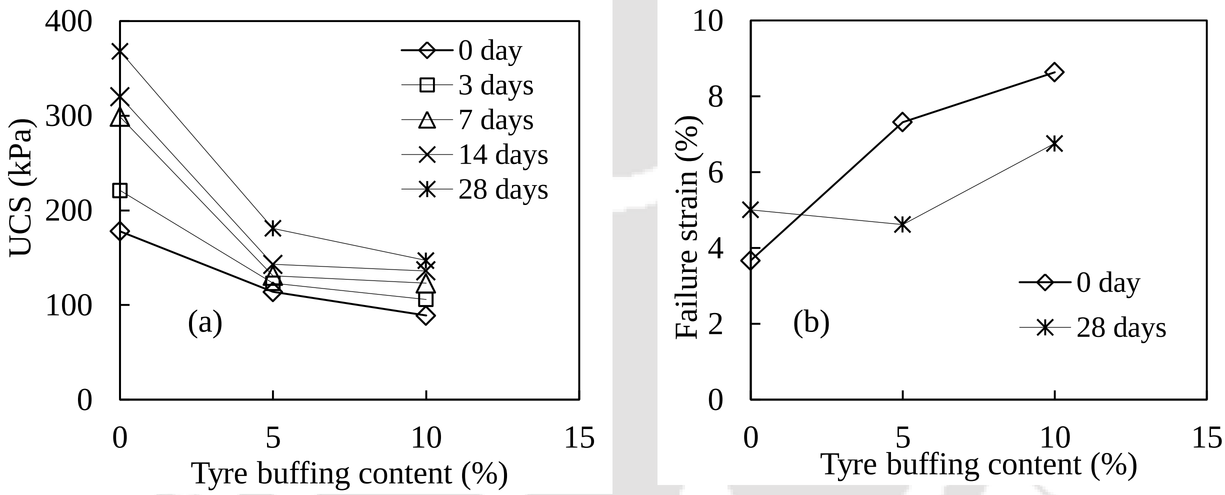


Fig. 5.4 Effect of tyre buffing content on (a) UCS and (b) failure strain of red soil mixes at different curing periods

5.3.3 Compressive Strength of Red Soil-Fly Ash-Tyre Buffing Mixes

From the stress-strain plots shown in Figs. 5.5 to 5.6 it is seen that inclusion of tyre buffing to RS+FA mixes decreases the peak compressive stress of the mixes. This kind of observation can also be made from Table 5.2. Further decrease in UCS is observed as the TB content in RS+FA+TB mixes increases. Addition of tyre buffing to soil-fly ash mixes also decreases the stiffness. Fig. 5.7 depicts that increase in tyre buffing content in RS+FA+TB mixes decreases the compressive strength. The decrease in compressive strength can be due to the inclusion of weaker material like tyre buffings which resembles the findings of Hazarika et al. (2010) and Guleria and Dutta (2011). In previous investigation it was also found that reduction in UCS could be caused by the entrapping of air by the increased tyre buffing content (Guleria and Dutta 2011), therefore possibility of weak tyre buffing-soil interface can also be the reason of reduction in compressive strength. It is also evident that increase in percentages of fly ash in RS+FA+TB mixes shows decrease in UCS. As such RS+20FA+5TB mixes show highest compressive strength than any other RS+FA+TB mixes. Curing has been found to be effective as per as gain in compressive strength is concerned. With the increase in curing period the UCS values of RS+FA+TB mixes are also increased. This may be due to the time dependent pozzolanic reaction that has occurred within the specimen.

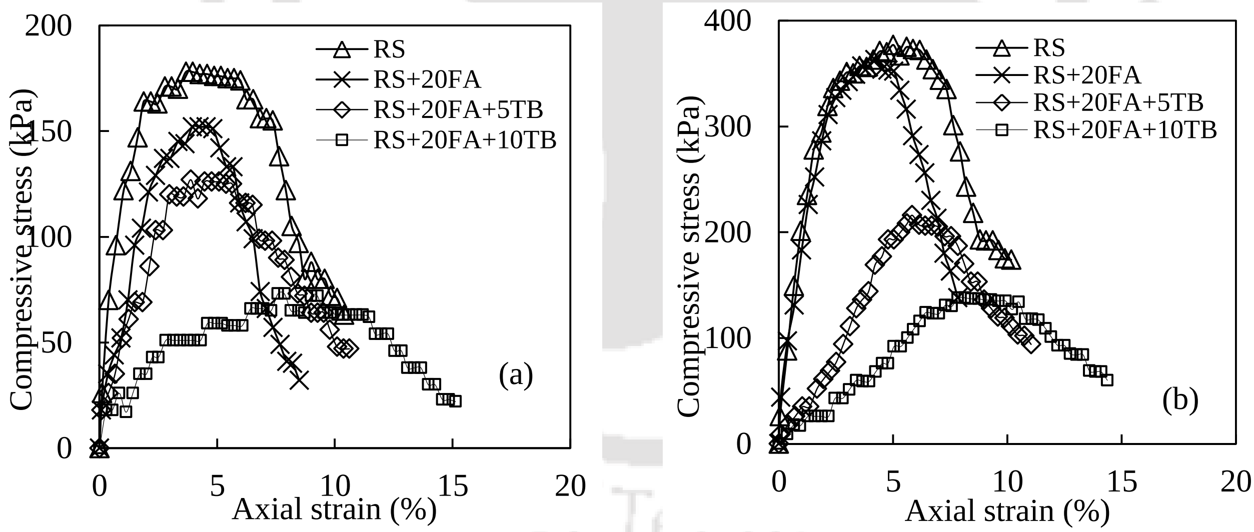


Fig. 5.5 Stress-strain plots of RS+20FA+TB mixes for (a) 0 day and (b) 28 days curing period

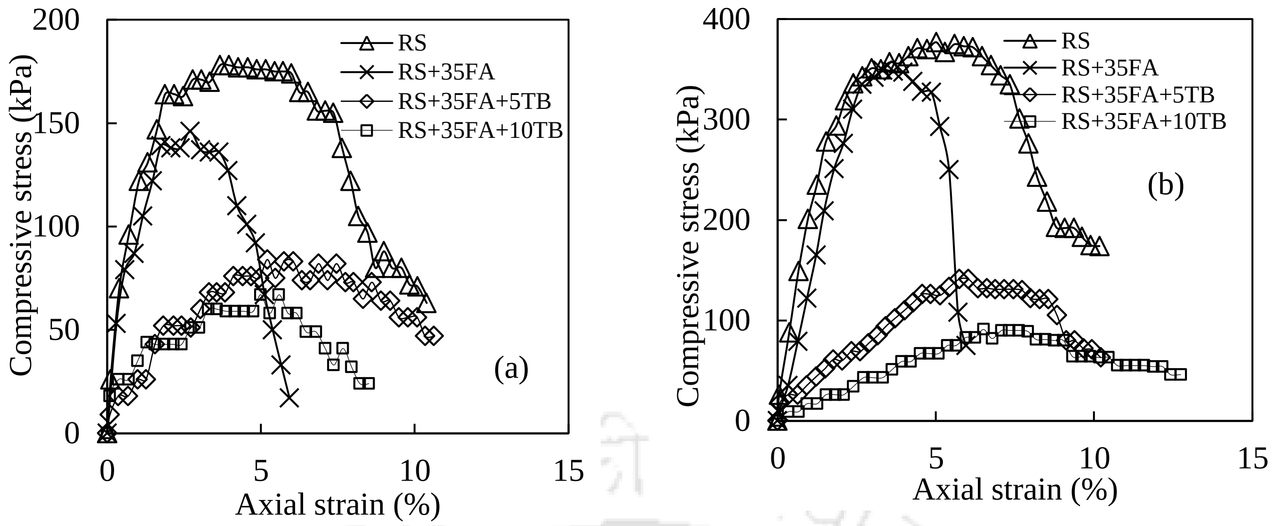


Fig. 5.6 Stress-strain plots of RS+35FA+TB mixes for (a) 0 day and (b) 28 days curing period

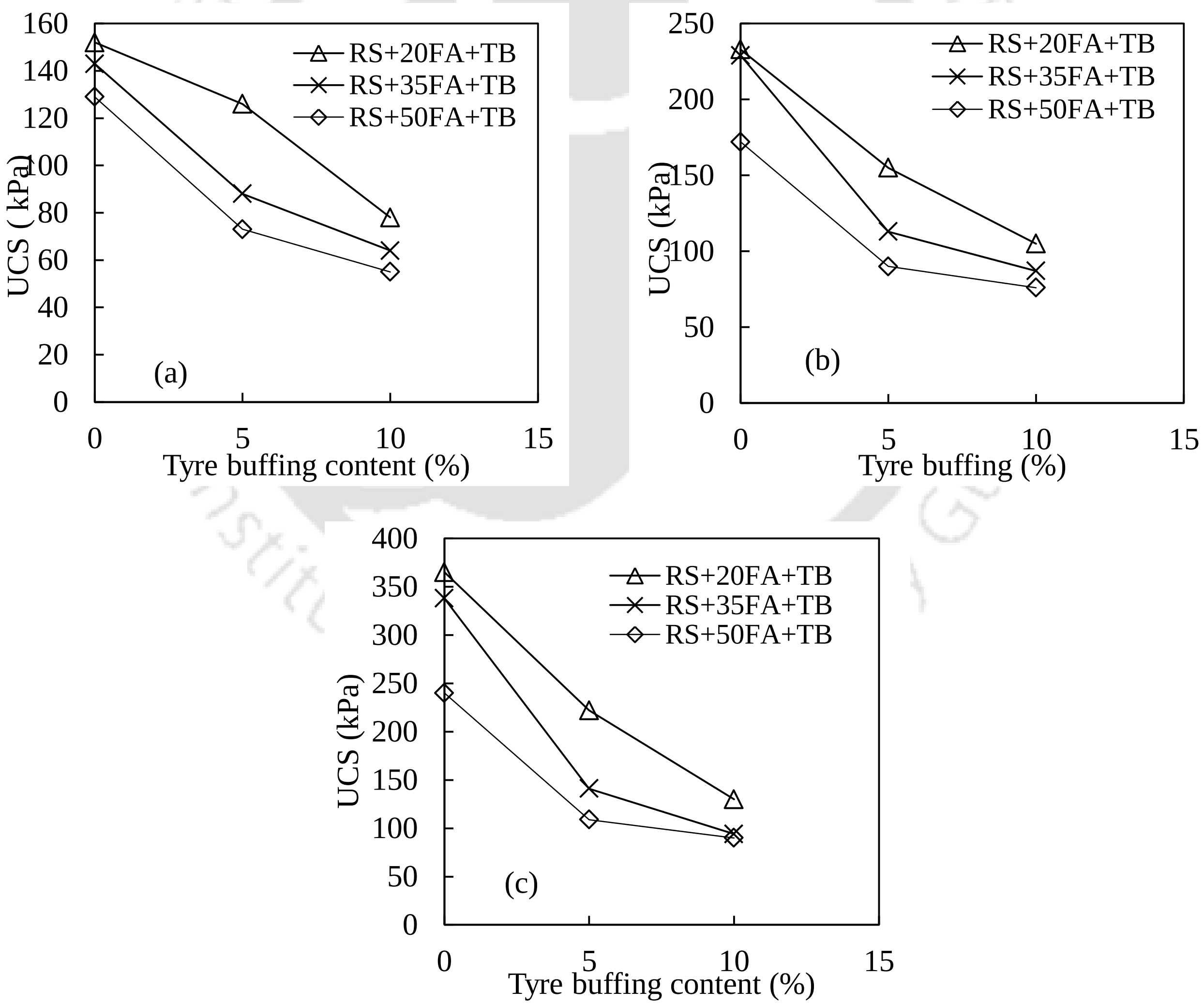


Fig. 5.7 Effect of tyre buffing content on UCS of RS+FA+TB mixes for (a) 0 Day; (b) 7 Days and (c) 28 Days curing period

Effect of tyre buffing content on failure strain of RS+FA+TB mixes is shown in Fig. 5.8. From these Figs. and Table 5.2 it is found that inclusion of tyre buffings to specimens results in failure at larger strain when compared to RS+FA mixes. It states that replacement of soil by TB which is an elastic material imparts ductility to soil or soil-fly ash mixes.

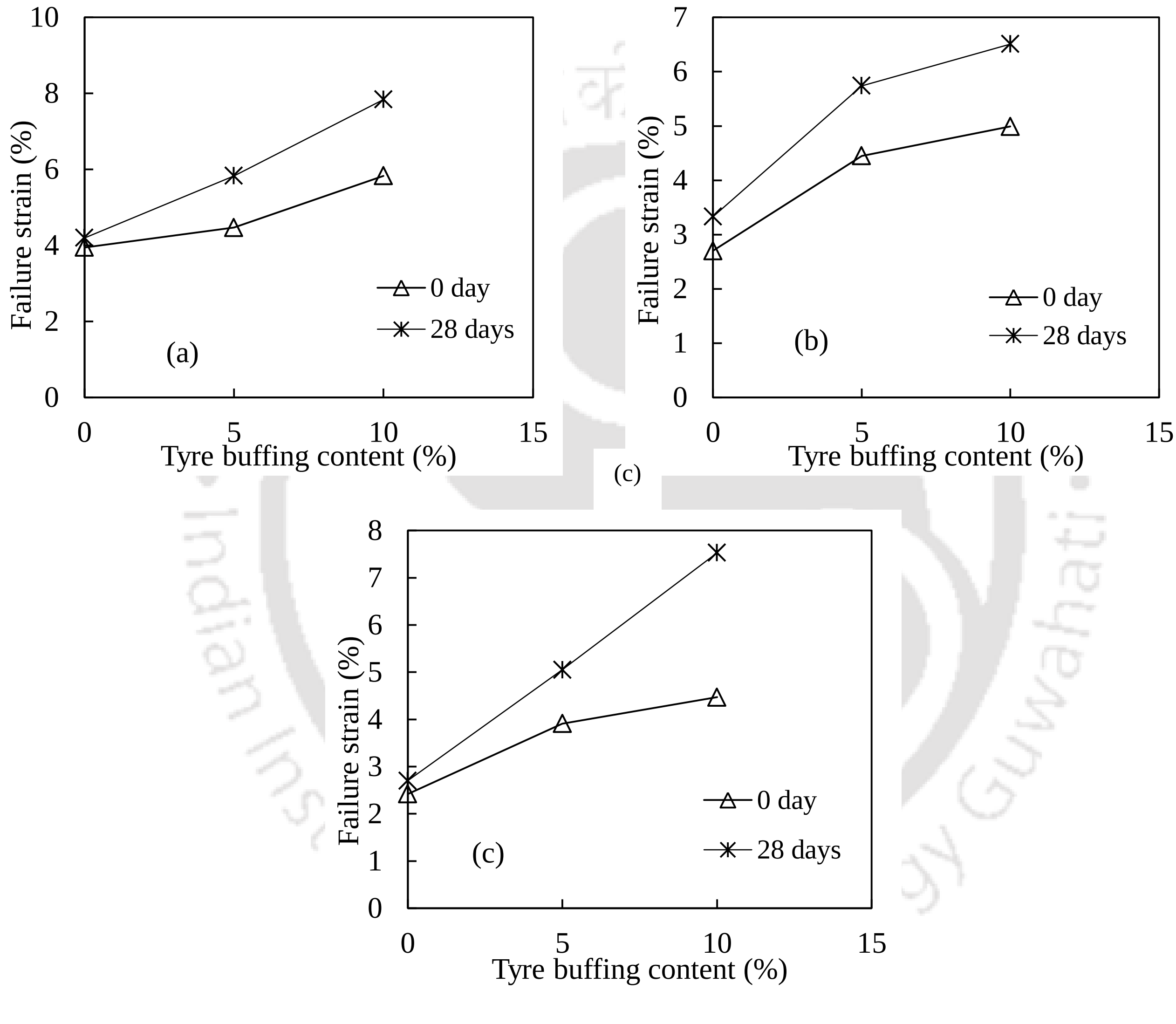


Fig. 5.8 Effect of tyre buffing content on failure strain of (a) RS+20FA+TB; (b) RS+35FA+TB and (c) RS+50FA+TB mixes

Table 5.3 shows failure patterns of UC test specimens for soil with 5% and 10% TB contents. Before conducting the tests, surface of the specimens was smooth. Clear crack patterns at failure are observed in RS+FA+5TB specimen, and generally the cracks are vertical. In RS+FA+10TB specimen cracks are distinguishable but irregular.

Table 5.2: Average unconfined compressive strength and failure strain of various red soil mixes

Mixtures	Curing period (Days)									
	0 Day		3 Days		7 Days		14 Days		28 Days	
	UCS (kPa)	Strain (%)	UCS (kPa)	Strain (%)	UCS (kPa)	Strain (%)	UCS (kPa)	Strain (%)	UCS (kPa)	Strain (%)
RS	178	3.67	221	3.33	299	3.07	320	3.11	368	5.01
FA	35	0.54	40	1.07	44	0.97	48	0.97	65	1.13
RS+20FA	152	3.95	208	1.83	233	2.3	280	2.75	365	4.2
RS+35FA	143	2.7	186	4.14	229	3.86	247	4.83	338	3.33
RS+50FA	129	2.42	150	2.75	172	2.39	206	2.21	240	2.7
RS+5TB	114	7.32	123	6.75	131	7.2	143	6.8	181	4.62
RS+10TB	89	8.64	106	8.14	123	7.17	136	8.74	147	6.76
RS+20FA+5TB	126	4.47	130	5.2	155	4.93	162	5.16	222	5.83
RS+20FA+10TB	78	5.83	101	7.53	105	6.41	125	6.32	130	7.84
RS+35FA+5TB	88	5.21	109	4.75	113	5.25	131	6.12	141	5.74
RS+35FA+10TB	64	4.99	82	7.41	87	6.99	88	8.97	90	6.51
RS+50FA+5TB	73	5.79	84	4.39	90	5.00	105	5.12	109	5.05
RS+50FA+10TB	55	4.76	70	5.41	76	4.47	80	5.74	94	7.53

Table 5.3: Failure patterns of red soil specimens tested in unconfined compression tests

		Curing period				
Mix	Before Test	0 day	3 days	7 days	14 days	28 days
RS						
RS+20FA						

RS+35FA						
RS+50FA						
RS+5TB						

RS+10TB						
RS+20FA+5TB						
RS+20FA+10TB						

RS+35FA+5TB						
RS+35FA+10TB						
RS+50FA+5TB						

RS+50FA+10TB						

5.3.4 Compressive Strength of Sand-Fly Ash Mixes

Fig. 5.9 depicts the influence of fly ash addition on the stress-strain plots of sand. Sand-fly ash mixes show greater strength than sand alone mixes. Moreover addition of fly ash to sand increases the stiffness of the mix. Table 5.4 also depicts that increase in percentages of fly ash content increases the UCS of the sand-fly ash mixes. It was observed that the addition of fly ash to sand led to an improvement in compressive strength. It is due to the creation of denser packing of different particles within the specimen which is evident from compaction results in Table 4.3 of Chapter 4.

Figs. 5.10(a) shows that addition of fly ash to sand increases the UCS and it goes on increasing as curing period increases. For example with no curing period, the sand and sand-50% fly ash specimens show increase of UCS from 6.36 to 24.29 kPa and finally, reaches a UCS value of 69.74 kPa at 28 days curing period. This is due to the occurrence of time-dependent pozzolanic reactions which resembles with previous findings by Kaniraj and Havanagi 1999 and Yilmiz 2015. This kind of behaviour is contrary to the results found in case of RS mixes.

Generally, as shown in Table 5.4 and Fig. 5.10(b), increase in fly ash content to sand causes the specimen to fail in lower axial strain. Curing periods were also found to be effective in reducing the failure strain of mixes. Table 5.5 shows that failure pattern of UC test specimens for sand-fly ash mixes are distinct which is clearly shown in BS+50FA mix.

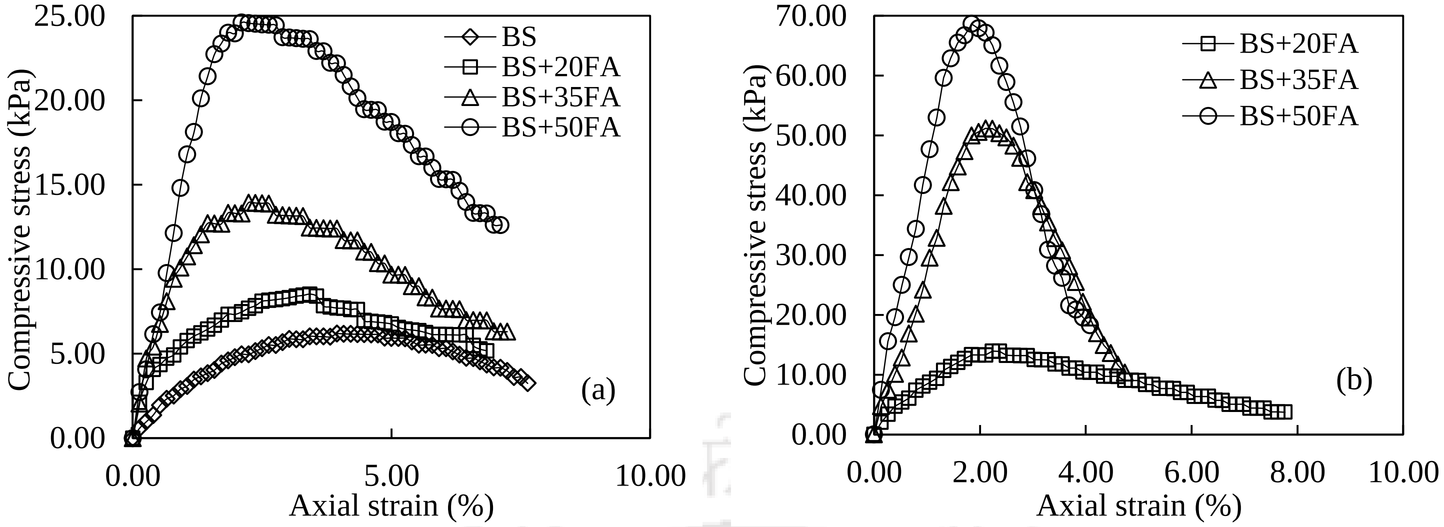


Fig. 5.9 Stress-strain plots of sand and BS+FA mixes for (a) 0 day and (b) 28 days curing period

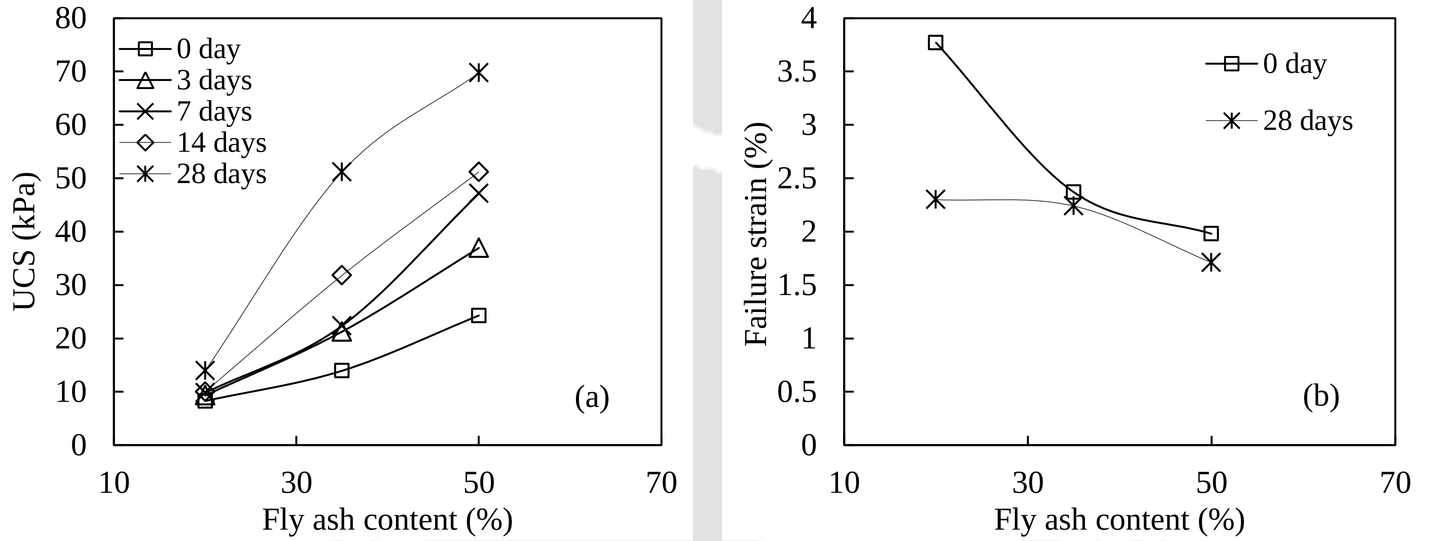


Fig. 5.10 Effect of fly ash content on (a) UCS and (b) failure strain of BS+FA mixes at different curing periods

5.3.5 Compressive Strength of Sand-Tyre Buffing Mixes

From Table 5.4 and Fig. 5.11 it is seen that inclusion of tyre buffing to sand decreases the UCS of the mixes, the decrease is more as the content of TB increases from 5% to 10%. As tyre buffing is a weak material, therefore inclusion of TB to sand reduces the strength of BS+TB mixes which is also depicted in Fig. 5.12(a). From Fig. 5.12(b) it can be seen that addition of tyre buffing beyond 5% makes the specimens to fail in lower strain.

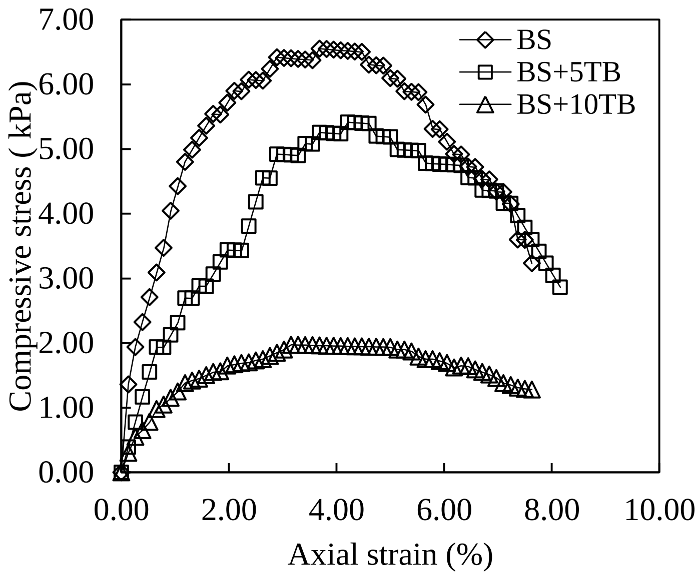


Fig. 5.11 Stress-strain plots of sand and BS+TB mixes for 0 day curing period

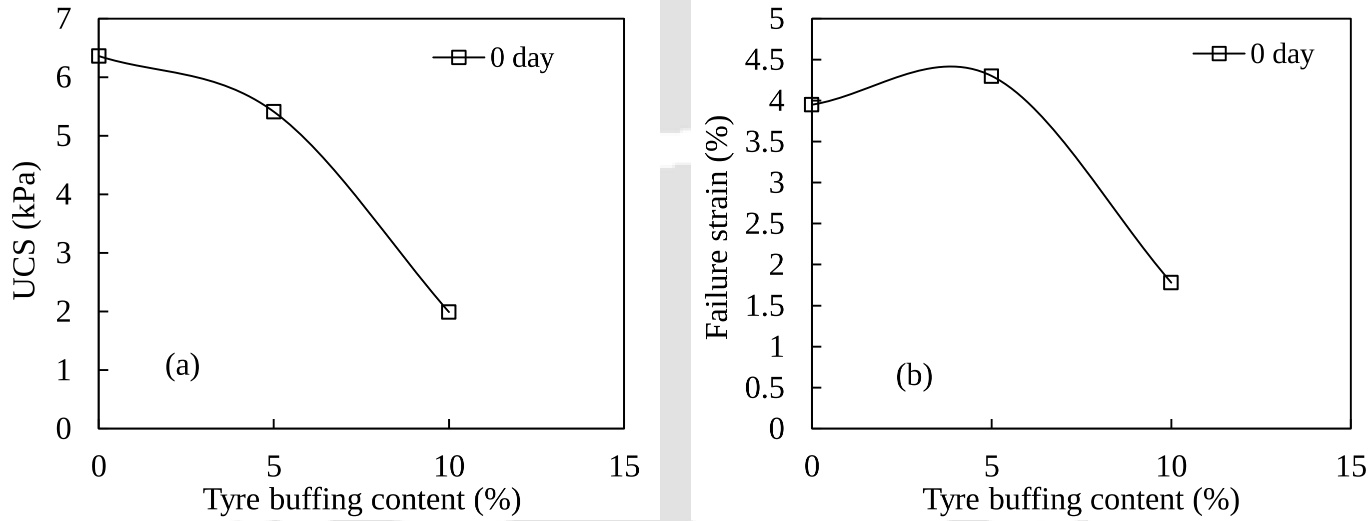


Fig. 5.12 Effect of tyre buffings on (a) UCS and (b) failure strain at 0 day curing period

5.3.6 Compressive Strength of Sand-Fly Ash-Tyre Buffing Mixes

Figs. 5.13 and 5.14 show the stress-strain plots of different sand-fly ash-tyre buffing mixes. In all cases inclusion of tyre buffings shows reduction in peak compressive stress and stiffness as well. From Fig. 5.15 and Table 5.4 it is clearly seen that compressive strength of BS+FA+TB mixes decreases with the increase in tyre buffing content. This decrease in UCS is caused by the entrapping of air by the increased tyre buffing content, and the soft particle like behaviour of the tire buffing. However, improvement in UCS of BS+FA+TB mixes occurs with the increase in percentage of fly ash mixes. Increase in FA content in BS+FA+TB mixes makes the internal structure of composite matrix a more dense state than the sand alone mixes. It results in gain in UCS of mixes. Yilmiz (2015) also reported similar kind of findings. It is also observed that increase in curing period causes increase in UCS of the mixes. BS+50FA+5TB mixes show highest UCS value than any other BS+FA+TB mixes.

It is evident from Table 5.4 and Fig. 5.16 that addition of tyre buffings to sand-fly ash mixes causes the specimen to fail in larger strain. It states that replacement of soil by TB which is an elastic material reduces the brittle behaviour of soil-fly ash mixes.

Table 5.5 shows the failure pattern of different BS+FA+TB mixes for different curing periods. It has been found that increase in percentages of tyre buffing in mixes changes the failure pattern of specimens.

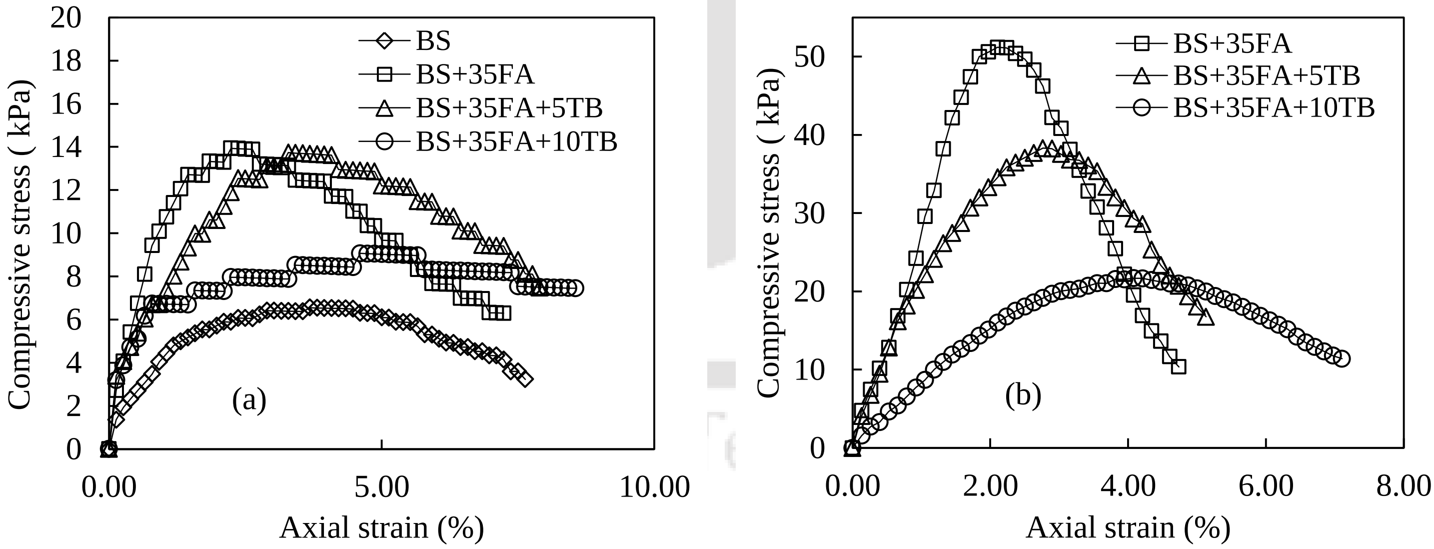


Fig. 5.13 Stress-strain plots of sand and BS+35FA+TB mixes for (a) 0 day and (b) 28 days curing period

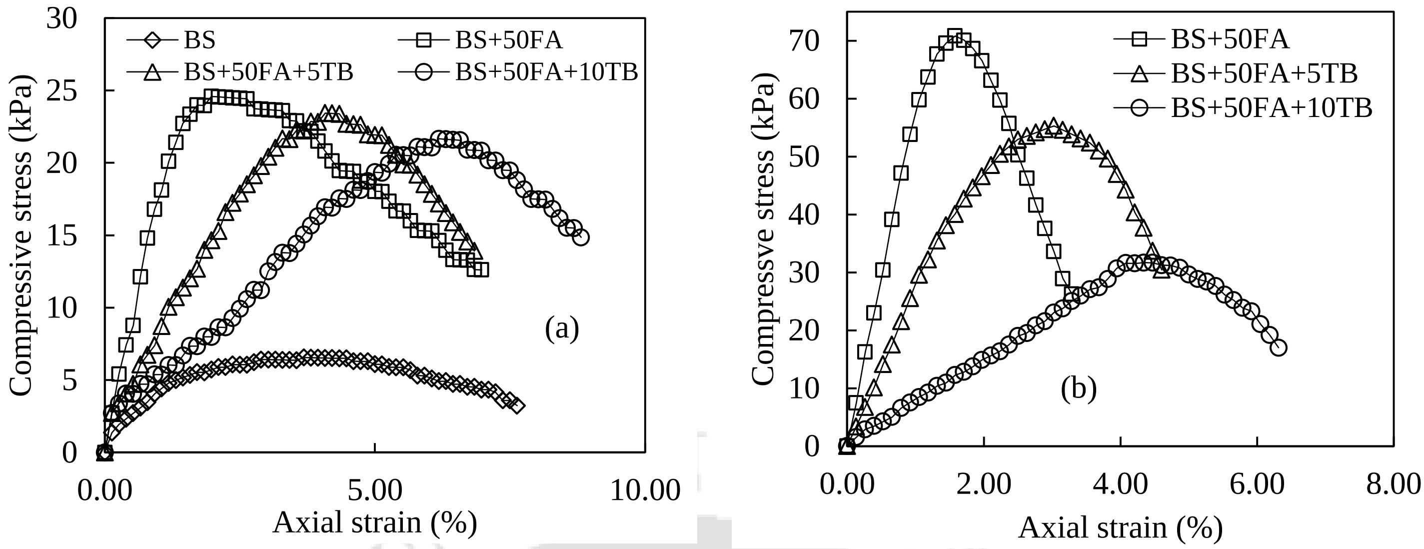
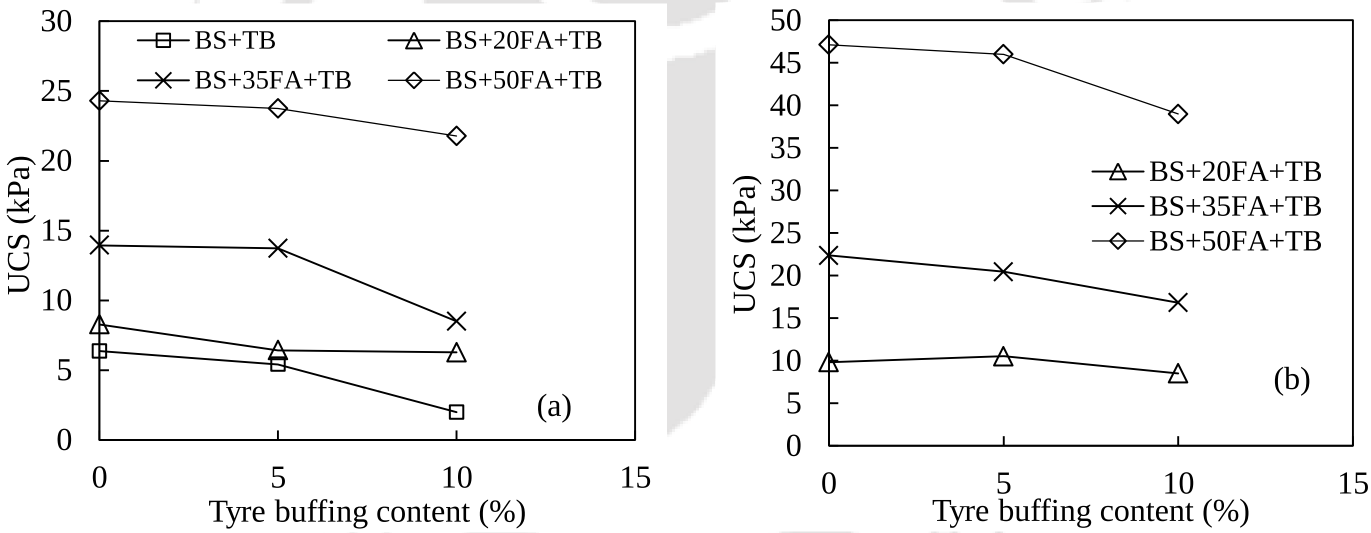


Fig. 5.14 Stress-strain plots of sand and BS+50FA+TB mixes for (a) 0 day and (b) 28 days curing period



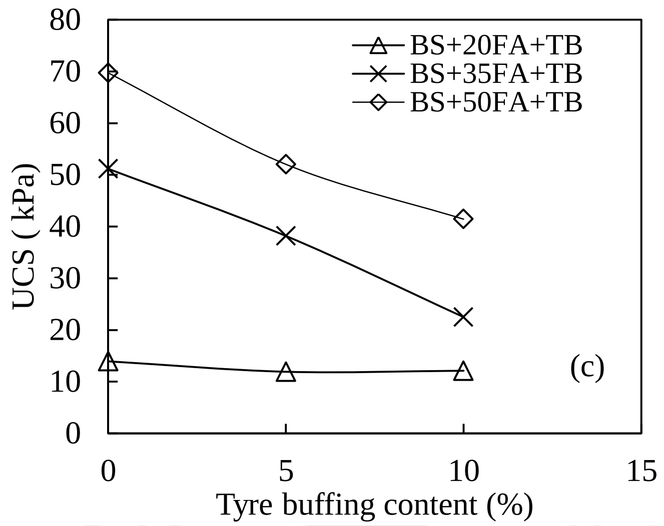


Fig. 5.15 Effect of tyre buffings and fly ash content on UCS of BS+FA+TB mixes for (a) 0 day, (b) 7 days and (c) 28 days curing period

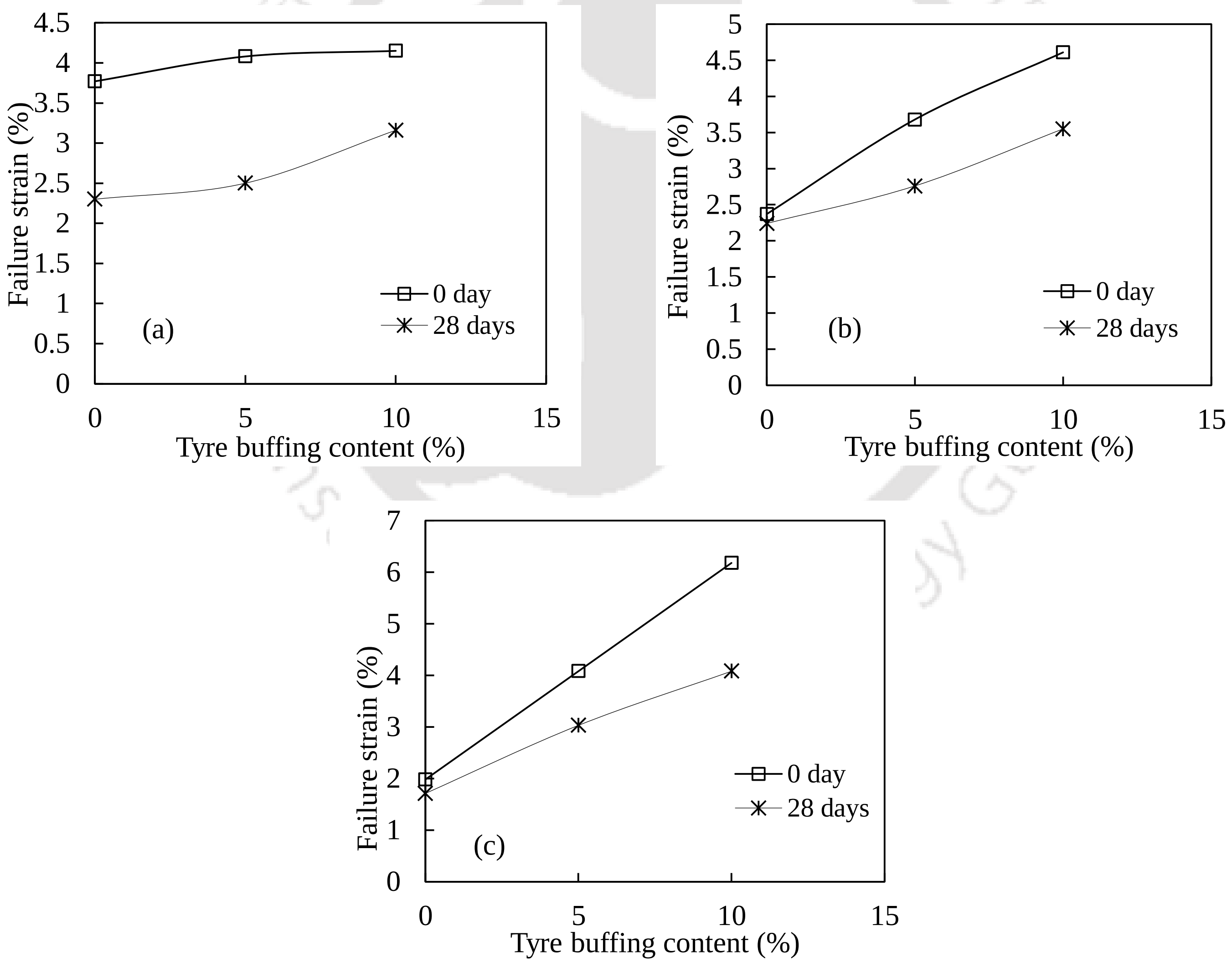


Fig. 5.16 Effect of tyre buffings on failure strain of (a) BS+20FA+TB, (b) BS+35FA+TB and (c) BS+50FA+TB mixes at different curing period

Table 5.4: Average unconfined compressive strength and failure strain of various sand mixes

Mixtures	Curing period (Days)									
	0 Day		3 Days		7 Days		14 Days		28 Days	
	UCS (kPa)	Strain (%)	UCS (kPa)	Strain (%)	UCS (kPa)	Strain (%)	UCS (kPa)	Strain (%)	UCS (kPa)	Strain (%)
BS	6.36	3.95								
FA	35	0.42	40	0.81	44	0.82	48	1.2	65	1.76
BS+20FA	8.28	3.77	9.31	2.57	9.81	1.51	10.01	1.71	13.94	2.3
BS+35FA	13.94	2.37	21.27	2.19	22.36	1.71	31.8	1.75	51.18	2.24
BS+50FA	24.29	1.98	36.95	2.24	47.13	2.3	51.17	1.93	69.74	1.71
BS+5TB	5.41	4.3								
BS+10TB	1.99	1.78								
BS+20FA+5TB	6.42	4.08	7.88	2.96	10.51	3.29	11.24	3.07	11.92	2.5
BS+20FA+10TB	6.27	4.15	7.53	3.16	8.5	3.77	9.1	4.34	12.12	3.16
BS+35FA+5TB	13.73	3.68	19.65	3.55	20.44	3.29	27	2.89	38.19	2.76
BS+35FA+10TB	8.5	4.61	12.61	4.47	16.81	3.29	17.93	3.42	22.5	3.55
BS+50FA+5TB	23.74	4.08	27.89	4.21	41.04	3.55	46	3.29	52.05	3.03
BS+50FA+10TB	21.77	6.18	24.65	5.26	28.06	5	38.98	3.82	41.44	4.08

Table 5.5: Failure patterns of sand mixes tested in unconfined compression tests

		Curing period				
Mix	Before Test	0 day	3 days	7 days	14 days	28 days
BS						
BS+20FA						

BS+35FA						
BS+50FA						
BS+5TB						

BS+10TB						
BS+20FA+5TB						
BS+20FA+10TB						

BS+35FA+5TB						
BS+35FA+10TB						
BS+50FA+5TB						

BS+50FA+10TB						

5.3.7 Comparison Between Compressive Strength of Both Soil-Fly Ash Mixes

From Figs. 5.17(a) to (c) it is seen that inclusion of fly ash to soil mixes is effective only in case of sand mixes. But RS+FA mixes show higher compressive strength than their corresponding BS+FA mixes.

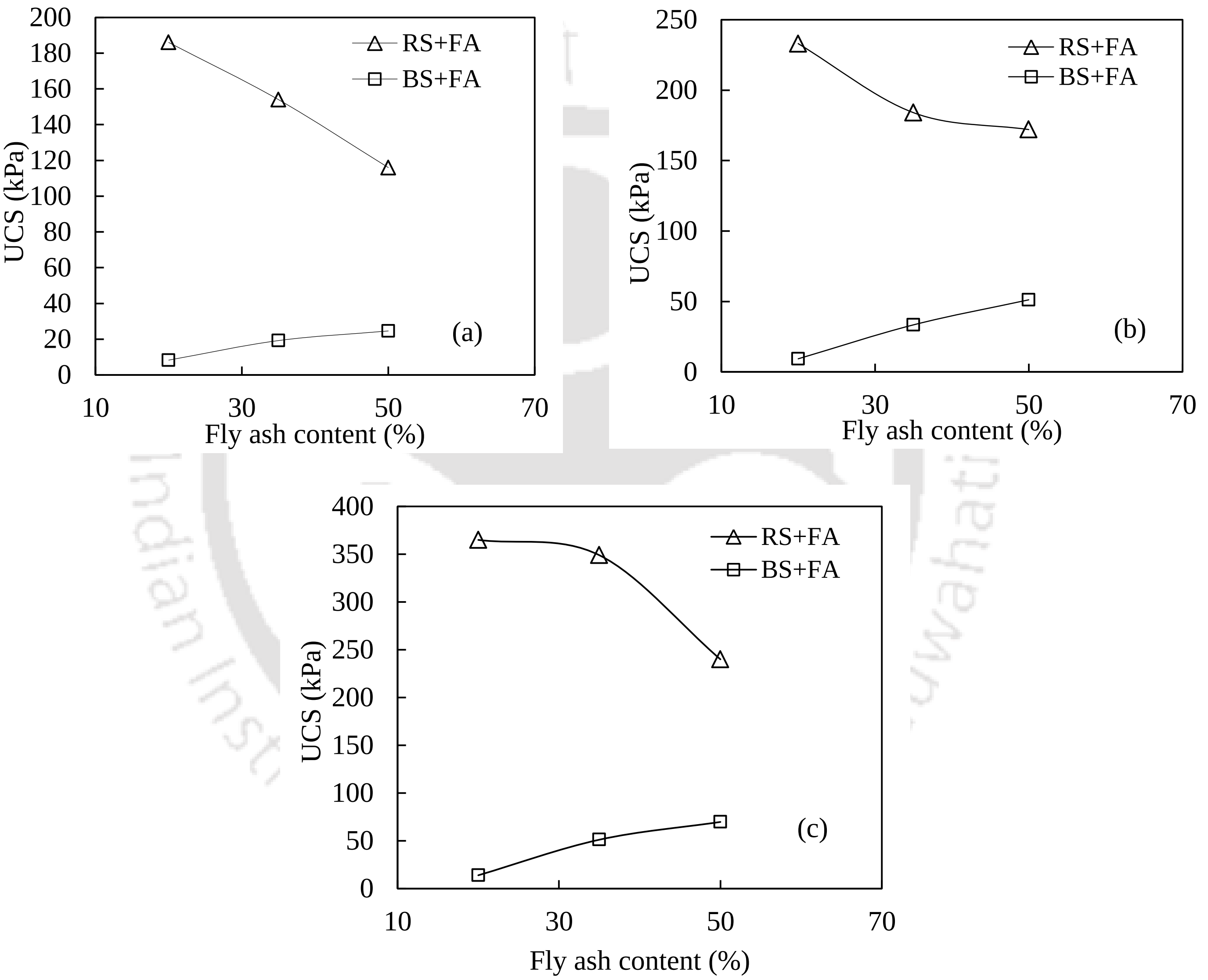


Fig. 5.17 Effect of fly ash content on UCS of BS+FA and RS+FA mixes for (a) 0 day, (b) 7 days and (c) 28 days curing periods

5.3.8 Comparison Between Compressive Strength of Both Soil-Tyre Buffing Mixes

From Fig. 5.18 it is seen that inclusion of tyre buffing to soil mixes, exhibits lower strength. But the reduction in compressive strength due to addition of tyre buffing is significantly less in sand mixes than red soil mixes.

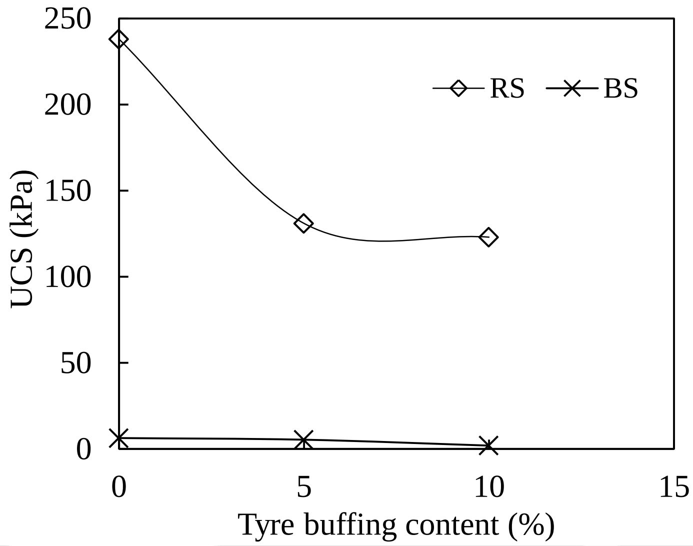


Fig. 5.18 Effect of tyre buffing content on UCS of BS and RS mixes for 0 days curing periods

5.3.9 Comparison Between Compressive Strength of Both Soil-Fly Ash-Tyre Buffing Mixes

From Figs. 5.19(a) to (c) it is seen that inclusion of tyre buffing to soil-fly ash mixes, exhibits lower strength. But the reduction in compressive strength due to addition of tyre buffing is significantly less in sand mixes than red soil mixes for all curing periods. The frictional component of the mixes plays important role in this case.

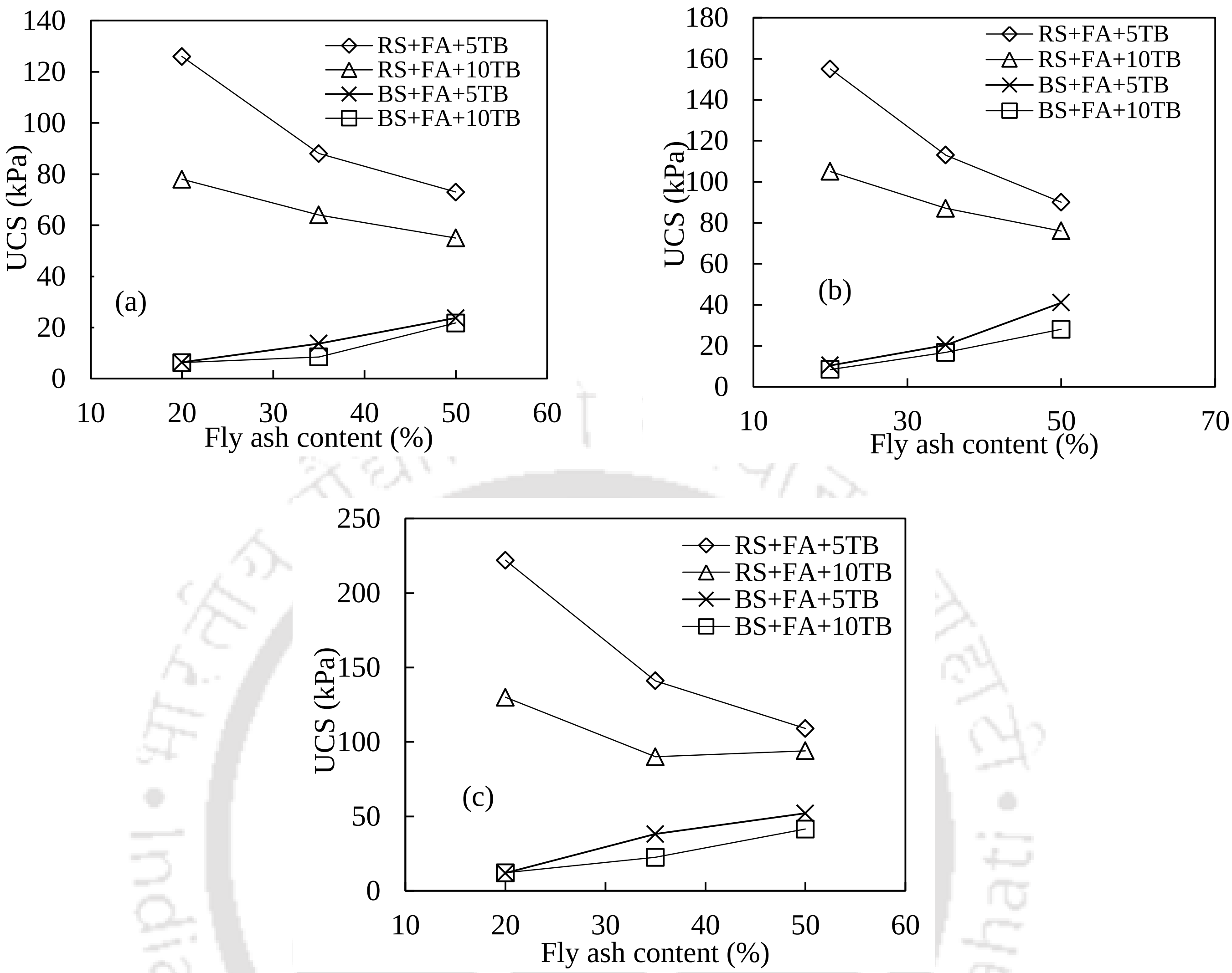


Fig. 5.19 Effect of fly ash content on UCS of BS+FA+TB and RS+FA +TB mixes for (a) 0 day, (b) 7 days and (c) 28 days curing periods

5.3.10 Effect of Fly Ash and Tyre Buffings on Strength Ratios of Different Soil Mixes

Yilmaz (2015) quantified the gain in UCS due to addition of fly ash as follows:

$$UCS^* = (UCS_{mix} - UCS_{soil}) / (UCS_{soil}) \times 100(\%) \quad (5.1)$$

where, UCS*= gain in UCS, %; UCS_{soil} = average UCS of the untreated soil; and UCS_{mix} = UCS of the mixture.

Similarly, a parameter called strength ratio (SR) is introduced to study the effect of fly ash and tyre buffings inclusion on UCS of soil. For red soil and sand mixes strength ratio is denoted by SR_{RS} and SR_{BS} respectively. Mathematically, it is expressed by the following equation:

$$SR = (UCS_{mix})/ (UCS_{soil}) \quad \ldots\ldots\ldots\ldots \quad (5.2)$$

where, UCS_{soil} = average UCS of the untreated soil; and UCS_{mix} = UCS of the mixture used in this study.

The effect of fly ash content, tyre buffings and curing period on strength ratio is depicted in Fig. 5.20 and it is certain that the variation of strength ratio is different for both the soil types. For all red soil mixes strength ratio values are smaller than 1.0 as shown in Fig. 5.20 (a). It indicates reduction in compressive strength of mixes due to the inclusion of fly ash and tyre buffings to red soil. Further decrease in UCS is observed as the fly ash and tyre buffing content in mixes increases. Marginal change in SR_{RS} is seen up to 14 days curing period. But SR_{RS} values at 28 days curing period is found to be smaller than SR_{RS} values at any other curing period.

From Fig. 5.20(b) it is seen that strength ratio values for sand mixes (SR_{BS}) are greater than 1.0 indicating improvement of UCS on addition of fly ash and tyre buffings. SR_{BS} value increases with the increase in both fly ash content and curing period. However reduction in SR_{BS} values are observed as the tyre buffing content in mixes increases. As such SR_{BS} values of sand-50% FA-5%TB mix at 28 days curing period are greater than any other values among sand-FA-TB mixes.

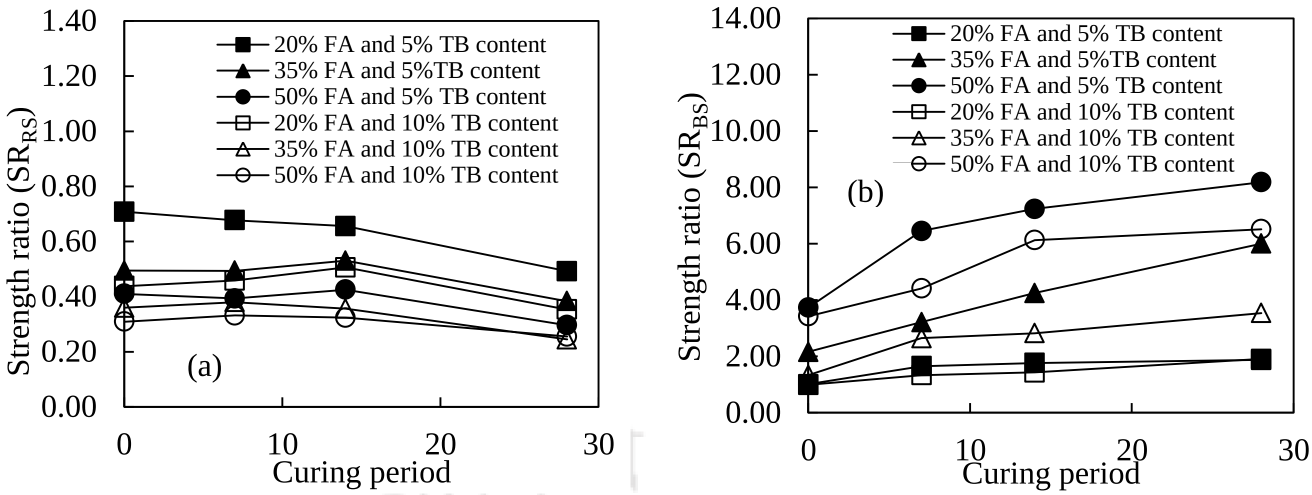


Fig. 5.20 Strength ratios for (a) RS and (b) BS mixes at different curing periods

5.3.11 Effect of Fly Ash and Tyre Buffings on Secant Elastic Modulus of Different Soil Mixes

Secant modulus of elasticity is used to characterize the stiffness of different soil mixes. The value is expressed as the secant modulus, E_{100} which was used by some previous researchers (N.Cristelo et al., 2015; and Patel and Singh 2017). Mathematically,

$$E_{100} = q_{100} / \epsilon_{100} \qquad (5.3)$$

where, q_{100} is 100% of the peak stress i.e. the compressive strength from UC test and ϵ_{100} is the corresponding axial strain.

As a general tendency inclusion of tyre buffings to soil-fly ash mixes, decreases the E_{100} values (Figs. 5.21 and 5.22). With an increase in tyre buffing content, the secant modulus values of both red soil and sand mixes show a continuous decrease up to the highest content of 10% indicating decrease of stiffness, and similar behaviour is observed in the all curing period. However increase in curing period from 0 to 28 days increases the E_{100} values. Hazarika et al. (2010) also observed that addition of tyre chips decreases the stiffness of cement treated clay. Muntohor et al. (2013) also characterized stiffness or elasticity of soil by using secant modulus. The results showed that the unstabilised soil specimen had the smallest secant modulus among other mixture specimens. Addition of lime increased the secant moduli values of the soil from 0.8–2.15 MPa. The mixing of the rice husk ash in lime/soil mixture increased and doubled the secant modulus value from 2.15 to 5.08 MPa. Addition of fibers to the lime/rice husk ash and soil mixtures increased the secant modulus.

At any tyre buffing content, the secant modulus of red soil specimen is the maximum for 20% fly ash content, followed by the specimens with 35% and 50% fly ash contents. From Fig. 5.21, it can be noted that at the two tyre buffing contents of 5 and 10%, and at 20% fly ash content, the corresponding secant modulus values are 38.1 and 16.6 kPa for 28 days curing period, whereas the secant modulus of red soil alone specimen is 73.45 kPa for the same curing period. On the other hand, secant modulus of sand is 1.61 kPa at 0 day curing period which is assumed to remain same up to 28 days curing period. For inclusion of 5 and 10% tyre buffings and 50% fly ash content, E_{100} values of sand mixes increases to 17.18 and 10.16 kPa respectively. Moreover at any tyre buffing content, the secant modulus of sand specimen is the maximum for 50% fly ash content, followed by the specimens with 35% and 50% fly ash content. Kaniraj and Havanagi (1999) conducted unconfined compression tests on specimens containing soil (silt and sand), class F type fly ash and cement varying from 3-9%. They reported that gain in strength and secant modulus increased as cement content increased, but decreased as fly ash content increased. The cement content had significantly higher influence than the fly ash content.

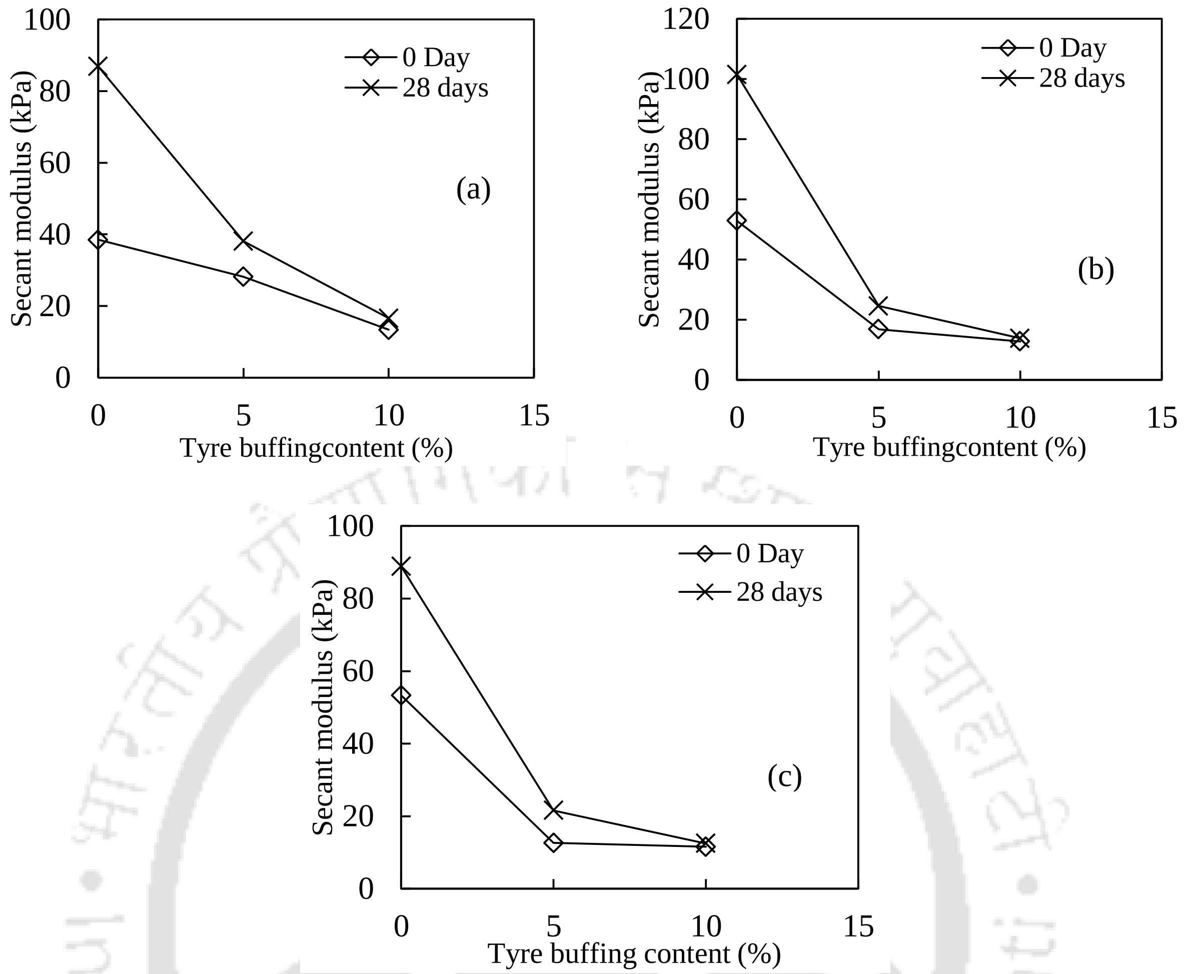
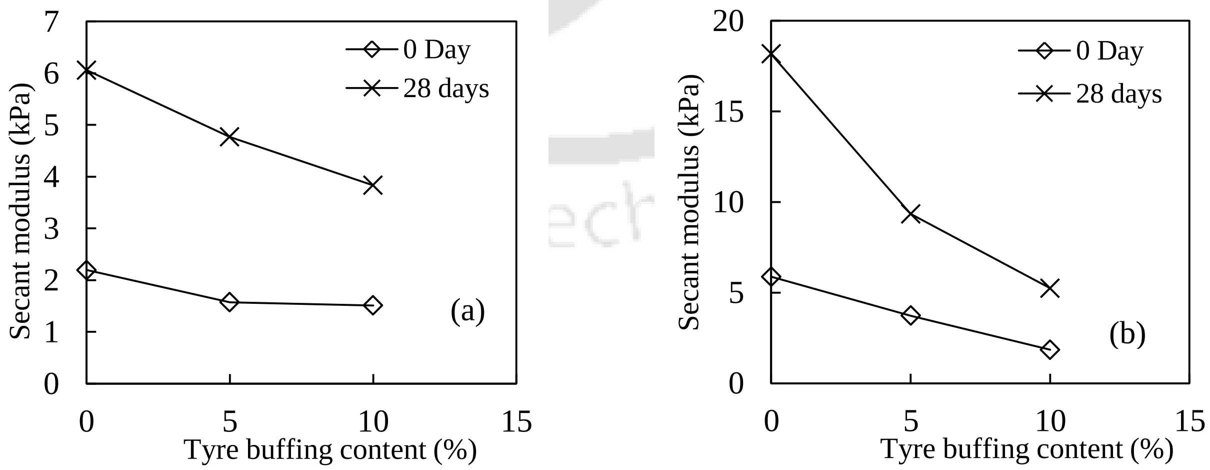


Fig. 5.21 Effect of tyre buffings on secant modulus for (a) RS+20FA+TB (b) RS+35FA+TB and (b) RS+50FA+TB mixes at 0 and 28 curing periods



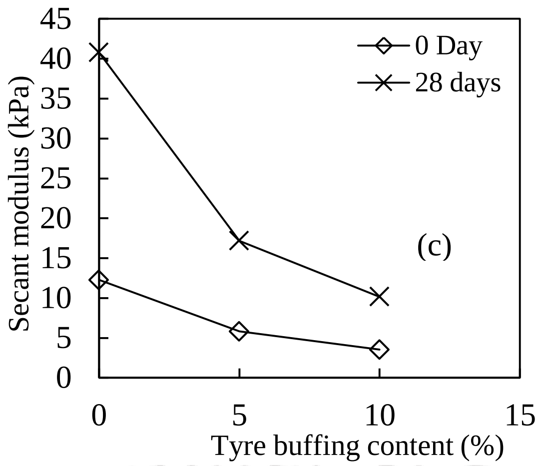


Fig. 5.22 Effect of tyre buffings on secant modulus for (a) BS+20FA+TB (b) BS+35FA+TB and (b) BS+50FA+TB mixes at 0 and 28 curing periods

5.3.12 Effect of Tyre Buffings on Ductility of Different Soil-Fly Ash Mixes

Ductility or brittleness can be studied to investigate the deformation behaviour of various soil mixes. In triaxial testing, steady state stress condition can be achieved in order to determine brittleness index of specimen to study the brittleness of the specimen. But in unconfined compression tests it is difficult to obtain this kind of condition. Therefore, a parameter called ductility ratio (DR) is introduced to study the effect of fly ash and tyre buffings inclusion on ductility of soil. For red soil and sand mixes ductility ratio is denoted by DR_{RS} and DR_{BS} respectively. Mathematically, it is expressed by the following equation:

$$DR = (\epsilon_{mix})/(\epsilon_{soil}) \quad (5.4)$$

where, ϵ_{soil} = average axial strain at failure of the untreated soil; and ϵ_{mix} = average axial strain at failure of soil-fly ash-tyre buffing mixes used in this study.

From Fig. 5.23 it is seen that inclusion of tyre buffing to soil-fly ash mixes increases the ductility ratio. Improvement in ductility of treated clay by addition of tyre materials was also reported by Mitrai et al. (2008) and Hazarika et al. (2010). In these two research works, specimens containing dredged clay, cement and tyre chips were used. In general, increase in FA content in RS+FA+TB mixes decreases the DR_{RS} values of the mixes as shown in Fig. 5.23 (a), whereas increase in FA content increases the DR_{BS} values of the mixes which is evident from Fig. 5.23(b). Increase in curing period reduces the ductility ratio values of mixes which in turn reduces the ductility.

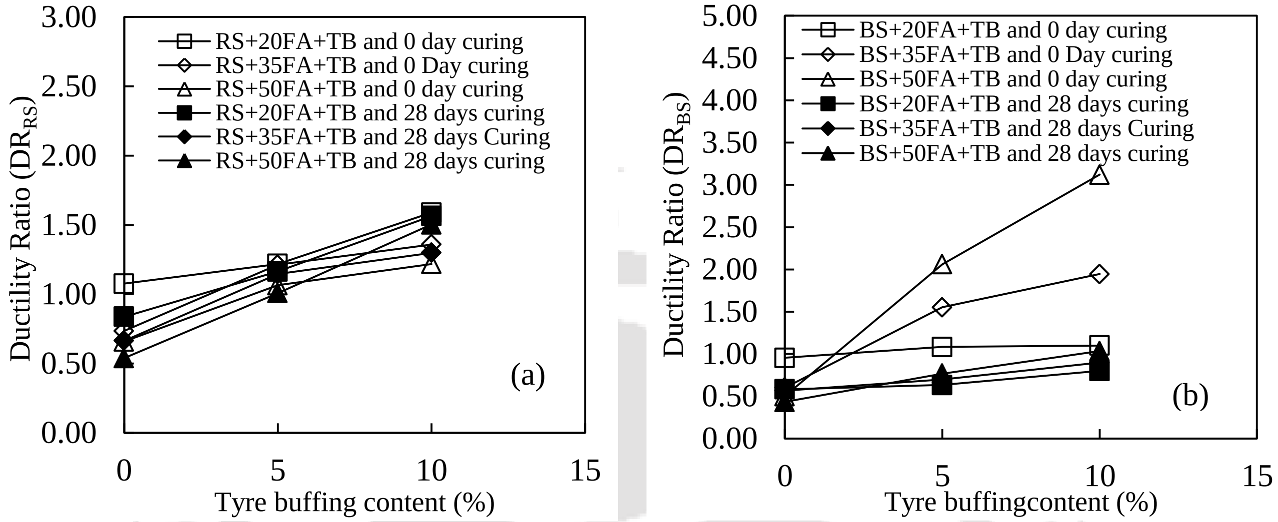


Fig. 5.23 Ductility ratios for (a) RS and (b) BS mixes at 0 and 28 days curing periods

5.3.13 Effect of Fly Ash and Tyre Buffings on EAC of Different Soil Mixes

Energy absorption capacity is defined as the energy obtained by the area under the stress-strain curve to a reverence strain level (ASTM C 1018). In this study, effect of fly ash content, tyre buffing content and curing on EAC were studied considering the failure axial strain for each specimen as a reference strain level. An increase in EAC with the addition of fly ash and tyre buffings indicates the peak stress or failure strain or both.

Effect of fly ash content on the EAC of soil is depicted in Fig. 5.24. Addition of fly ash to red soil decreases the EAC of the specimens and reaches minimum values at 50% fly ash content as shown in Fig. 5.24(a). Different kind of behaviour has been observed on addition of fly ash to sand [Fig. 5.24(b)]. Increase in fly ash content improves the EAC values of sand mixes. At 28 days curing period, EAC values of the specimens are found to be highest.

From Fig. 5.25(a), it is seen that further addition of tyre buffings to red soil-fly ash mixes decreases the EAC of the red soil mixes. For example, inclusion of 10% tyre buffings to RS+50FA mixes reduces the EAC values of RS+50FA mix from 571 kJ/m^3 to 450 kJ/m^3 at 28 days curing period. In most of the RS+FA+TB specimens increase in FA content reduces the EAC values of the specimens. Unlike RS+FA+TB mixes, increase in tyre buffing content in BS+FA+TB mixes generally improves energy absorption capacity of specimens (Fig. 5.26). Increase in fly ash content also increases the EAC of the sand-fly ash-tyre buffing mixes. At 28 days curing period, EAC values of BS+50FA and BS+50FA+10TB are 76.83 kJ/m^3 and 115.84 kJ/m^3 respectively, whereas RS+50FA and RS+50FA+10TB mixes have EAC values of 571 kJ/m^3 and 450 kJ/m^3 respectively. Curing period also plays an important role in improving the EAC of all mixes irrespective of soil type. Effect of curing period on EAC values of the mixes are found to be the highest at 28 days curing period

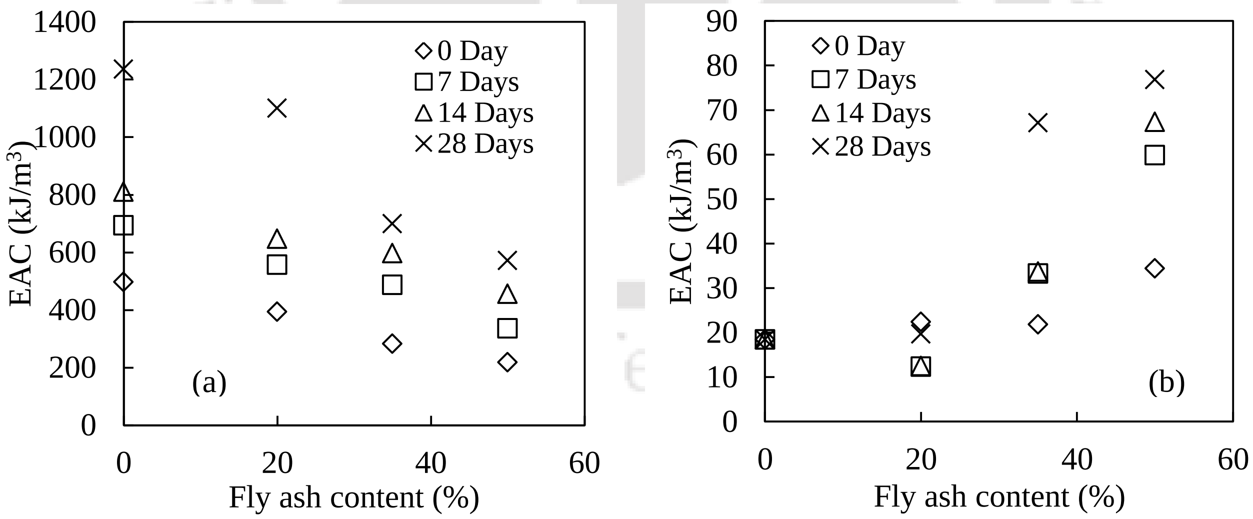


Fig. 5.24 Effect of tyre buffings on EAC for (a) RS+FA and (b) BS+FA mixes at different curing periods

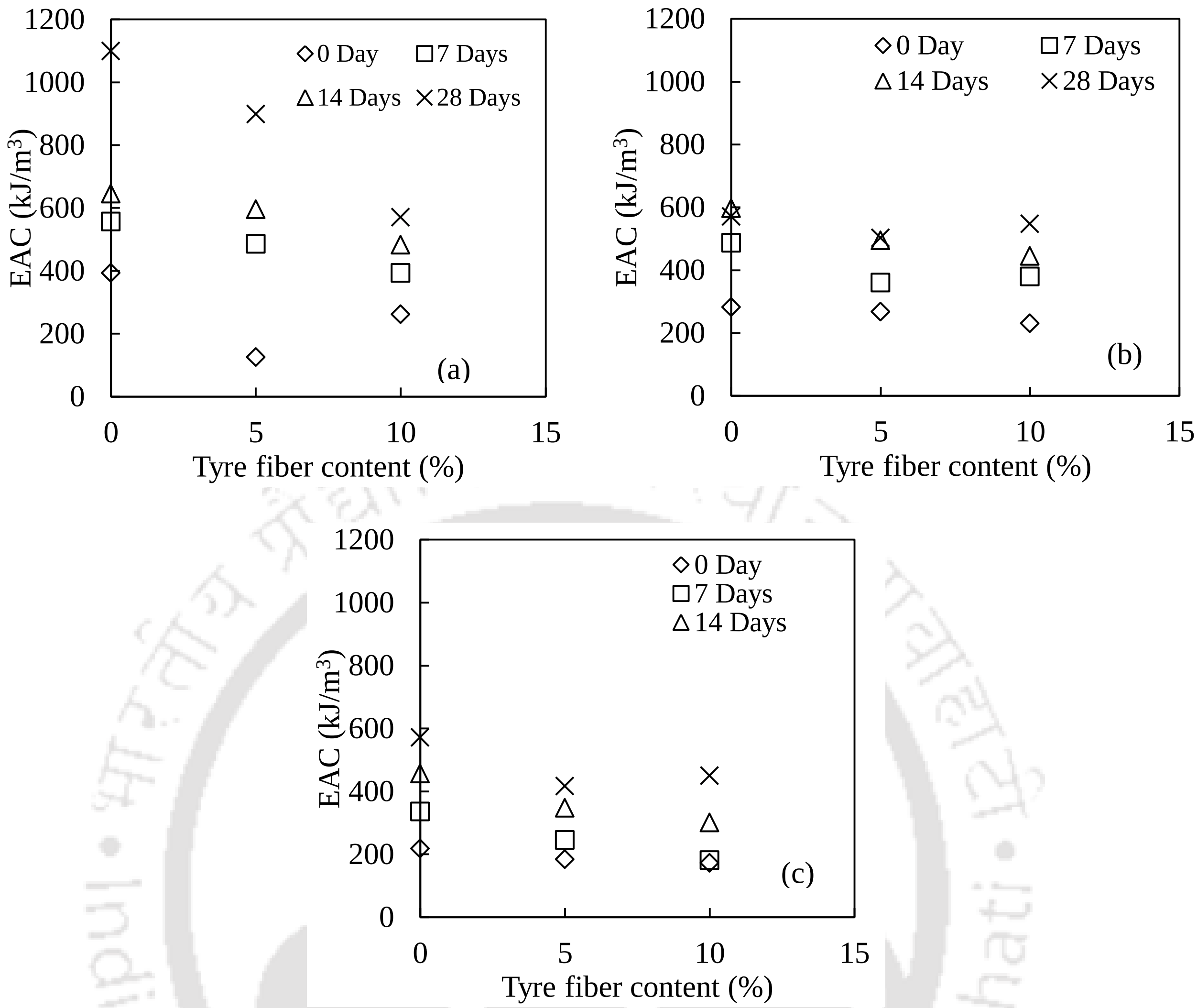
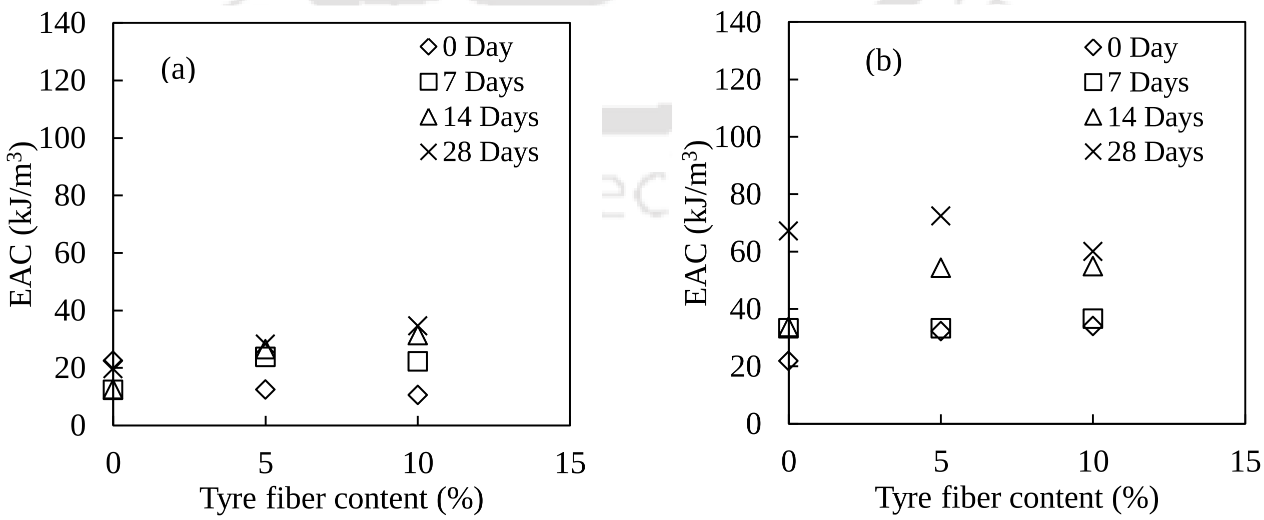


Fig. 5.25 Effect of tyre buffings on EAC for (a) RS+20FA+TB (b) RS+35FA+TB and (c) RS+50FA+TB mixes at different curing periods



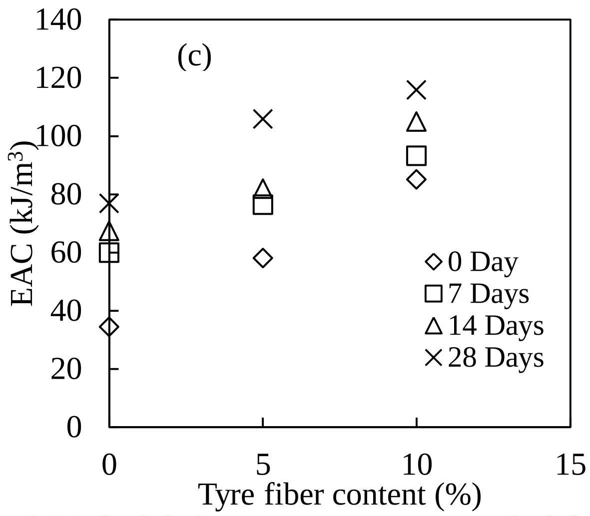


Fig. 5.26 Effect of tyre buffings on EAC for (a) BS+20FA+TB (b) BS+35FA+TB and (c) BS+50FA+TB mixes at different curing periods

5.4 REGRESSION ANALYSIS

To investigate the effect of various factors on unconfined compressive strength of specimens of soil mixed with fly ash and tyre buffings in different proportions, multiple-regression statistical analysis was conducted based on the experimental results. In multiple regression analysis, the relationship between dependent and independent variables can be presented as follows:

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_k x_{ik} \quad \ldots\ldots (5.5)$$

Where,

$i = 1, 2, 3\ldots, n$ is the number of observations;

y_i = dependent variable;

$x_{i1}, x_{i2}, \ldots, x_{ik}$ = independent variables and

$\beta_0, \beta_1, \beta_2, \ldots, \beta_k$ = regression coefficients.

The different influencing parameters identified as independent variables in the model are fly ash content (FA), tyre buffing content (TB) and curing period. The effects of these parameters on UCS of various RS specimens have been evaluated by the following regression model:

UCS = 220.15–0.09(FA)-29(TB) +5.62(curing period) -0.024$(FA)^2$+1.53$(TB)^2$ - 0.086$(\text{curing period})^2$ ……………(5.6)

The model developed to investigate the effects of different parameters as mentioned above on UCS of various BS specimens is as follows:

UCS = 6.11–0.08(FA)-0.18(TB) -0.078(curing period) -0.024(FA×TB) + 0.023(curing perio+0.013 $(FA)^2$ ………………. (5.7)

The respective values of R^2 for equations 5.6 and 5.7 are 0.883 and 0.945 respectively. It is observed that the equations 5.6 and 5.7 obtained by regression analysis indicate the goodness of fit to the data. Hence it can be stated that the relationship between the unconfined compressive strength and other influencing parameters can be well explained by those regression equations.

5.5 CONCLUDING REMARKS

The effect of tyre buffings addition on soil specimens prepared at MDU and OMC was studied through unconfined compression tests. The specimens were tested at optimum condition with varying fly ash and tyre buffings contents for different curing periods. The effect of fly ash and tyre buffings inclusion on stress-strain response, specimen failure mode, failure strain, stiffness, and EAC beahviour was investigated. The following conclusions have been drawn from the test results:

1. Addition of fly ash to the red soil immediately reduces the compressive strength of the mixes with significant change in stress-strain response of the mixes. With smaller fraction of fly ash, the mixes tend to behave like the soil alone. Tyre buffing inclusion to red soil-fly ash mixes effects the stress-strain behaviour by causing change in peak stress, stiffness and ductility of the material. Curing also plays an important role in altering the overall stress-strain-strength characteristics of the mixes.

2. UCS values are observed to be the highest for mixes with 20% fly ash content followed by 35% fly ash content. The UCS values of red soil-50FA mixes are less than that of the red soil alone. This kind of behaviour is attributed to the increased content of non-cohesive fraction in red soil-fly ash mixes. Due to lower strength of tyre buffings, inclusion of this material to red soil or red soil-fly ash mixes weakens the specimens which results in reduction in compressive strength as in the case of red soil-fly ash mixes, the fly ash added sand mixes also shows decrease in the failure strain.
3. Unlike red soil addition of fly ash to the sand results in progressive increase in compressive strength with fly ash content and also with curing duration. As in the case of red soil-fly ash mixes, the fly ash added sand mixes also show decrease in the failure strain. Presence of fly ash in sand mixes improves the strength by facilitating time-dependent pozzolanic reactions. As tyre buffings are added to the sand, the unconfined compressive strength is decreased. Due to the ductility of tyre buffings, the sand-fly ash-tyre buffing specimens fail at larger strain than sand-fly ash specimens. Increase in fly ash content in BS+FA+TB mixes is more effective and as such BS+50FA+5TB mix bears the highest compressive strength.
4. Inclusion of tyre buffings to soil-fly ash mixes improves ductility of the specimens but reduces the stiffness. However, different kinds of behaviour are observed for red soil-fly ash-tyre buffing and sand-fly ash-tyre buffing mixes. Increase in fly ash content in red soil-fly ash-tyre buffing mixes reduces the secant modulus values of mixes whereas these values are increased in sand-fly ash-tyre buffing mixes.
5. Addition of fly ash and tyre buffings in soil also effects energy absorption capacity. Increase in FA content in RS+FA and RS+FA+TB mixes reduces EAC values of mixes. In contrary to that, increase in FA content in BS+FA and BS+FA+TB mixes increases the EAC values of mixes. Further addition of TB in soil-fly ash mixes

decreases the EAC values of RS+FA mixes but improves absorption energy of BS+FA mixes.

CHAPTER - 6
TRIAXIAL COMPRESSION CHARACTERISTICS

6.1 INTRODUCTION

Unconfined compression tests showed that addition of fly ash to sand only resulted in improvement of strength but a decrease was observed when fly ash was admixed with red soil. Further addition of tyre buffings to both the soil types reduced the strength of the mixes (Chapter-5). A detailed study is required for complete understanding of the shear strength response of blended soil mixed with tyre buffings. Triaxial compression tests were carried out on the soil mixed with fly ash and tyre buffings with the addition of cement later on to understand:

i) the overall stress-strain-strength characteristics of the soil and changes in its behaviour due to the addition of fly ash and tyre buffings of different sizes,

ii) the influence of curing period on the shear strength behaviour of the mixes, and

iii) The effect of addition of cement on the shear strength behaviour of soil mixed with fly ash and tyre buffings.

6.2 TEST PROGRAMME

Tables 6.1 and 6.2 summarize the composition of the selected mixes used in the triaxial test programme. Fly ash addition was up to 50% only. Two types of tyre materials (tyre buffings and tyre crumb) were added to the soil and soil- fly ash mixes at contents of 5% and 10%. The cement contents used in the soil-fly ash mixes were 1% and 2%. However, the cement content used in the soil-fly ash-tyre buffing and red soil-fly ash-tyre crumb mixes was only 2%.

6.3 RESULTS AND DISCUSSION

The triaxial test data has been analysed to determine the stress-strain and strength characteristics of different soil mixes. For determination of shear strength parameters cohesion (c) and angle of internal friction (ϕ), p-q plots have been made. In the *p-q* plot, the K_f line is obtained by joining the maximum stress points of the failure circles for the four tests. The intercept of the K_f line with the Y-axis is *d*, and the angle that the K_f line makes with the horizontal is α .

The equation of the K_f line and the equation of the shear strength envelope are related as follows:

$$\tan\alpha = \sin\phi \quad (1)$$

$$c = \frac{d}{\cos\phi} \quad (2)$$

where, ϕ = angle of shearing resistance, and

c = cohesion intercept of the shear strength envelope

For all tested specimens, the shear strength parameters, namely cohesion and angle of shearing resistance were determined by using Eqns. 1 and 2.

6.3.1 Effect of Fly Ash on Behaviour of Red Soil Mixes

6.3.1.1 Stress-Strain Behaviour

Typical stress-strain plots of RS, FA and RS+FA mixes obtained at confining pressure of 300 kPa are shown in Fig. 6.1 for curing periods of 0, 7, 14 and 28 days. It is seen that addition of fly ash tends to increase the stiffness and the peak deviator stress of the soil mix. Among all the mixes, RS+35FA mix shows the maximum peak deviator stress (Table 6.10). However the increase in non-cohesive fraction in RS+FA mixes at 50% fly ash content causes reduction in strength. Initially, the frictional resistance plays an important role in the improvement of peak strength in triaxial tests. At 50% fly ash content, significant reduction in cohesive force minimizes the peak deviator stress values of mixes. It is also observed that in most of the cases, the strength of fly ash added mixes has a tendency to increase with the increase in curing period. This happens due to the occurrence of pozzolanic reaction within the specimen.

The failure strain obtained for each specimen is the average failure strain values of the specimens for the range of curing periods considered in this study. As shown in Fig. 6.2, the addition of fly ash to red soil reduces the failure strain values of the mixes; hence RS+50FA mixes show the minimum value of failure strain among RS+FA mixes. Moreover, increase in confining pressure makes the specimen to fail in larger strain. From Table 6.3 it is seen that red soil specimen shows a bulging kind of failure, whereas a clear failure surface has been observed in fly ash added red soil specimens except RS+35FA specimens.

Table 6.1 Composition of various red soil mixes for triaxial compression tests

Red soil	Red soil-fly ash mixes	Red soil-tyre buffing (TB)	Red soil-cement mixes	Red soil-fly ash-tyre buffing (TB) mixes	Red soil-fly ash-cement mixes	Red soil-fly ash-tyre buffing (TB) –cement mixes	Red soil-fly ash-tyre crumb (TC) –cement mixes
RS	RS+20FA	RS+5TB	RS+1C	RS+20FA+5TB	RS+20FA+1C	RS+20FA+5TB+2C	RS+20FA+5TC+2C
	RS+35FA	RS+10TB	RS+2C	RS+20FA+10TB	RS+20FA+2C	RS+20FA+10TB+2C	RS+20FA+10TC+2C
	RS+50FA						
				RS+35FA+5TB	RS+35FA+1C	RS+35FA+5TB+2C	RS+35FA+5TC+2C
				RS+35FA+10TB	RS+35FA+2C	RS+35FA+10TB+2C	RS+35FA+10TC+2C
				RS+50FA+5TB	RS+50FA+1C	RS+50FA+5TB+2C	RS+50FA+5TC+2C
				RS+50FA+10TB	RS+50FA+2C	RS+50FA+10TB+2C	RS+50FA+10TC+2C

Table 6.2 Composition of various sand mixes for triaxial compression tests

Red soil	Red soil-fly ash mixes	Red soil-tyre buffing (TB) mixes	Red soil-cement mixes	Red soil-fly ash-tyre buffing (TB) mixes	Red soil-fly ash-cement mixes	Red soil-fly ash-tyre buffing (TB) –cement mixes
BS	BS+20FA	BS+5TB	BS+1C	BS+20FA+5TB	BS+20FA+1C	BS+20FA+5TB+2C
	BS+35FA	BS+10TB	BS+2C	BS+20FA+10TB	BS+20FA+2C	BS+20FA+10TB+2C
	BS+50FA					
				BS+35FA+5TB	BS+35FA+1C	BS+35FA+5TB+2C
				BS+35FA+10TB	BS+35FA+2C	BS+35FA+10TB+2C
				BS+50FA+5TB	BS+50FA+1C	BS+50FA+5TB+2C
				BS+50FA+10TB	BS+50FA+2C	BS+50FA+10TB+2C

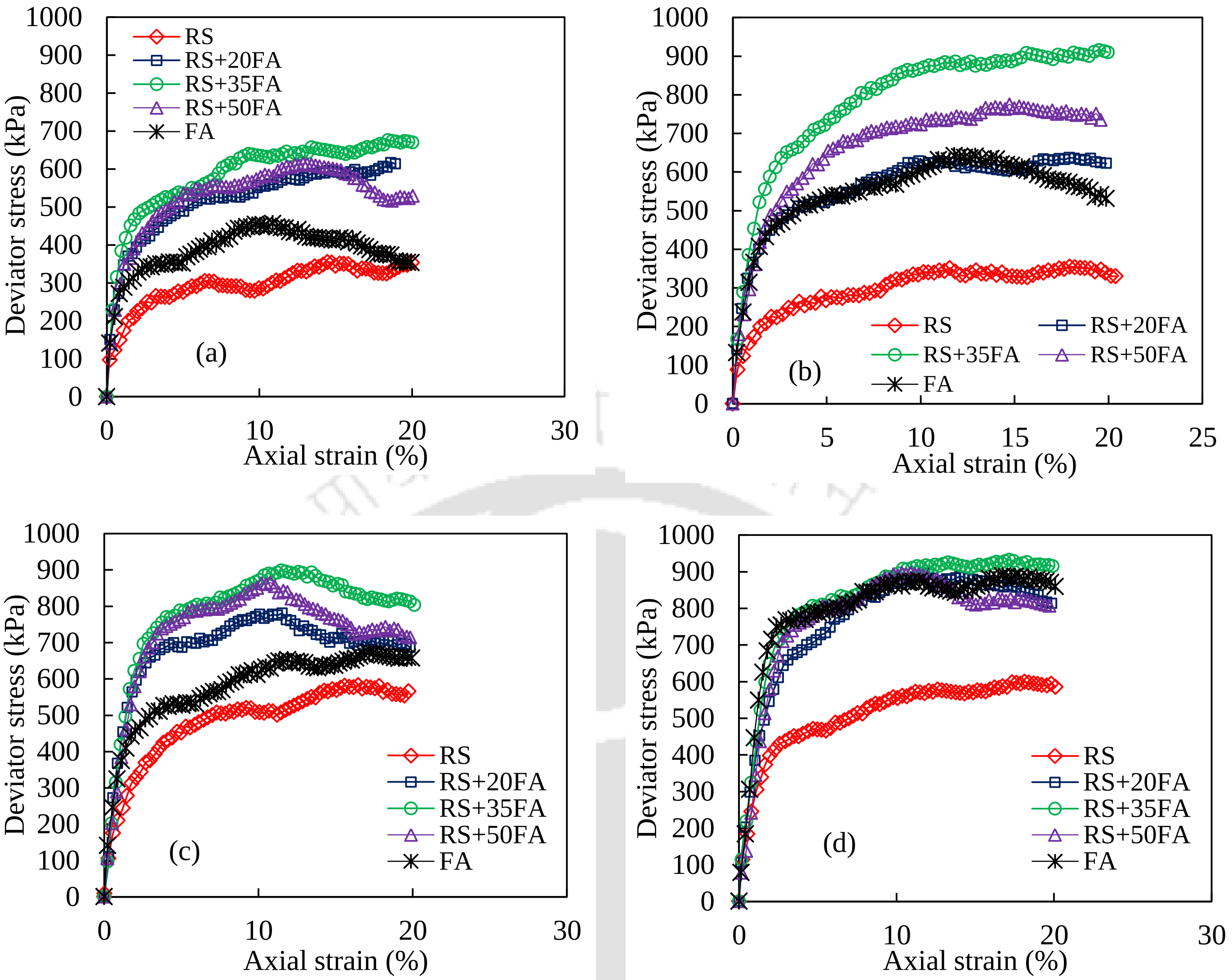


Fig. 6.1 Stress-strain behaviour of RS+FA at 300 kPa confining pressure at (a) 0, (b) 7 days, (c) 14 days and (d) 28 days curing

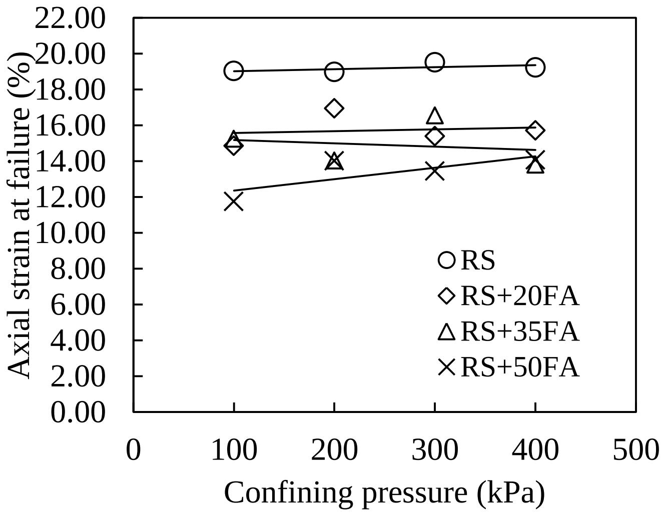


Fig.6.2 Variation of failure axial strain of RS alone and RS+FA mix with confining pressure

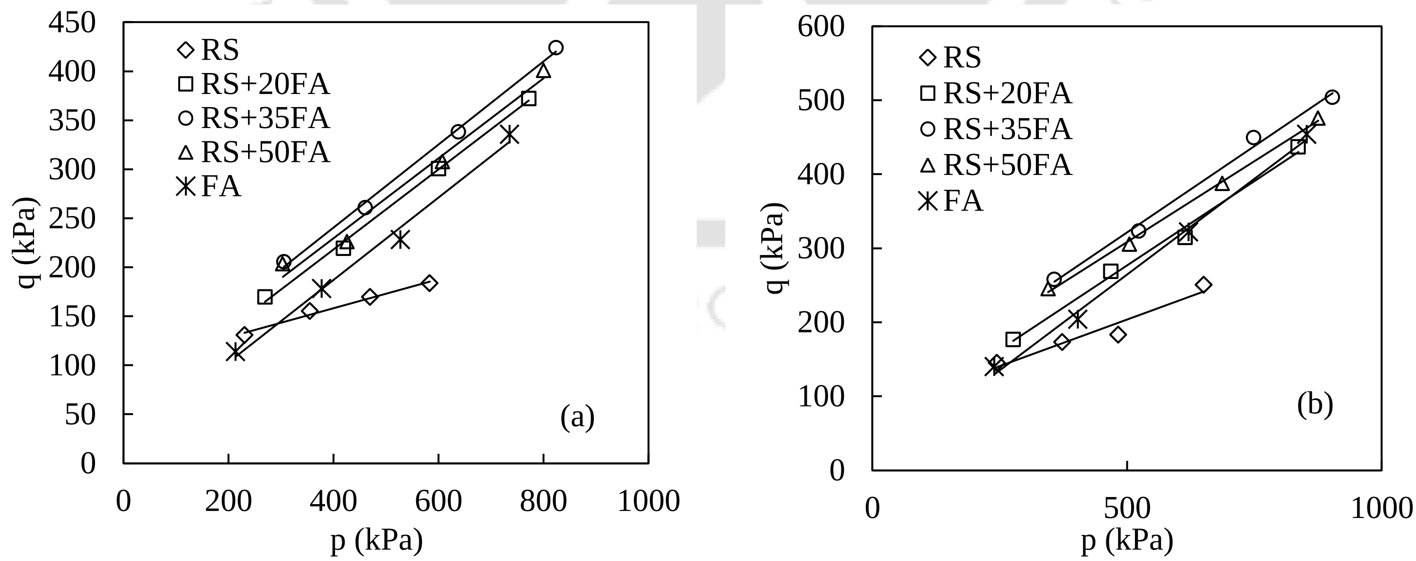
Table 6.3: Failure patterns of RS+FA mixes tested at 300 kPa confining pressure

Curing	Mix			
	RS	RS+20FA	RS+35FA	RS+50FA
0 Day				
7 Days				
14 Days				
28 Days				

6.3.1.2 Shear Strength Characteristics

Fig. 6.3 shows the p-q [$p = (\sigma_1 + \sigma_3)_f/2$, $q = (\sigma_1 - \sigma_3)_f/2$] plots for RS+FA mixes with 0, 7, 14 and 28 days of curing period. It is observed that generally on addition of fly ash to red soil, peak strength increases and it is more effective up to 35% fly ash content. However RS+50FA mix shows greater strength than RS alone mix.

Table 6.14 depicts the variations of cohesion and internal friction angle with fly ash content at different curing periods. It is observed in most of the cases that on addition of fly ash to soil mixes, cohesion value decreases but internal friction angle increases. This kind of behaviour is due to the change in the texture with increase in non-cohesive fraction in the soil mixes. As the internal friction angle of the fly ash is more than that of the red soil, inclusion of fly ash to soil results in a rise in ϕ values. On the other hand, curing results in self-hardening effect related to the presence of free lime and also loss of moisture from the sample during curing period. Therefore, it is expected that increase in curing period increases the cohesion component.



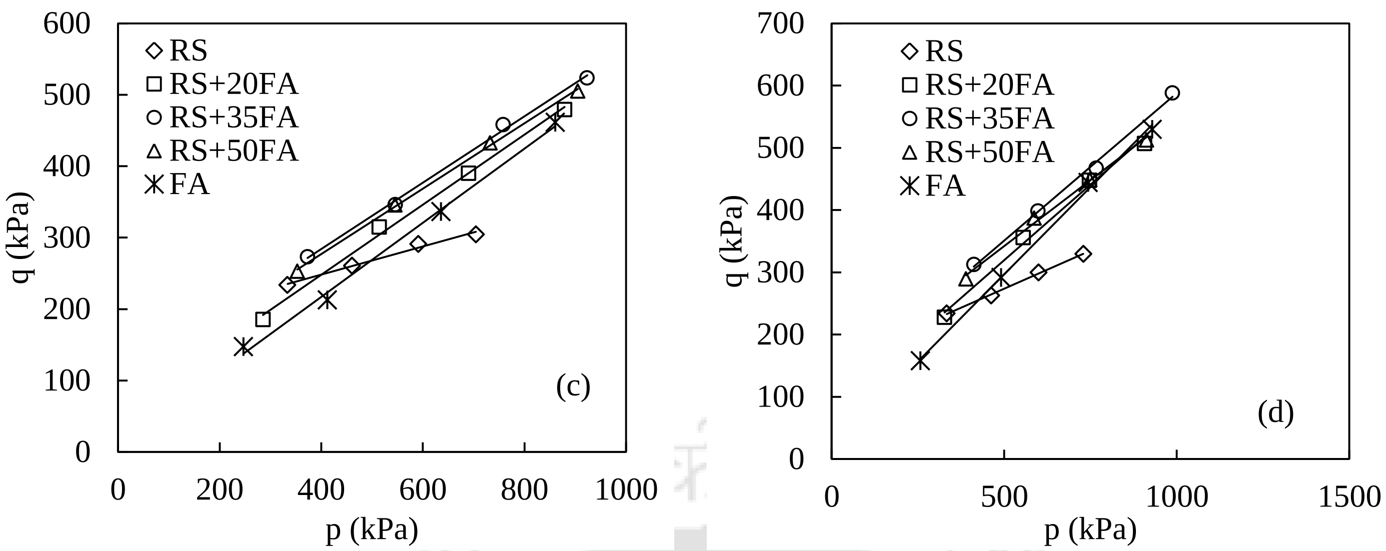


Fig. 6.3 p-q plots of RS+FA mix at (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing period

6.3.2 Effect of Tyre Buffing (TB) Inclusion on Behaviour of Red Soil Mixes

6.3.2.1 Stress-Strain Behaviour

Fig. 6.4 shows the variation of the deviator stress (σ_1 - σ_3) with axial strain (ε) for the RS alone, RS+5TB and RS+10TB specimens at 200 kPa confining pressure for different curing periods. In most of the soil-tyre buffings specimens, no peak deviator stress was reached even at 20% axial strain. This is a manifestation of the ductile behaviour induced by the tyre fiber inclusions. It is evident that addition of tyre buffing to red soil decreases the peak deviator stress and stiffness of the mix. It is also seen that usually peak deviator stress of RS+TB mixes changes with the curing period (Table 6.10).

Ozkul and Baykal (2007) reported that the contribution of rubber fibers to the strength of clay decreases with increasing levels of confinement for the specimens prepared at modified compaction energy. The composite should not be used at stresses exceeding the limiting confining stress. For the specimens prepared at standard compaction effort, it is observed that addition of tyre buffing increases the peak strength at all levels of confinement.

As shown in Fig. 6.5, inclusion of tyre buffings to red soil reduces the failure strain of the mixes marginally. Table 6.4 shows no trace of failure surface in the specimen. This kind of behaviour is attributed to the elastic behaviour of tyre buffings.

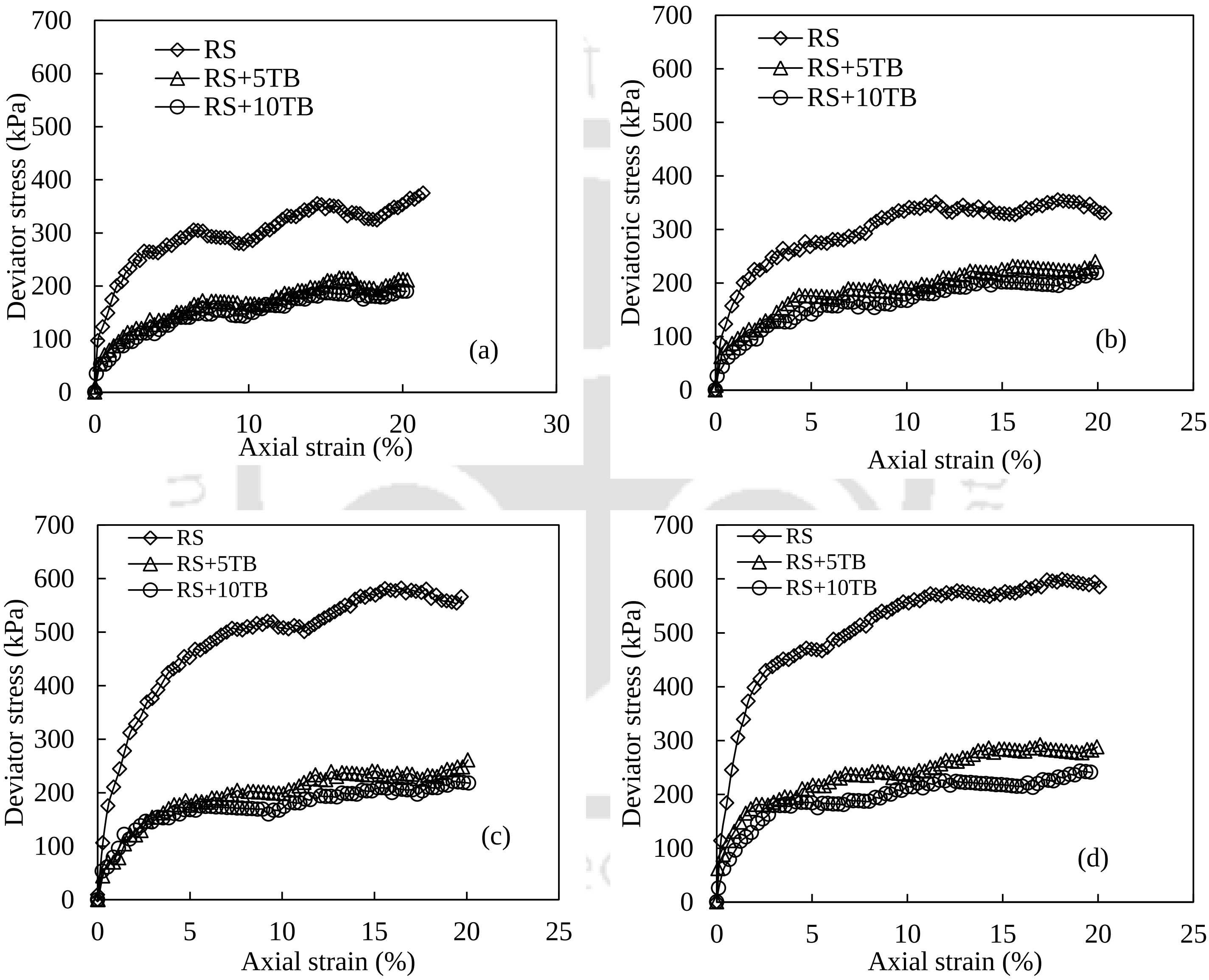


Fig. 6.4 Stress-strain behaviour of RS+TB mix at (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing period

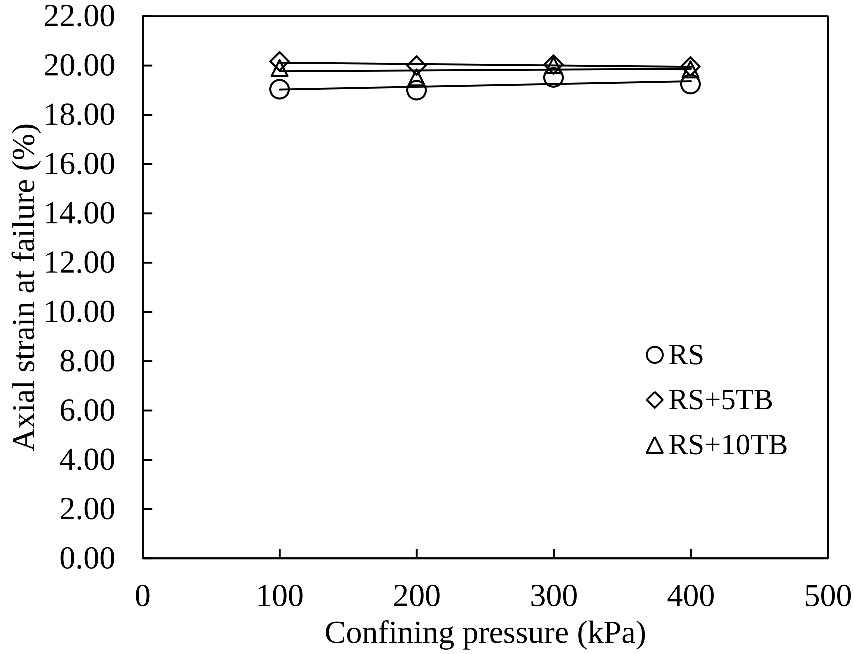


Fig. 6.5 Variation of faliure axial strain of RS alone and RS+TB mix with confining pressure

Table 6.4: Failure patterns of RS+TB mixes tested at 300 kPa confining pressure

Curing	Mix		
	RS	RS+5TB	RS+10TB
0 Day			
7 Days			

14 Days			
28 Days			

6.3.2.2 Shear Strength Characteristics

Fig. 6.6 shows the effect of tyre buffing inclusion on p-q plots of various soil mixes at 0, 7, 14 and 28 days of curing. It is seen that inclusion of TB reduces the strength of RS mixes. Generally, increase in tyre buffing content from 5% to 10% in the mixes decreases the strength of the mixes.

Table 6.14 shows the effect of tyre buffing inclusion on cohesion and internal friction angle of RS mixes with curing. It is obvious that inclusion of 5% TB content reduces the cohesion of RS mixes and also internal friction angle to some extent. Moreover, TB added mixes show non-linear behaviour as per as variation of internal friction angle is concerned.

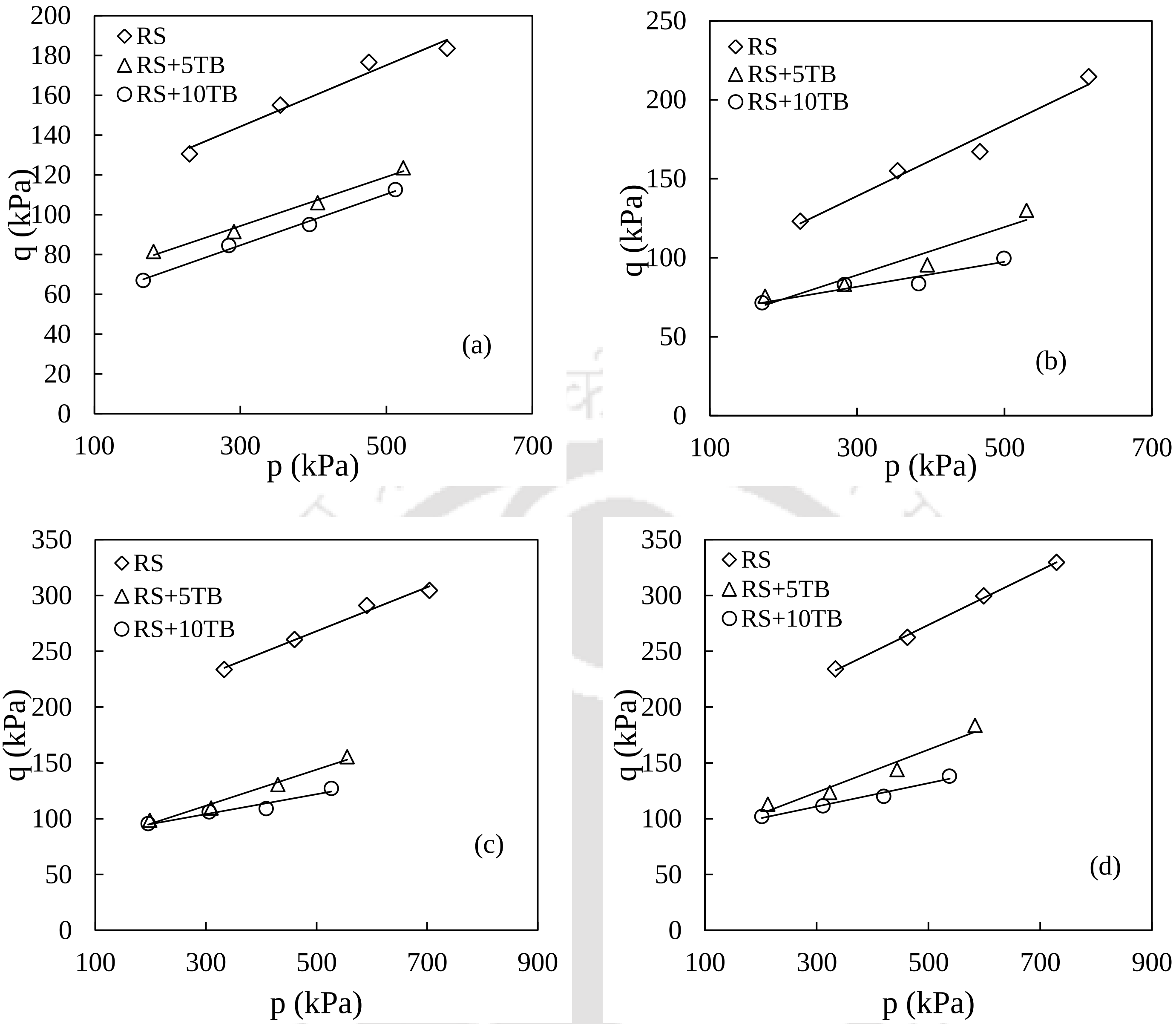


Fig. 6.6 p-q plots of RS+TB mix at (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing period

6.3.3 Effect of Cement Addition on Behaviour of Red Soil Mixes

6.3.3.1 Stress-Strain Behaviour

Typical stress-strain plots of RS+C and RS+FA mixes obtained at confining pressure of 300 kPa are shown in Fig. 6.7 for curing periods of 0, 7, 14 and 28 days. It is seen that addition of cement increases the peak deviator stress and stiffness of the soil matrix. In 28 days curing period, peak deviator stress has been found to be maximum in stress-strain plots of RS+2C mixes. After this peak value, further increase in strain reduces the deviator stress values of the mixes. Peak strength, stiffness and brittleness are changed as a consequence of effect of cement.

From Fig. 6.8, it is seen that addition of cement to red soil makes the specimen to fail in a lower axial strain. Table 6.5 reveals that cemented red soil mixes show brittle behaviour as compared to red soil alone mixes. Failure surface is visible in RS+C specimens.

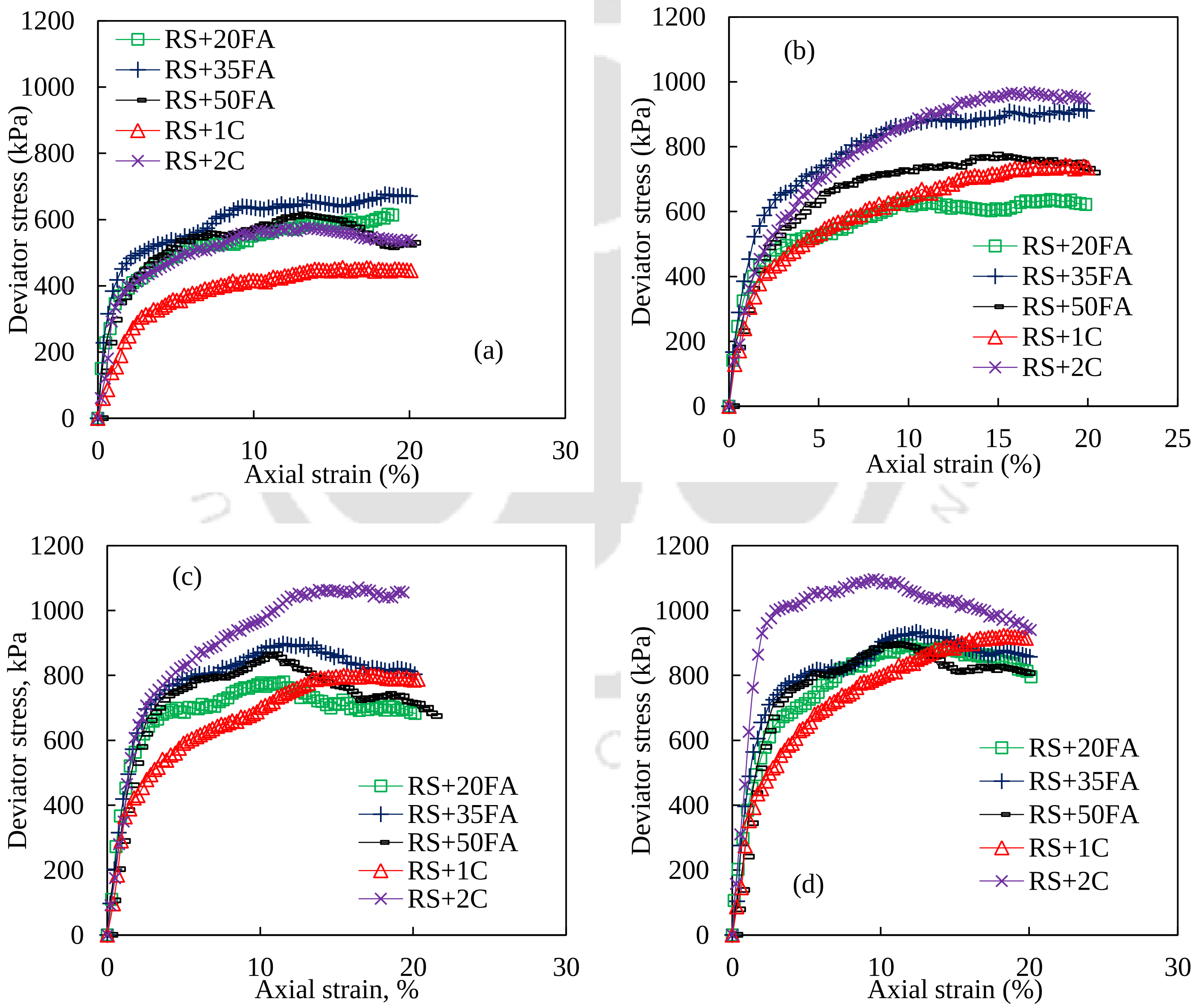


Fig. 6.7 Stress-strain behaviour of RS+FA and RS+C mixes at 300 kPa confining pressure at (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing period

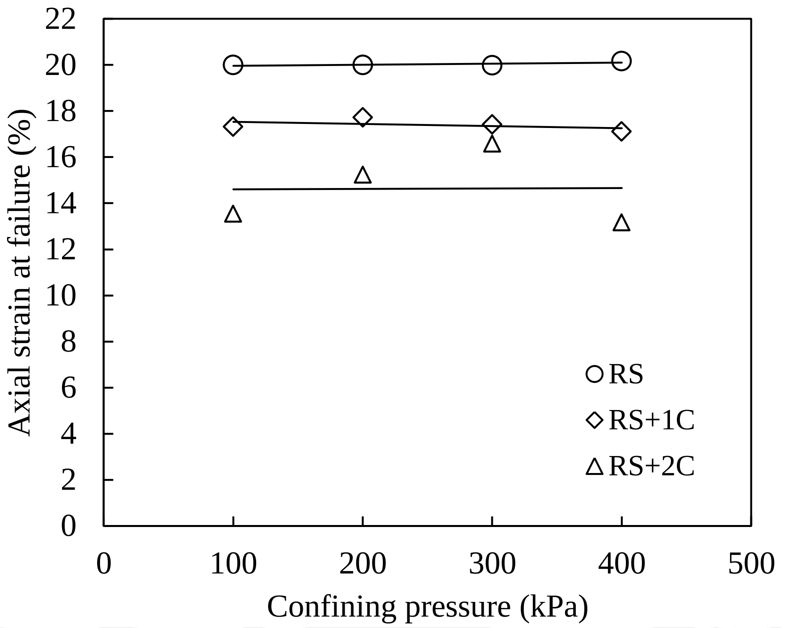


Fig. 6.8 Variation of faliure axial strain of RS alone and RS+C mix with confining pressure

Table 6.5: Failure patterns of RS+C mixes tested at 300 kPa confining pressure

Curing	Mix		
	RS	RS+1C	RS+2C
0 Day			
7 Days			

14 Days			
28 Days			

6.3.3.2 Shear Strength Characteristics

Fig. 6.9 shows the p-q plots of RS+FA and RS+C mixes respectively for the all curing periods. It is observed that increase in content of cement in RS+C mixes improves the strength of the mixes. But this improvement does not follow a trend. RS+2C mixes show higher strength than any other mixes. Beyond 1% cement addition RS+C mixes show higher strength than RS+FA mixes. Table 6.15 shows the effect of cement addition on cohesion and internal friction angle values of red soil mixes. Both c and ϕ values are increased with addition of cement to red soil.

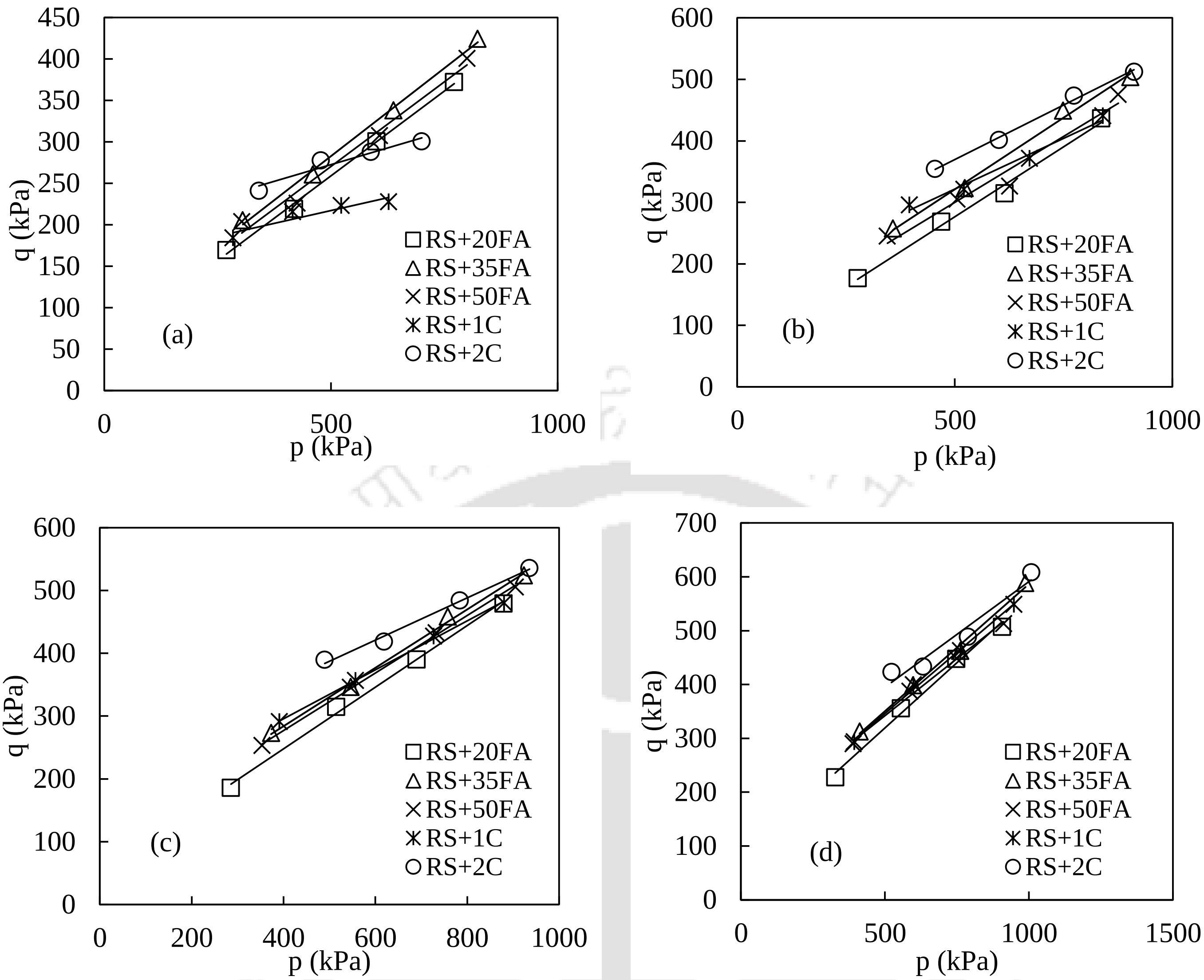


Fig. 6.9 p-q plots of RS+TB mix at (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing period

6.3.4 Effect of Tyre Buffing Inclusion on Behaviour of Red Soil-Fly Ash Mixes

6.3.4.1 Stress-Strain Behaviour

Figs. 6.10 to 6.12 show the variation of the deviator stress (σ_1 - σ_3), with axial strain (ε) for RS alone, RS+FA and RS+FA+TB specimens at 300 kPa confining stresses for 0, 7, 14 and 28 days curing periods. In most of the cases bulging failure has been observed in TB added specimens, and no peak deviator stress was reached even at 20% axial strain. This may be a manifestation of the ductile behaviour induced by the tyre buffing inclusions. In all cases it is found that inclusion of tyre buffing to soil mixed with fly ash decreases the deviator stress as compared to RS+FA mixes (Table 6.10). Curing causes improvement in peak deviator stress.

Inclusion of tyre buffings to red soil-fly ash mixes generally increases the failure strain (Fig. 6.13). This kind of behaviour is attributed to the elastic behaviour of tyre buffings. As shown in Table 6.6, no failure surface appears in RS+FA+TB mixes. Specimens containing tyre buffings show bulging failure even at 28 days curing period.

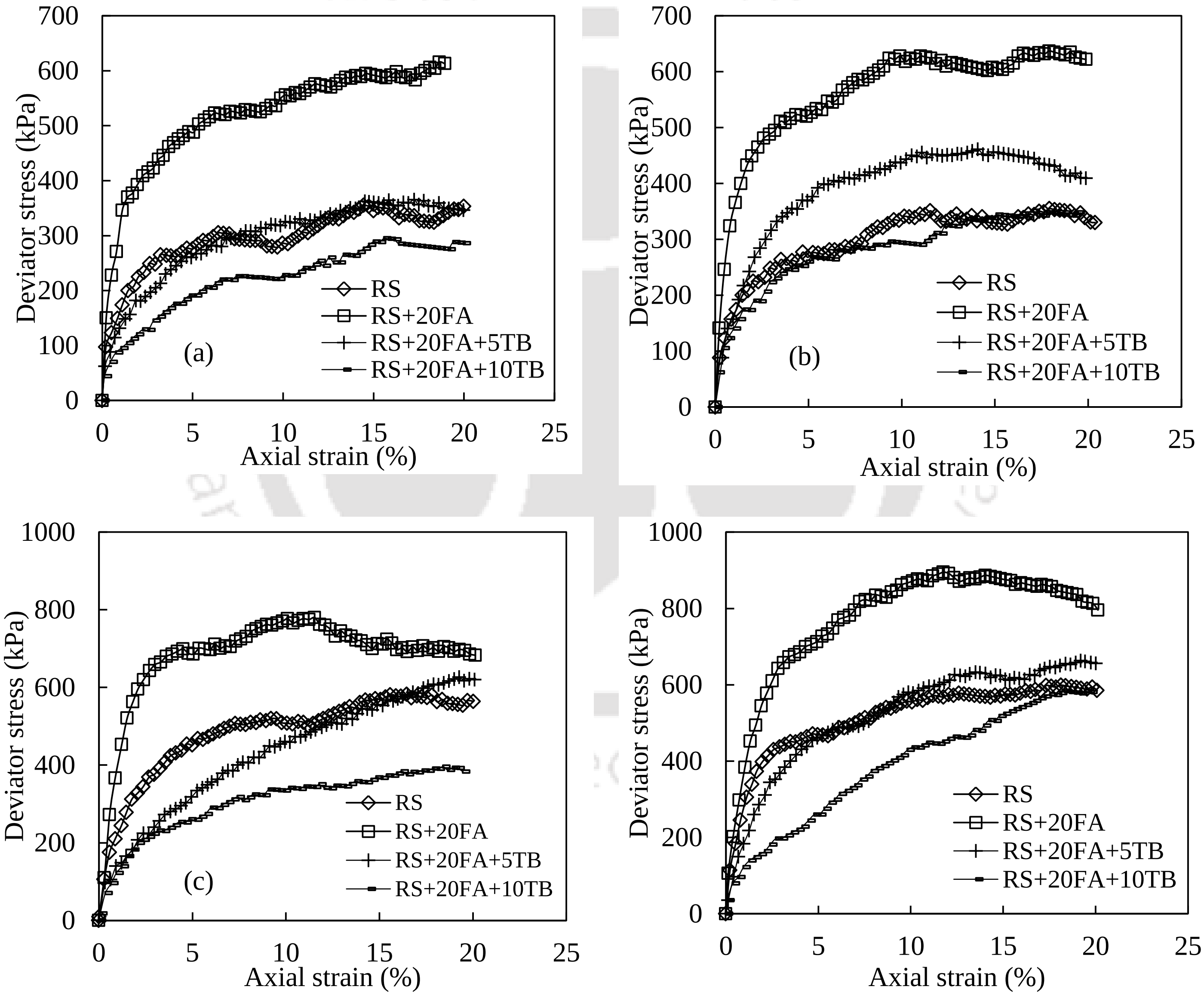


Fig. 6.10 Stress-strain behaviour of red soil alone, RS+20FA and RS+20FA+TB mix at (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing period

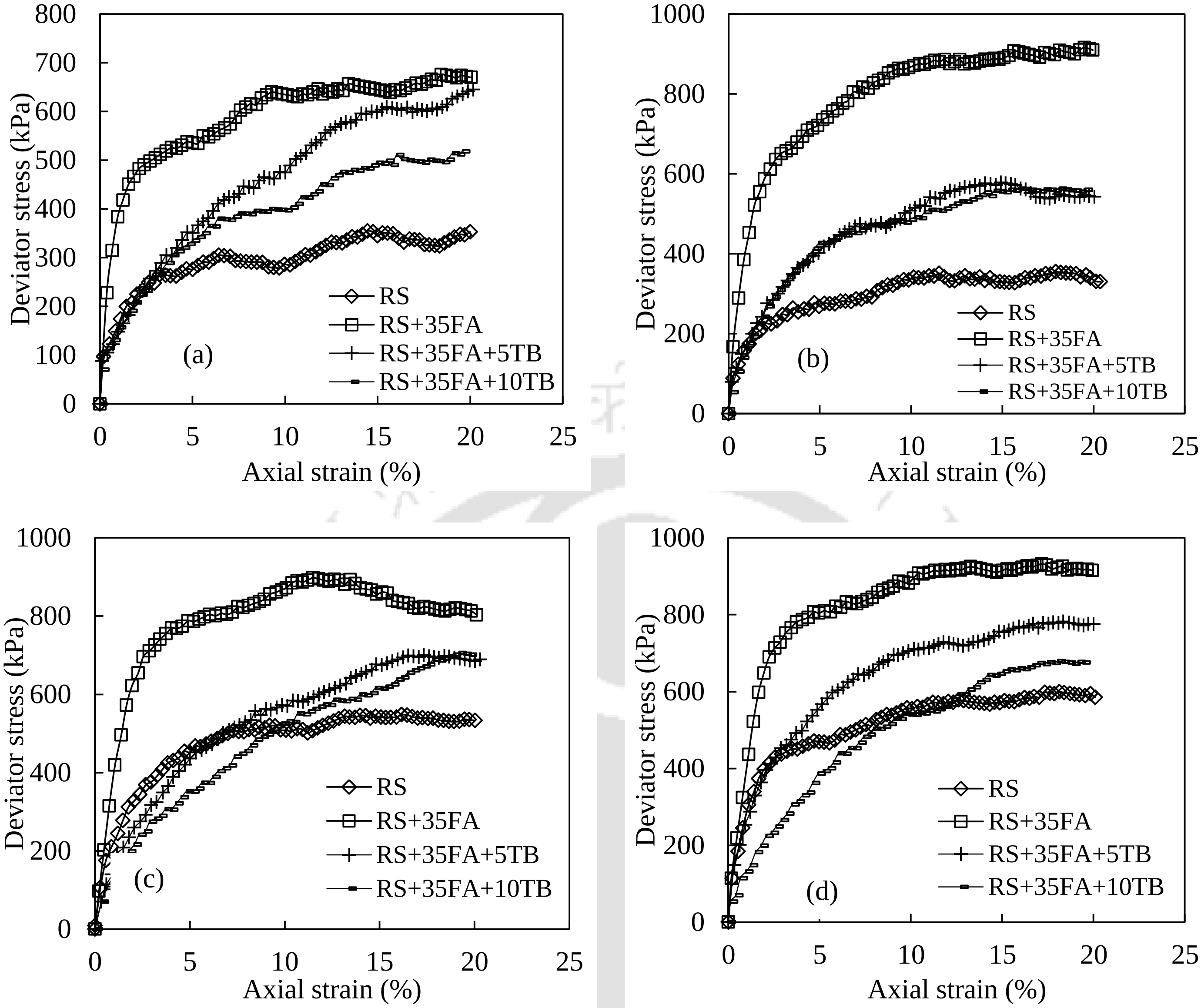


Fig. 6.11 Stress-strain behaviour of red soil alone, RS+35FA and RS+35FA+TB mix at (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing period

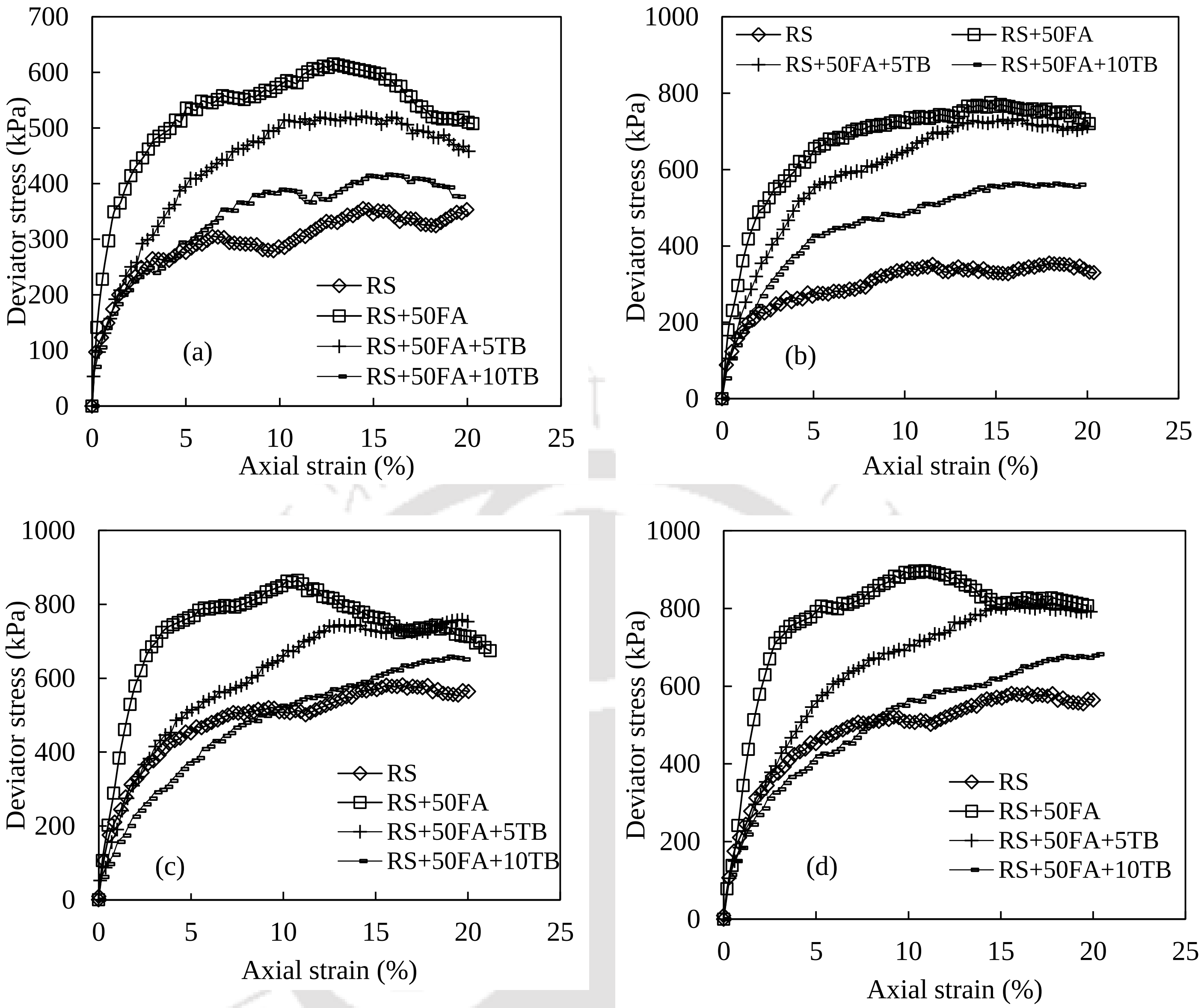


Fig. 6.12 Stress-strain behaviour of red soil alone, RS+50FA and RS+50FA+TB mix at (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing period

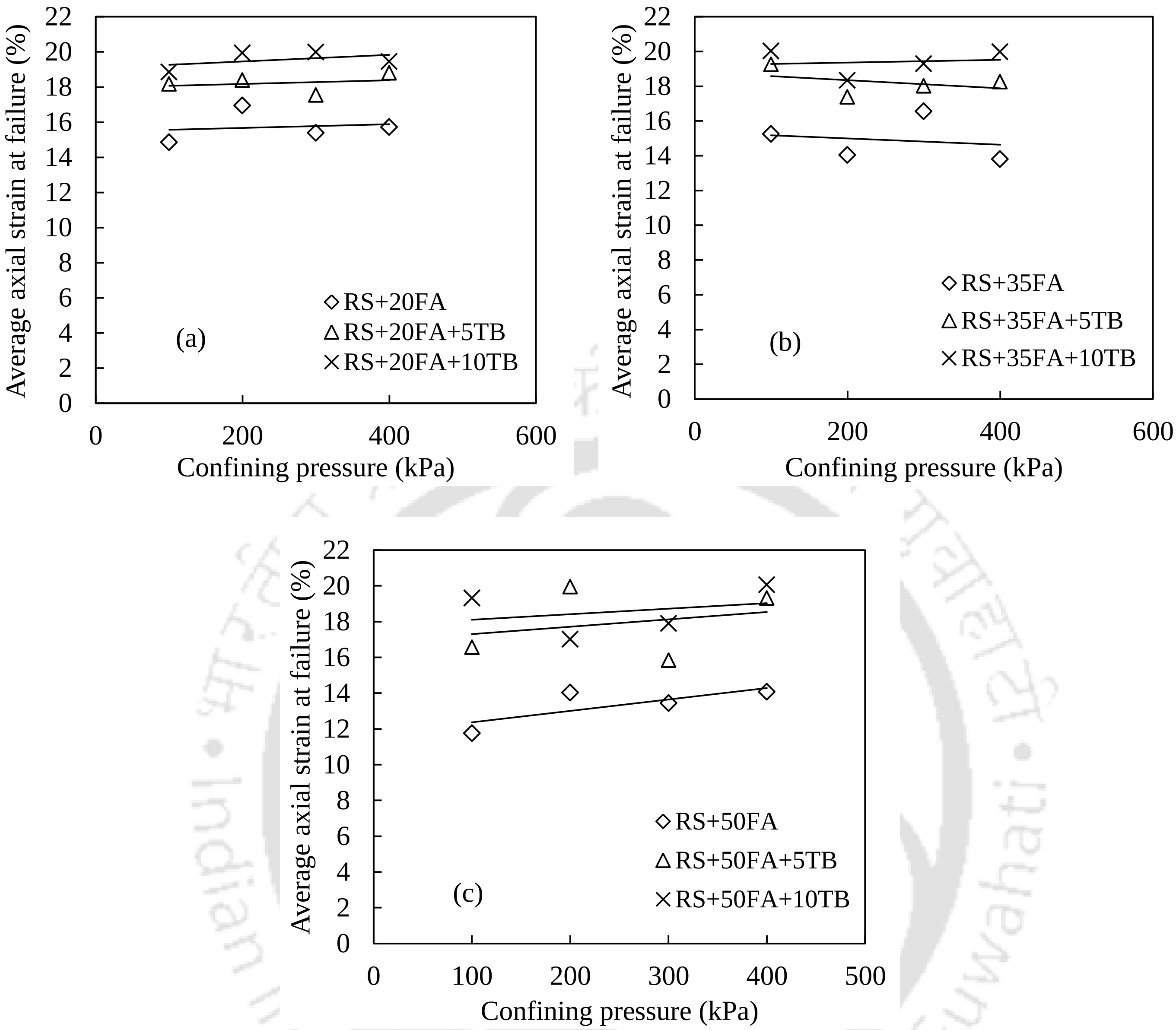


Fig. 6.13 Variation of failure axial strain of RS+FA and RS+FA+TB mixes at (a) 20%, (b) 35% and (c) 50% fly ash content

Table 6.6: Failure patterns of RS+FA+TB mixes tested at 300 kPa confining pressure

Curing	Mix			
	RS	RS+20FA+5TB	RS+35FA+5TB	RS+50FA+5TB
0 Day				
7 Days				
14 Days				
28 Days				
	Mix			
	RS	RS+20FA+10TB	RS+35FA+10TB	RS+50FA+10TB

0 Day				
7 Days				
14 Days				
28 Days				

6.3.4.2 Shear Strength Characteristics

Figs. 6.14 to 6.16 show the effect of tyre buffing inclusion on p-q plots of various soil mixes at 0, 7, 14 and 28 days of curing. It is seen that inclusion of TB reduces the strength of RS+FA mixes. Moreover, TB added mixes show greater strength than RS alone mixes and RS+35FA+5TB mix shows greater strength than any other mixes.

Variations of c and ϕ of RS+FA+TB mix with various curing periods are shown in Table 6.14. It is observed that RS+FA mixes show greater value of c and ϕ in comparison with RS+FA+TB mixes.

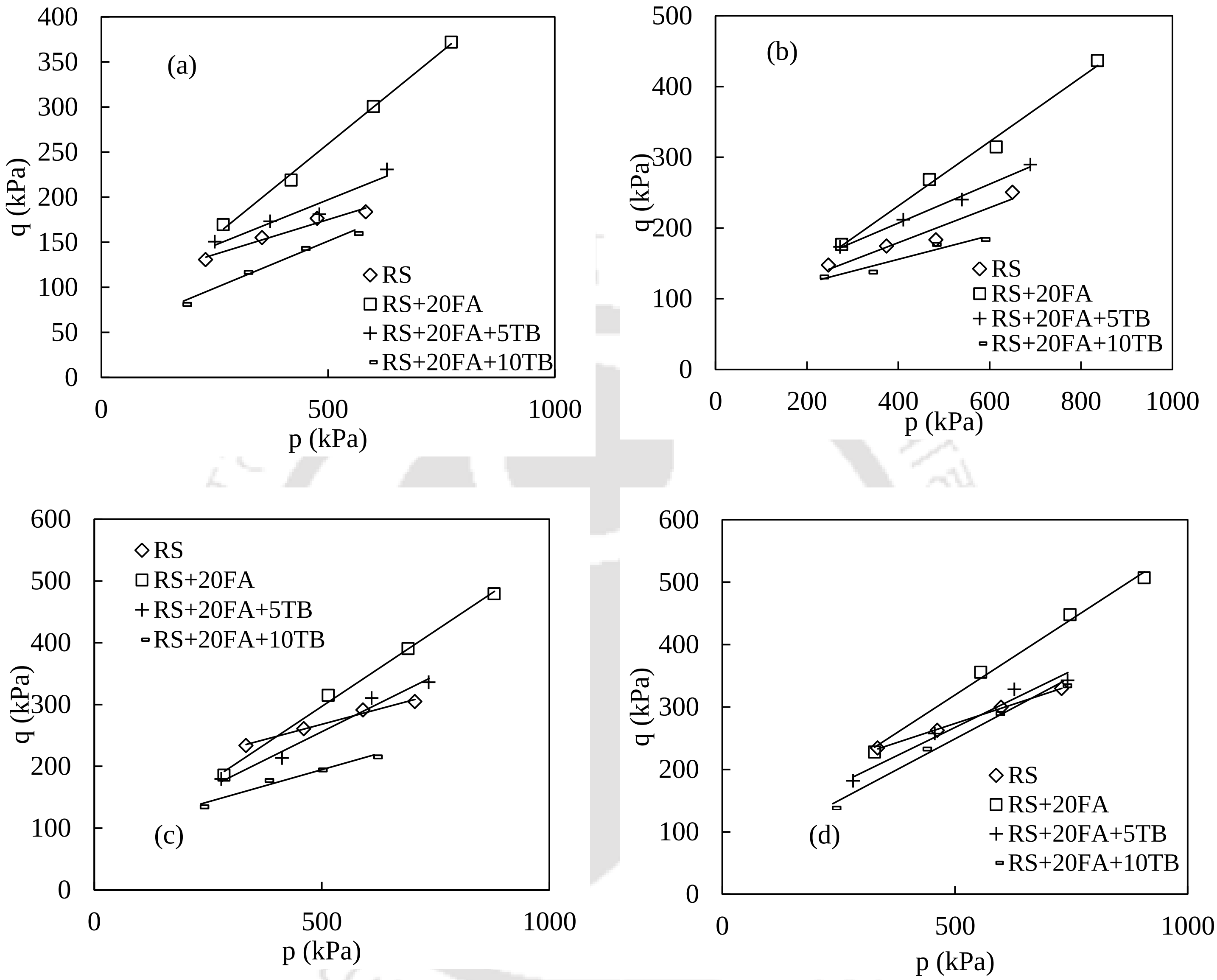


Fig. 6.14 p-q plots of red soil alone and RS+20FA+TB mixes for (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing

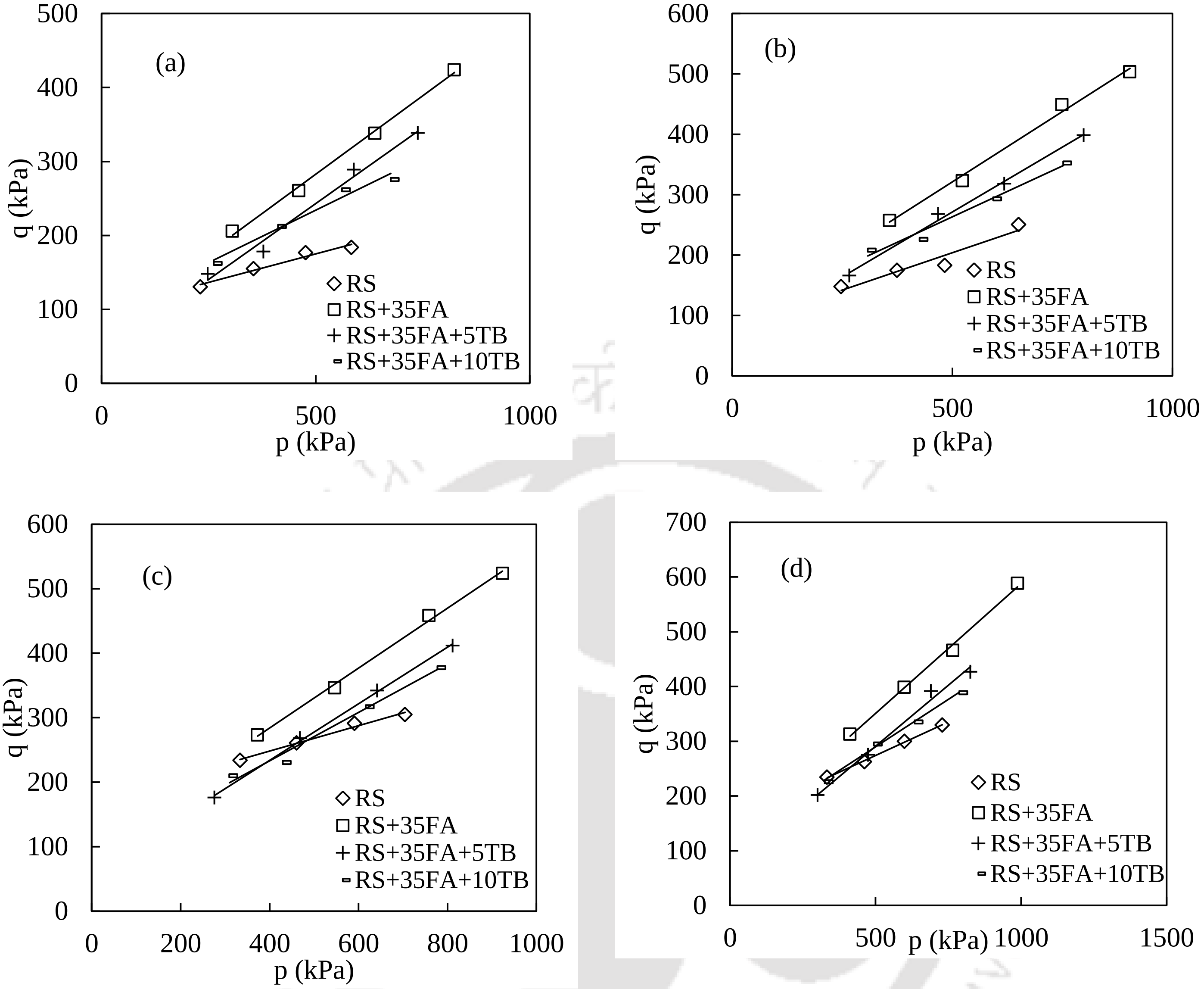


Fig. 6.15 p-q plots of red soil alone and RS+35FA+TB mixes for (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing

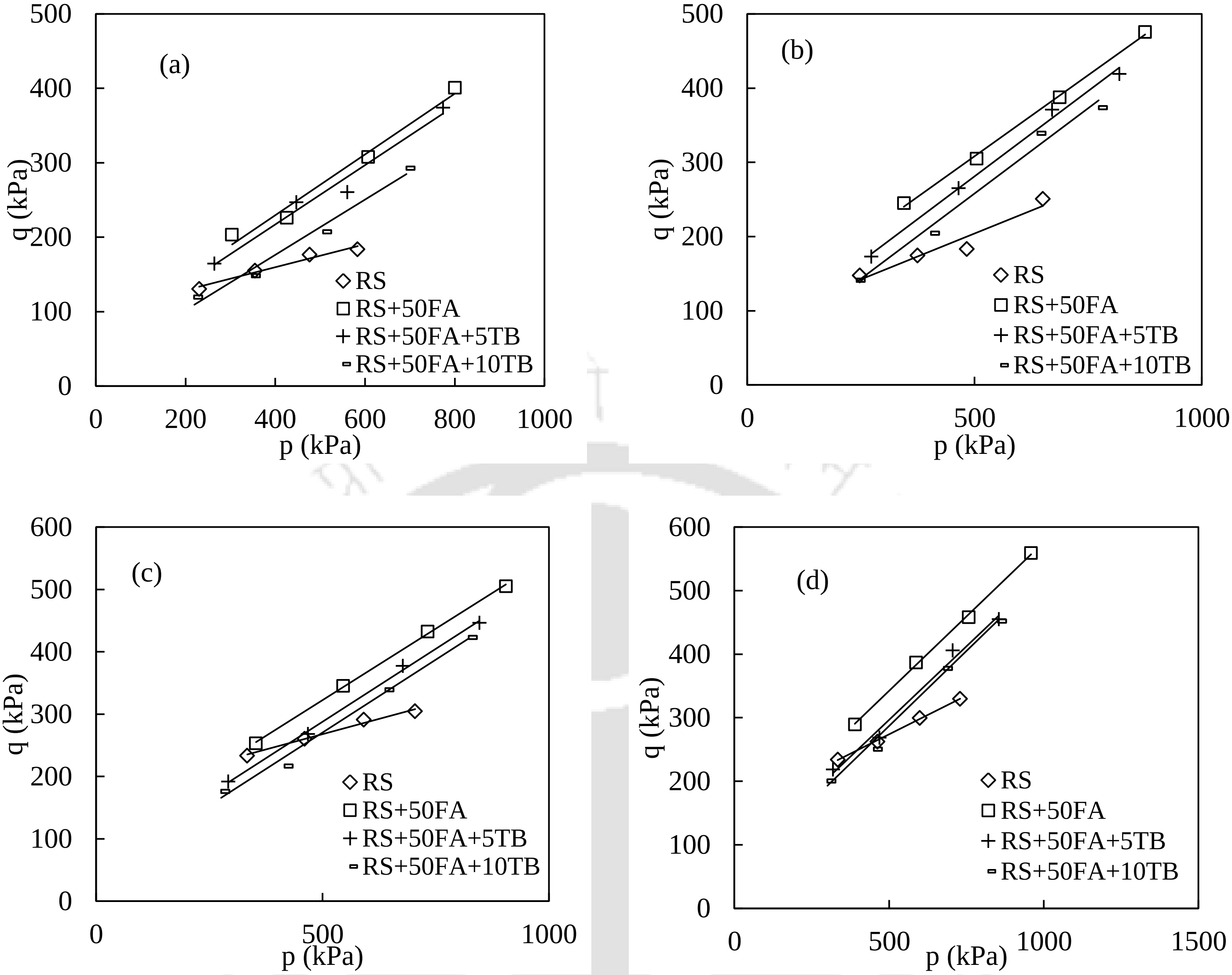


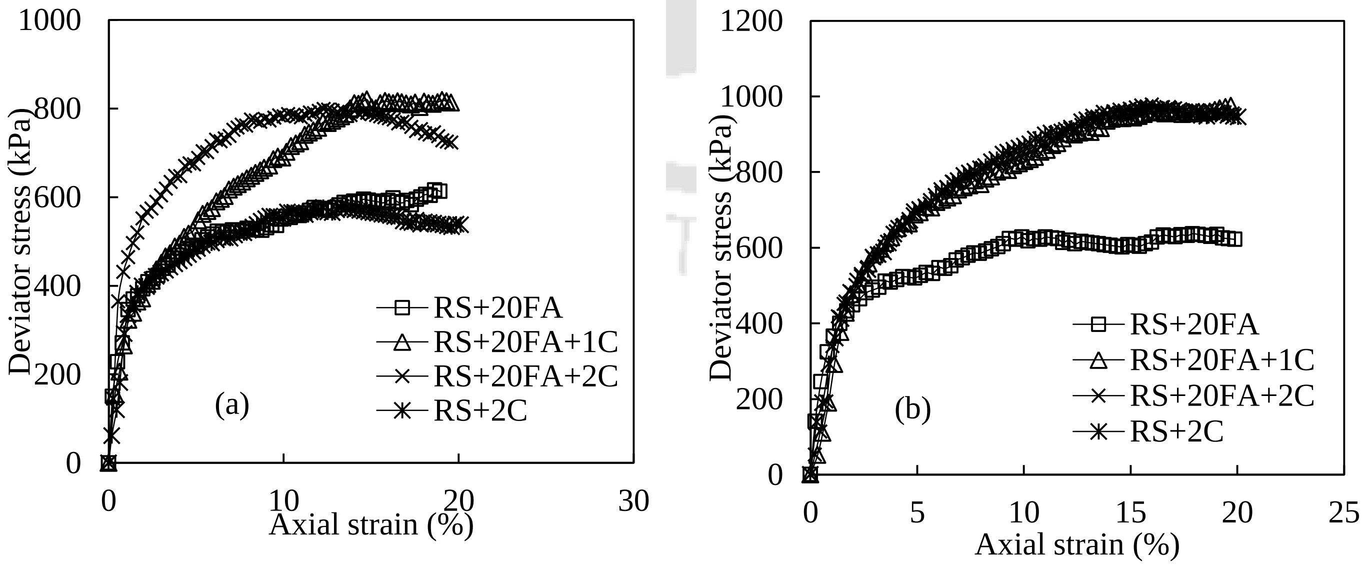
Fig. 6.16 p-q plots of red soil alone and RS+50FA+TB mixes for (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing

6.3.5 Effect of Cement Addition on Behaviour of Red Soil-Fly Ash Mixes

6.3.5.1 Stress-Strain Behaviour

Typical stress-strain plots of RS+FA+C, RS+2C and RS+FA mixes obtained at confining pressure of 300 kPa are shown in Figs. 6.17 to 6.19 for curing periods of 0, 7,14 and 28 days. It is seen that addition of cement increases the peak deviator stress and stiffness of the soil matrix. Peak strength, stiffness and brittleness are changed as a consequence of either the separate or combined effects of fly ash and cement. Among all mixes, RS+FA+2C mix shows greater peak deviator stress as shown in Table 6.11. It is seen that increase in cement content in RS+FA+C mixes improves the strength. Due to the occurrence of pozzolanic reaction, as the curing period increases the strength of cemented mixes also increases.

Effect of confining pressure and cement on variation of failure strain has been shown in Fig. 6.20. Table 6.7 depicts the failure patterns of different red soil-fly ash-cement mixes. Failure surface is seen in all cemented specimens. In 28 days curing period, failure surface is more clearly visible compared to other curing periods.



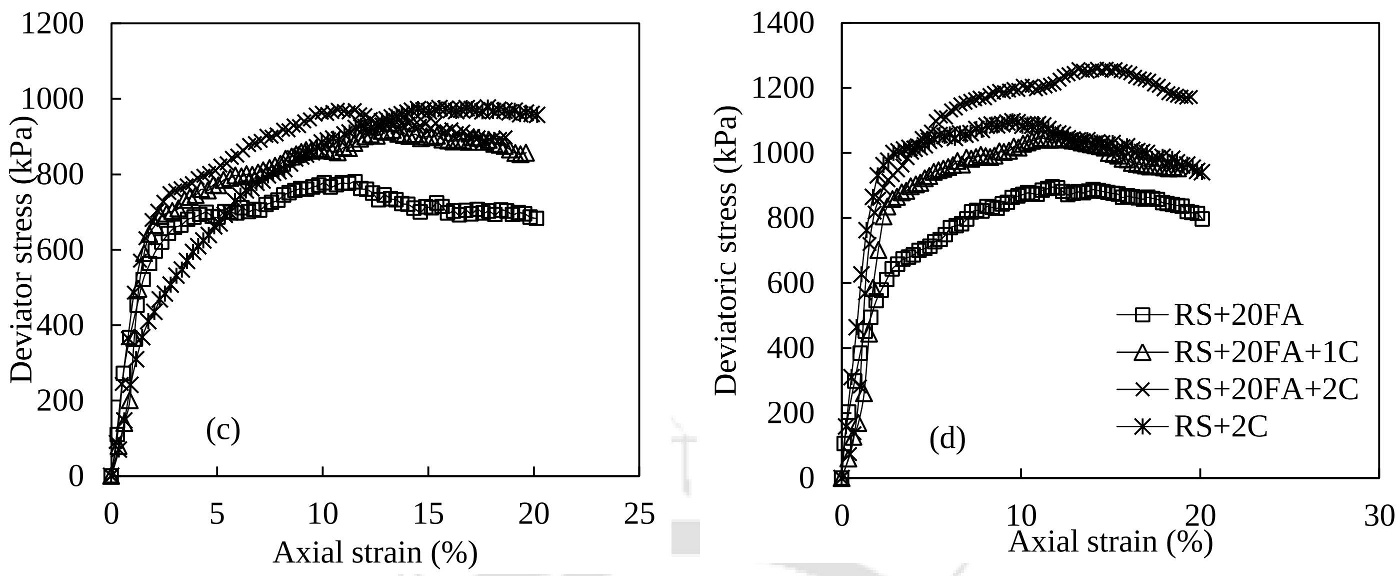
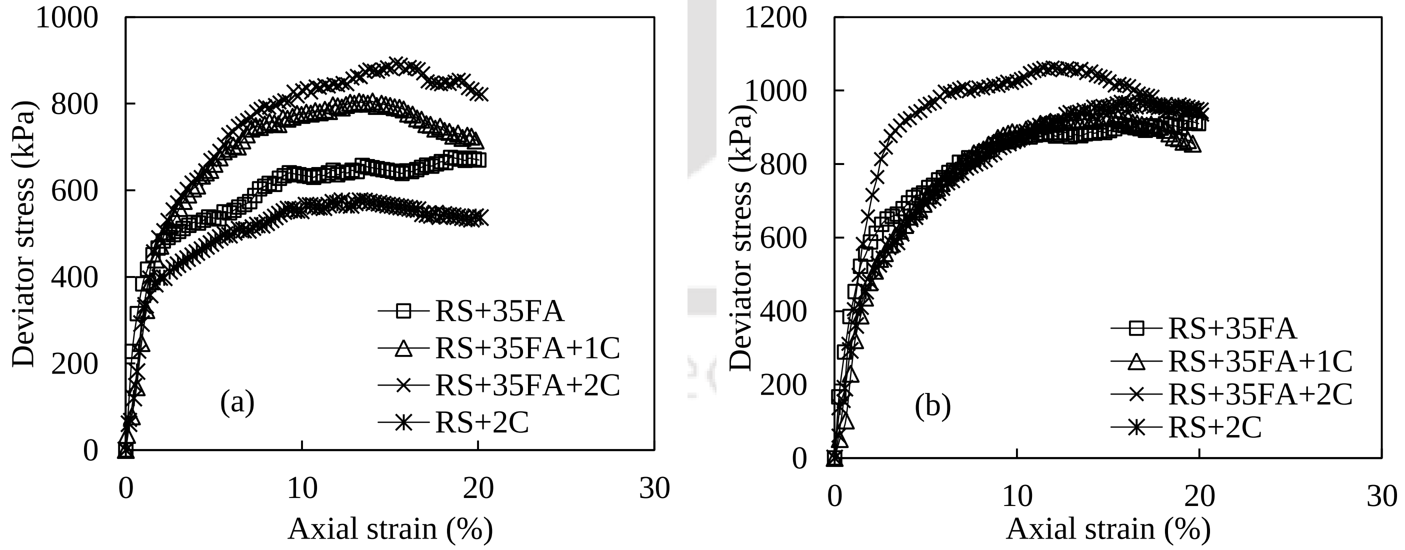


Fig. 6.17 Stress-strain behaviour of RS+2C and RS+20FA+C mixes at 300 kPa confining pressure for (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing period



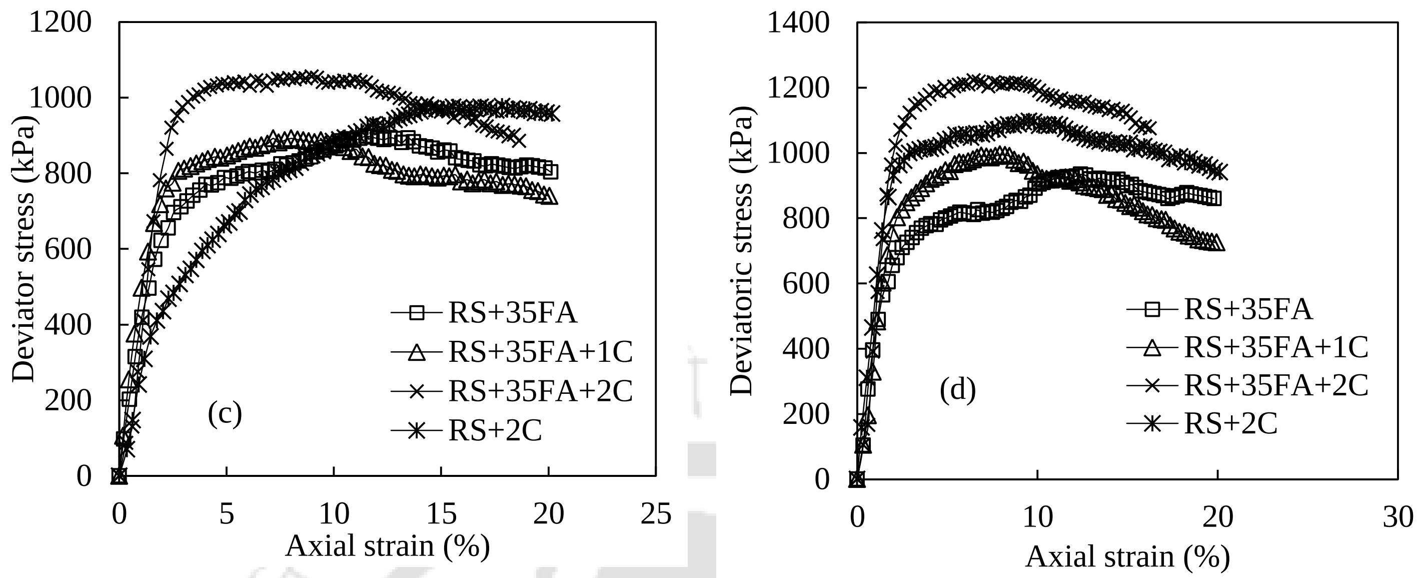
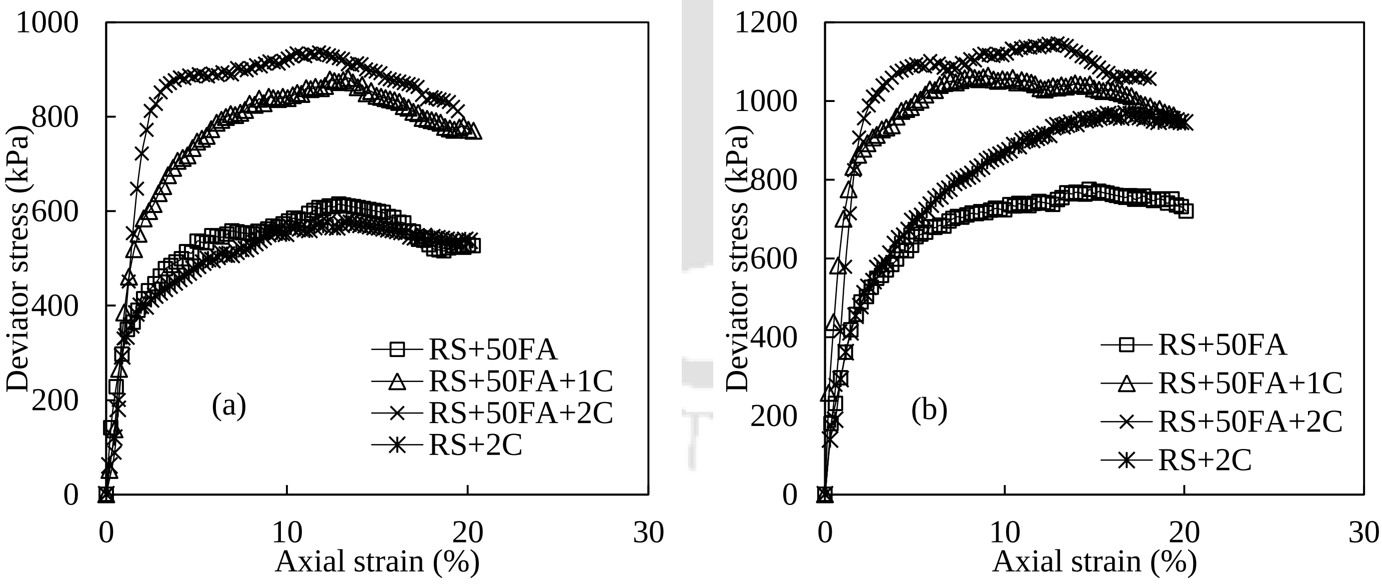


Fig. 6.18 Stress-strain behaviour of RS+2C and RS+35FA+C mixes at 300 kPa confining pressure for (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing period



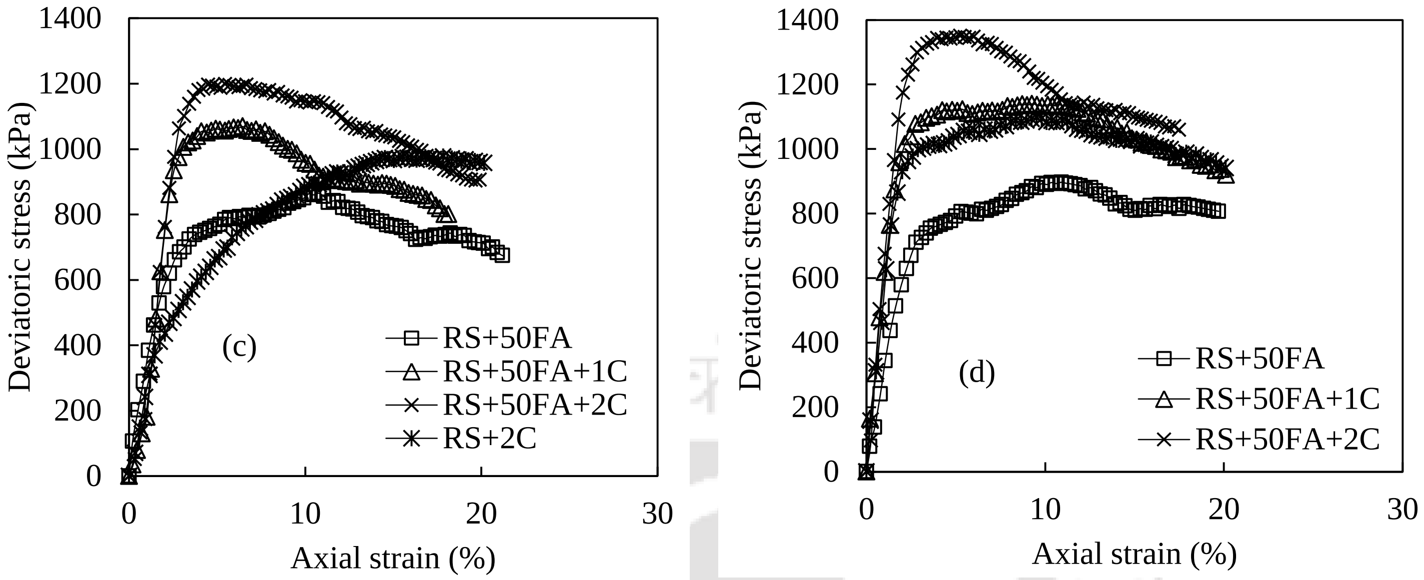
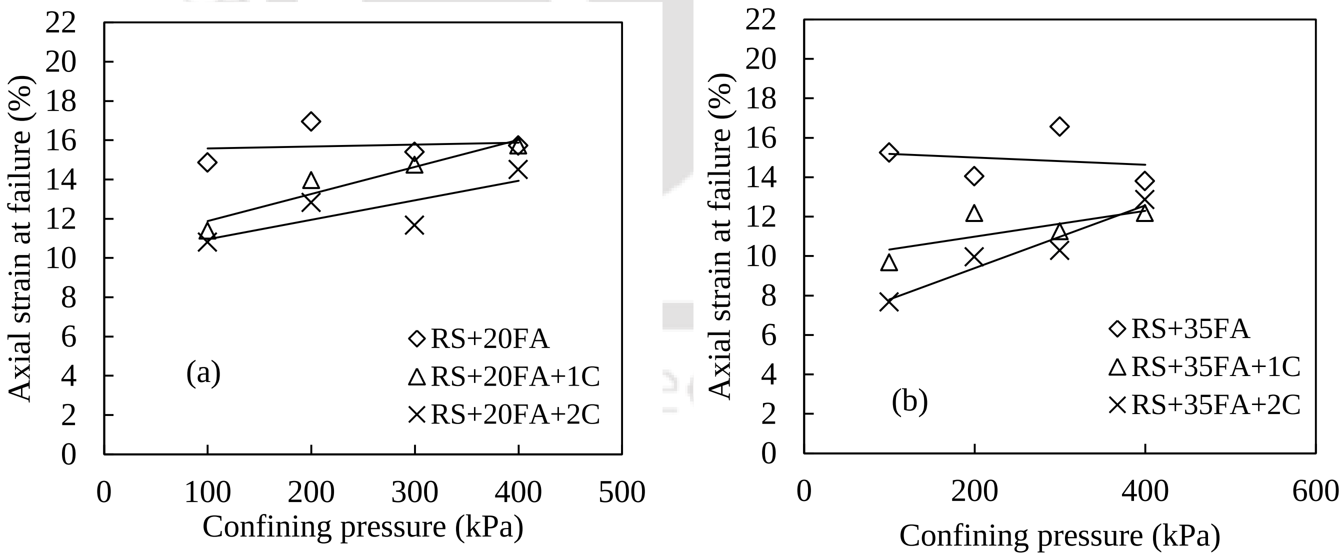


Fig. 6.19 Stress-strain behaviour of RS+2C and RS+50FA+C mixes at 300 kPa confining pressure for (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing period



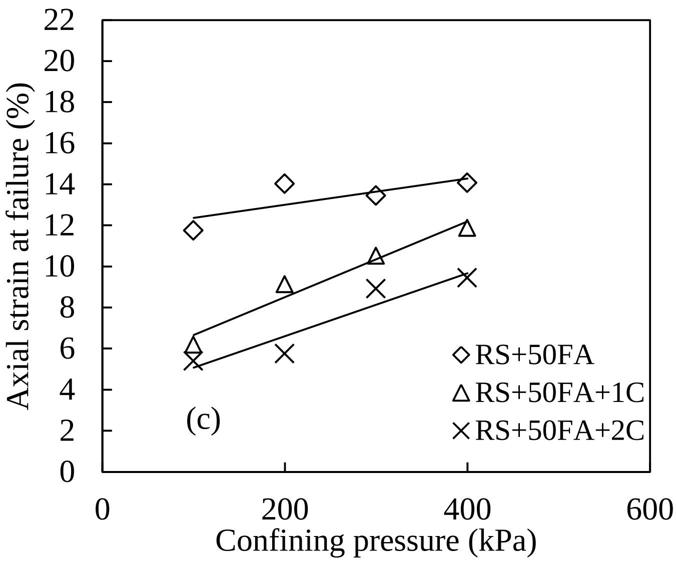


Fig. 6.20 Variation of failure axial strain of RS+FA and RS+FA+TC mixes at (a) 20%, (b) 35% and (c) 50% fly ash content

Table 6.7: Failure patterns of RS+FA+C mixes tested at 300 kPa confining pressure

Curing	Mix			
	RS	RS+20FA+1C	RS+35FA+1C	RS+50FA+1C
0 Day				
7 Days				

14 Days				
28 Days				
	Mix			
	RS	RS+20FA+2C	RS+35FA+2C	RS+50FA+2C
0 Day				
7 Days				

14 Days				
28 Days				

6.3.5.2 Shear Strength Envelope

Figs. 6.21 to 6.23 show the p-q plots of RS+FA and RS+FA+C mixes for 0, 7, 14 and 28 days of curing periods. It is observed that on addition of cement to red soil-fly ash mixes shear strength increases. Generally as the fly ash and cement content in the mix increases the strength also increases.

Table 6.15 shows the effect of fly ash and cement content on cohesion and internal friction angle of different RS mixes. It is seen that addition of 2% cement to soil-fly ash mixes increases the cohesion component (c). The increase in cohesion intercept reflects the increase in cementation, while the change in the friction angle is probably linked to alterations in soil texture. But a nonlinear behaviour has been seen in case of variation of internal frictional angle (ϕ) with fly ash and cement content of different soil mixes.

Pandian and Krishna (2002) reported the effect of cement addition on undrained shear strength behaviour of soil-fly ash mixes. The addition of cement has increased both friction angle and cohesion intercept of the fly ash-soils mixes. It can be observed that the strength development is significant within seven days curing.

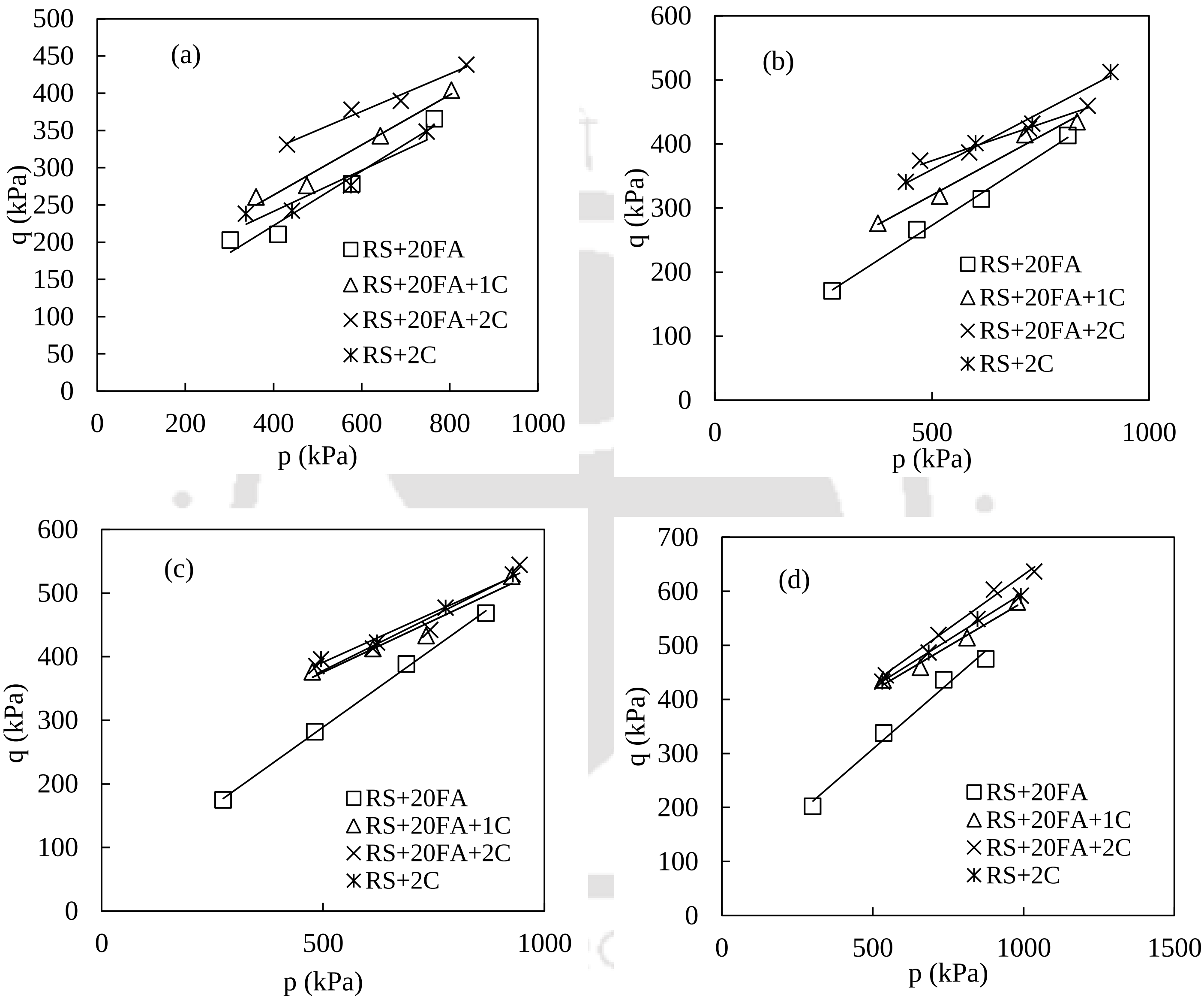


Fig. 6.21 p-q plots of RS+2C and RS+20FA+C mixes for (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing

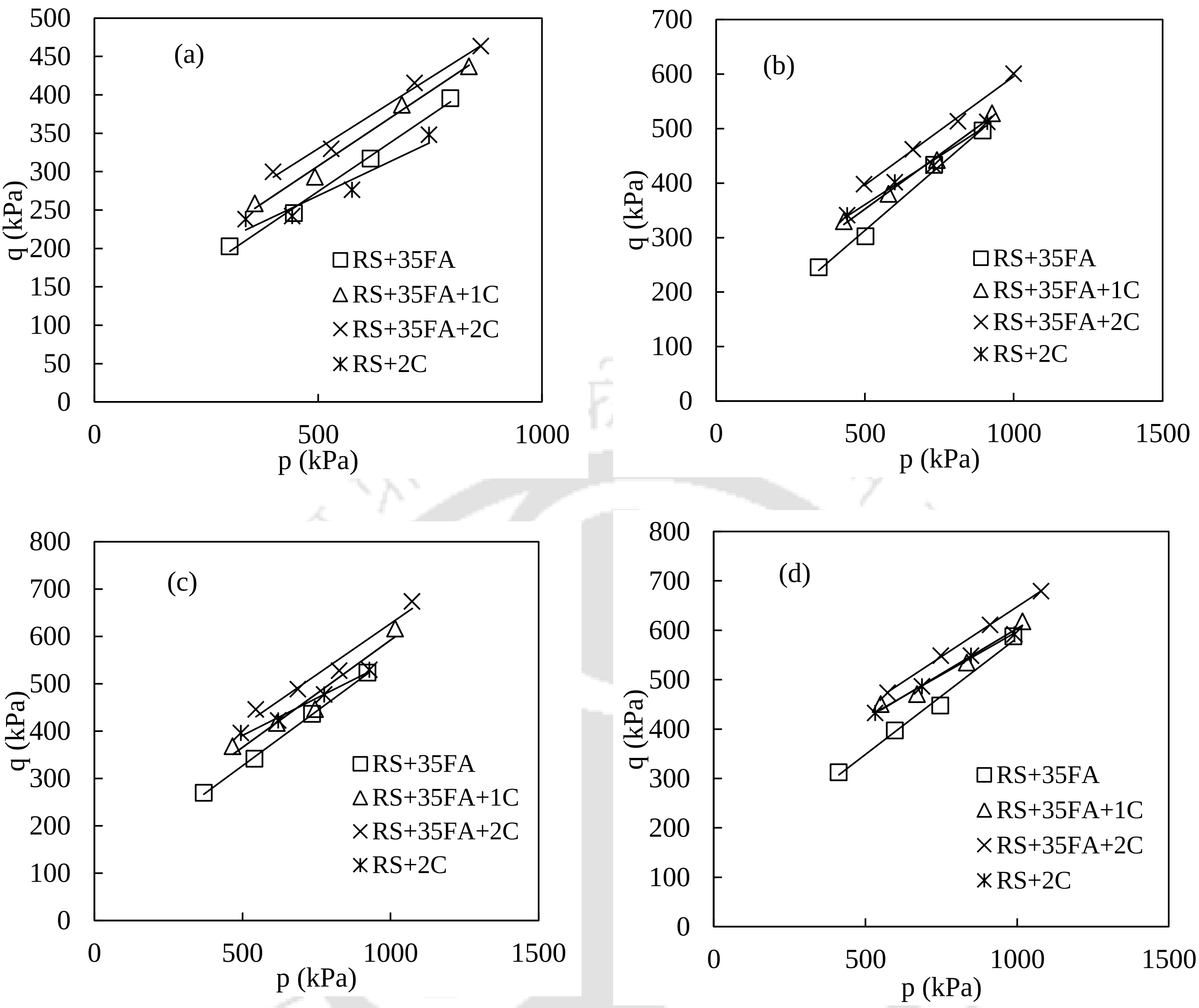


Fig. 6.22 p-q plots of RS+2C and RS+35FA+C mixes for (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing

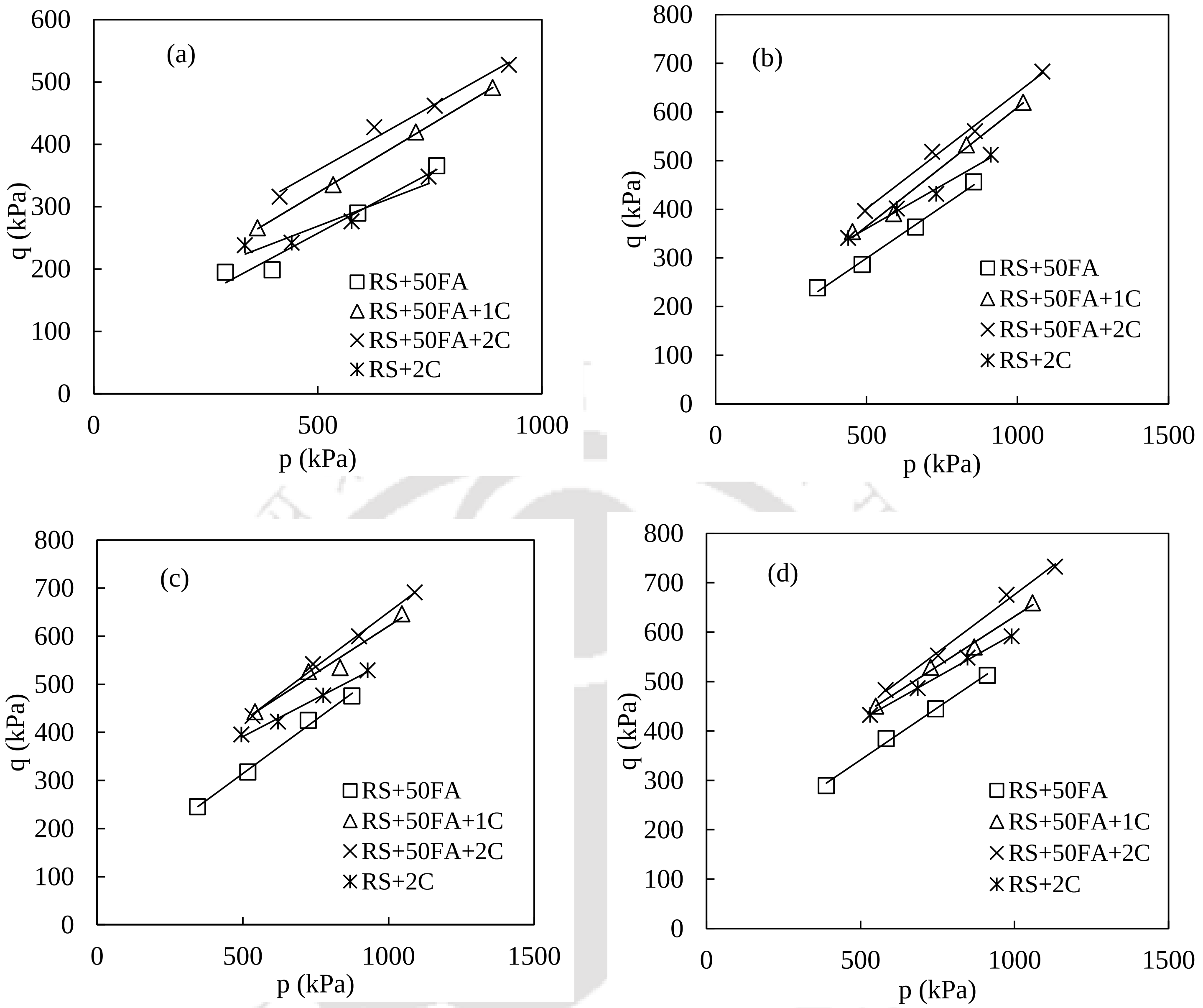


Fig. 6.23 p-q plots of RS+2C and RS+50FA+C mixes for (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing

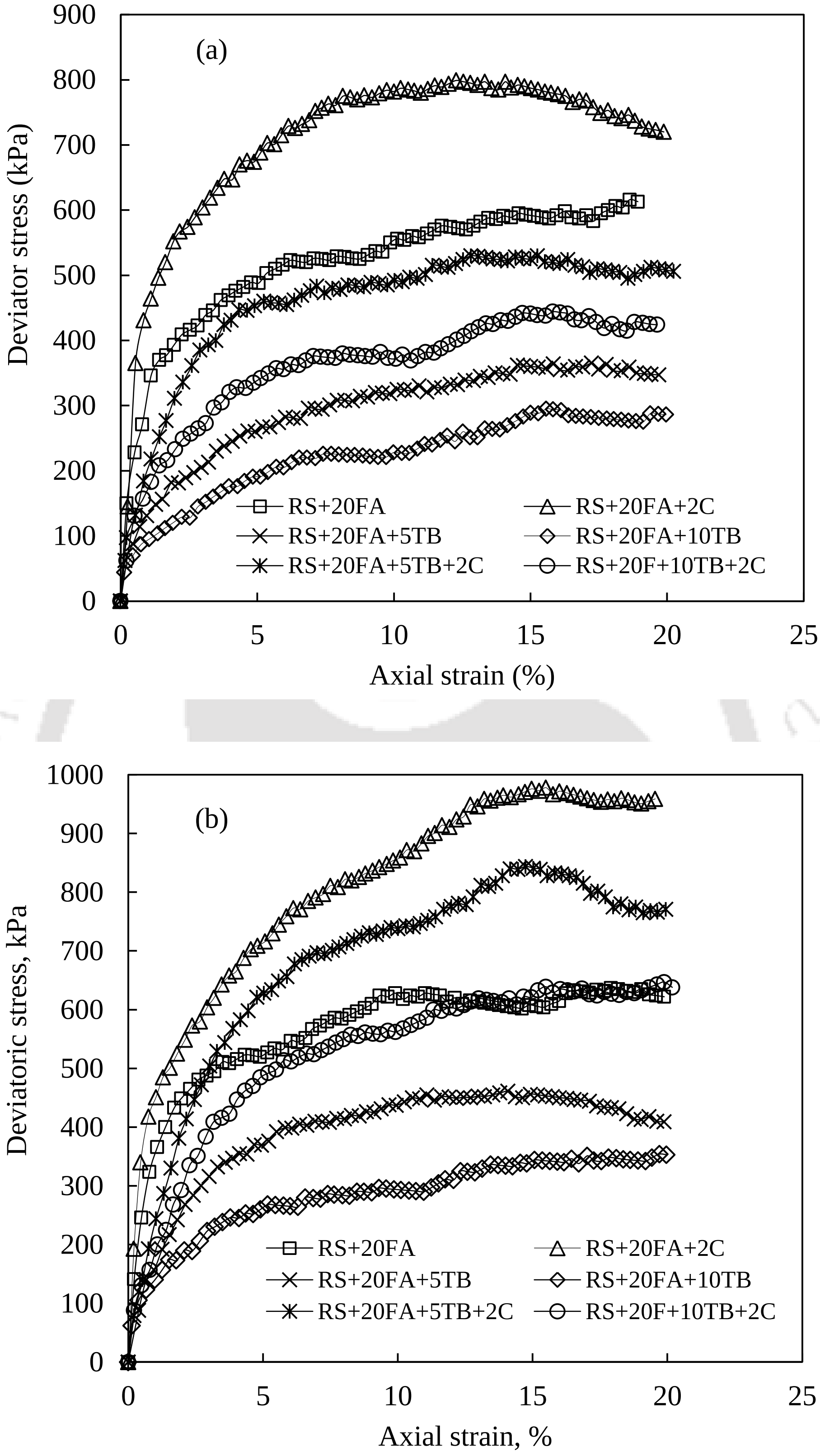
6.3.6 Effect of Cement Addition on Red Soil-Fly Ash-Tyre Buffing (TB) Mixes

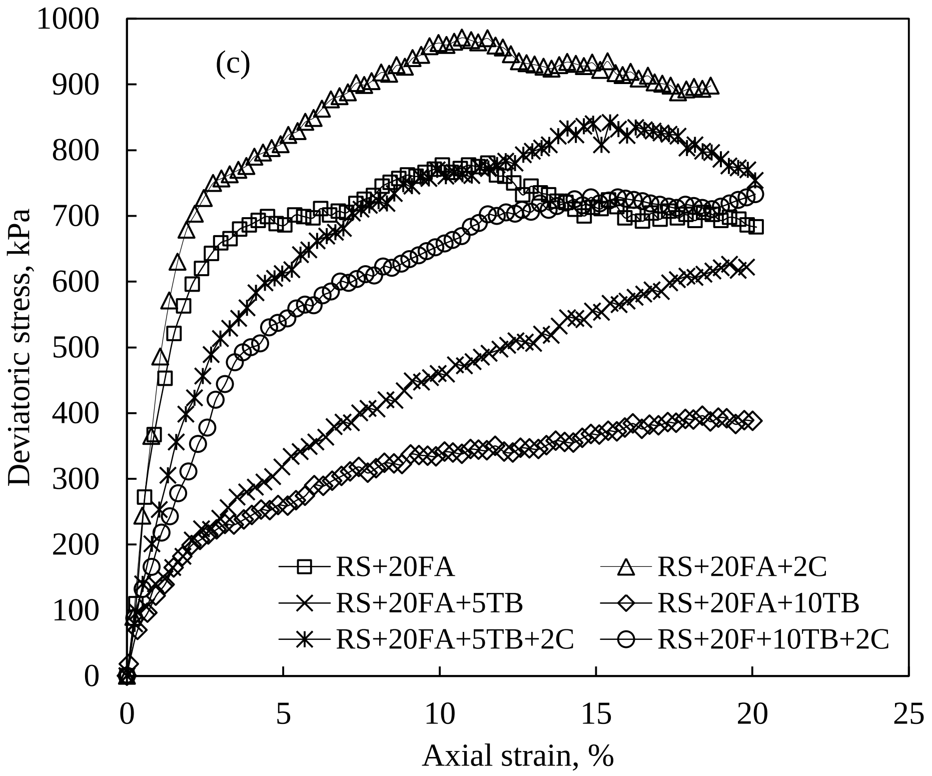
6.3.6.1 Stress-Strain Behaviour

Figs. 6.24 to 6.26 show that the addition of 2% cement to RS+FA+TB mixes increases the peak deviator stress of the specimens when compared to RS+FA mixes and it is more prominent for the specimens tested with curing period. RS+FA+TB+2C mixes fail at larger strain in comparison with RS+FA and RS+FA+2C mixes. Stiffness of RS+FA+TB+2C mixes is lower than RS+FA and RS+FA+2C mixes. Table 6.12 summarizes the peak deviator stress values of different cemented red soil-fly ash-tyre buffing mixes.

Hazarika et al. (2010) also found that the ductile behaviour in the triaxial tests improves as the tyre chip content in the mixes increases. Mixing of tyre chips with cement-treated clay adds a useful characteristic (toughness or ductility) to cement-treated clay which possesses a salient disadvantage of brittleness.

Fig. 6.27 reveals that addition of 2% cement to red soil-fly ash-tyre buffing mixes decreases the failure strain of the mixes. In some cases, bulging failure has been observed in TB added specimens as shown in Table 6.8, and no peak deviator stress was observed till 20% axial strain. This is due to the ductile behaviour induced by the tyre buffing inclusions. Specimens with TB fail at higher axial strain than those without TB. Inclusion of tyre buffing reduces the stiffness of soil mixes.


(a)
Deviator stress (kPa)
Axial strain (%)
RS+20FA
RS+20FA+2C
RS+20FA+5TB
RS+20FA+10TB
RS+20FA+5TB+2C
RS+20F+10TB+2C
(b)
Deviatoric stress, kPa
Axial strain, %
RS+20FA
RS+20FA+2C
RS+20FA+5TB
RS+20FA+10TB
RS+20FA+5TB+2C
RS+20F+10TB+2C



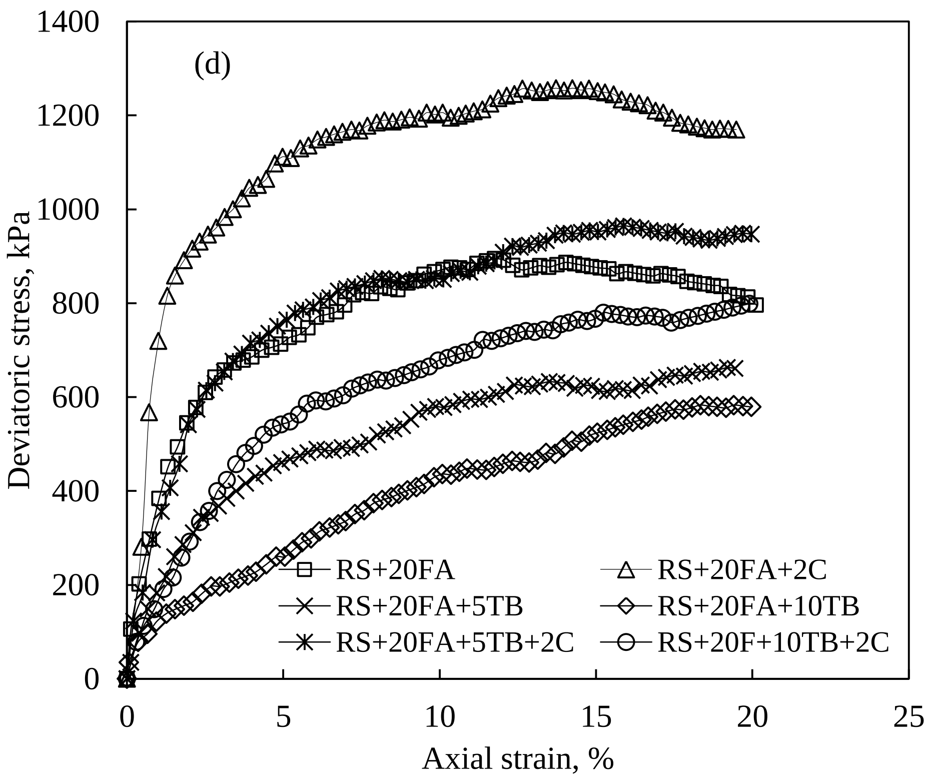
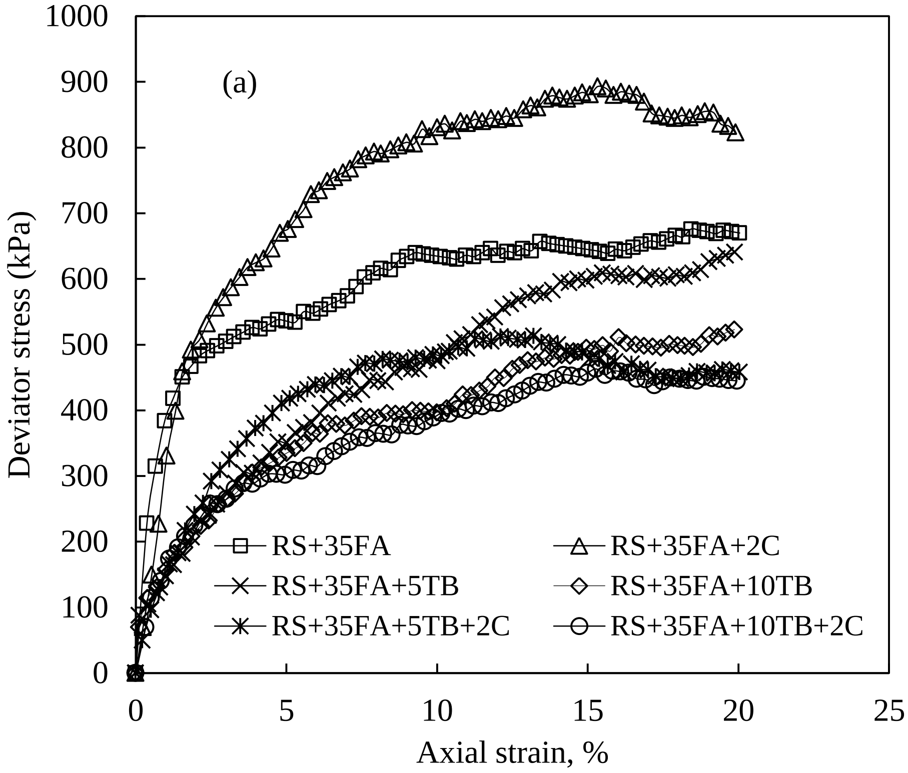
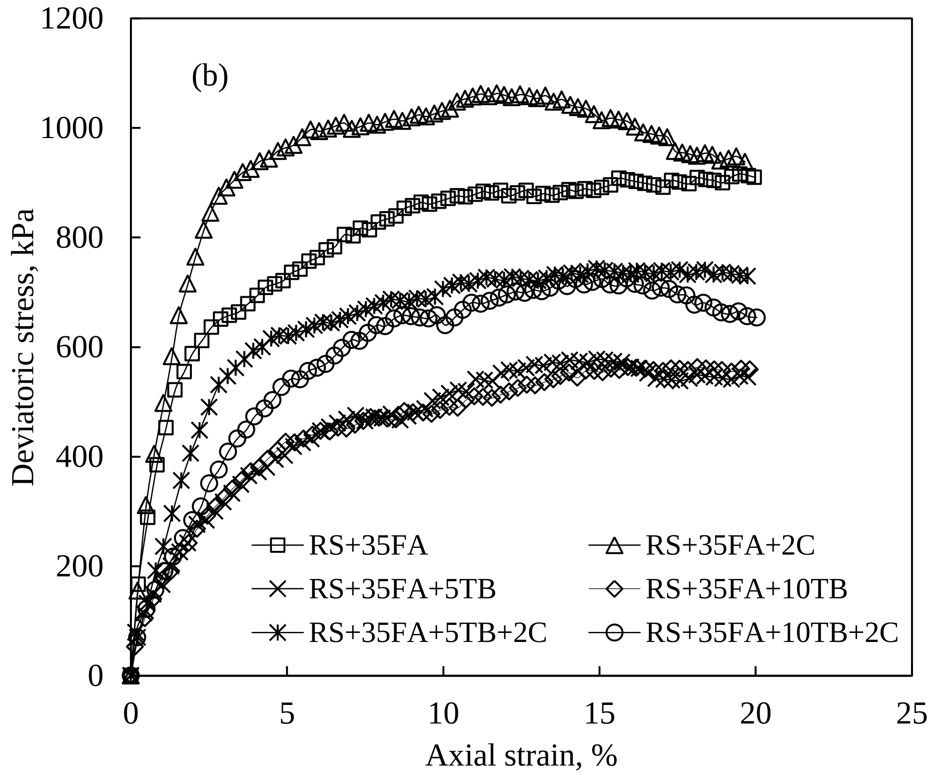
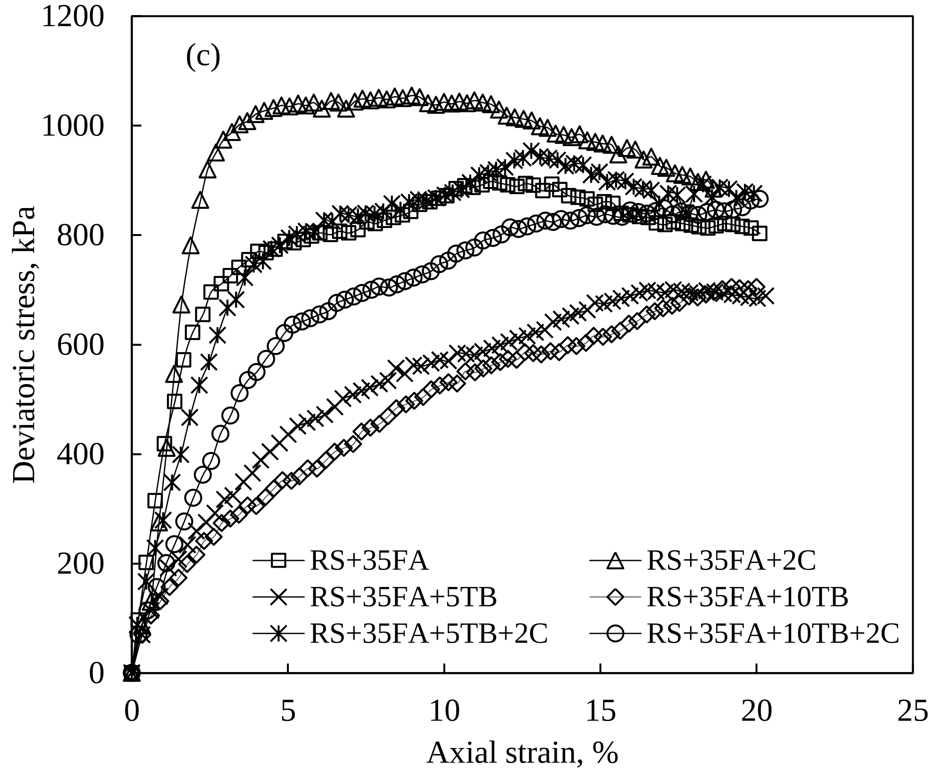


Fig. 6.24 Stress-strain behaviour of RS+20FA+TB+C mixes at 300 kPa confining pressure for (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing period


(a)
Deviator stress (kPa)
Axial strain, %
RS+35FA
RS+35FA+2C
RS+35FA+5TB
RS+35FA+10TB
RS+35FA+5TB+2C
RS+35FA+10TB+2C


(b)
Deviatoric stress, kPa
Axial strain, %
RS+35FA
RS+35FA+2C
RS+35FA+5TB
RS+35FA+10TB
RS+35FA+5TB+2C
RS+35FA+10TB+2C



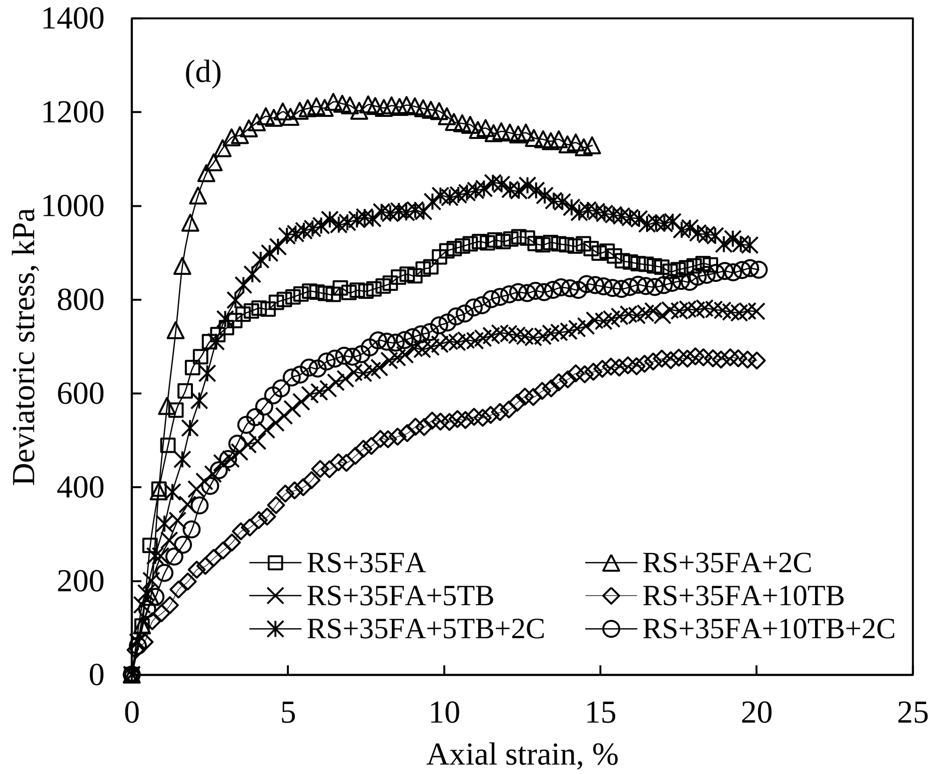
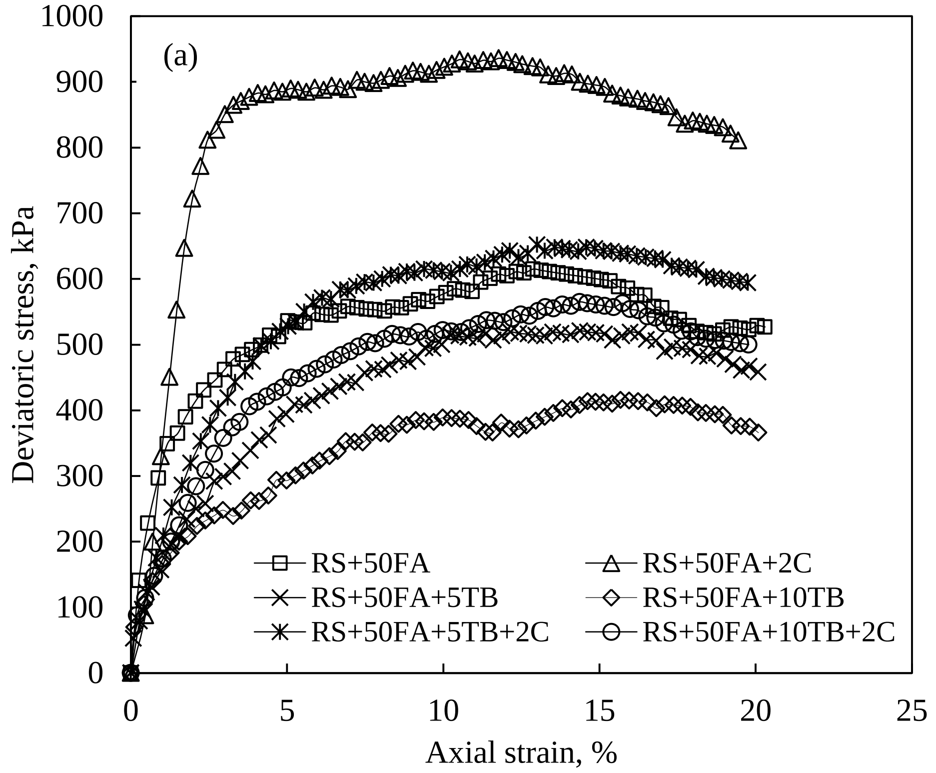
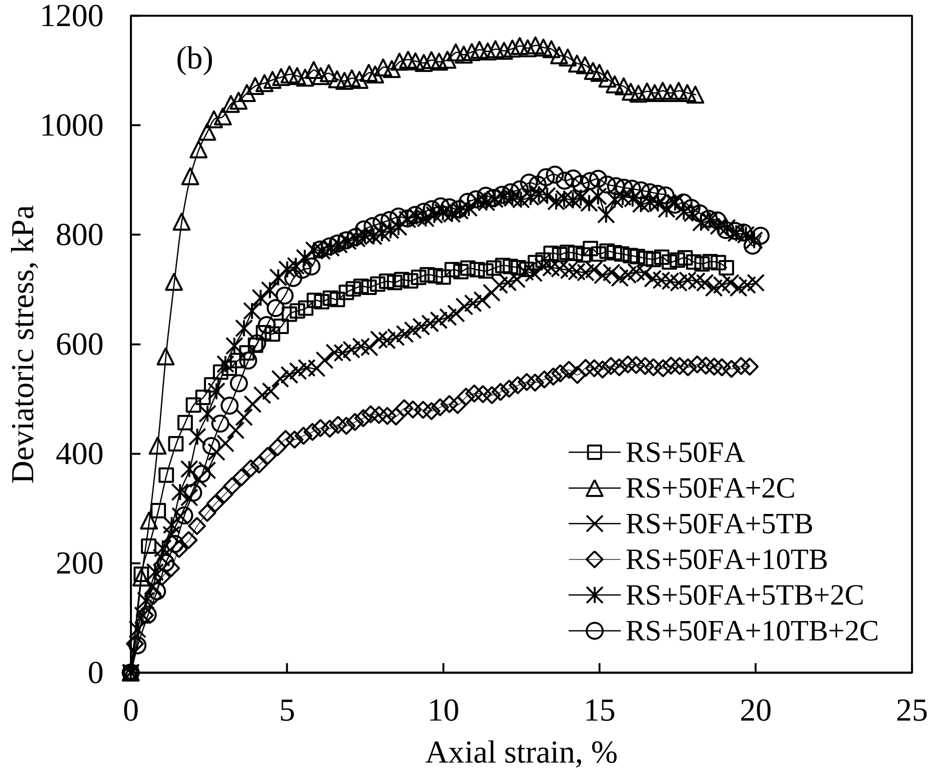


Fig. 6.25 Stress-strain behaviour of RS+35FA+TB+C mixes at 300 kPa confining pressure for (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing period



(a)
Deviatoric stress, kPa
Axial strain, %
RS+50FA
RS+50FA+2C
RS+50FA+5TB
RS+50FA+10TB
RS+50FA+5TB+2C
RS+50FA+10TB+2C



(b)
Deviatoric stress, kPa
Axial strain, %
RS+50FA
RS+50FA+2C
RS+50FA+5TB
RS+50FA+10TB
RS+50FA+5TB+2C
RS+50FA+10TB+2C

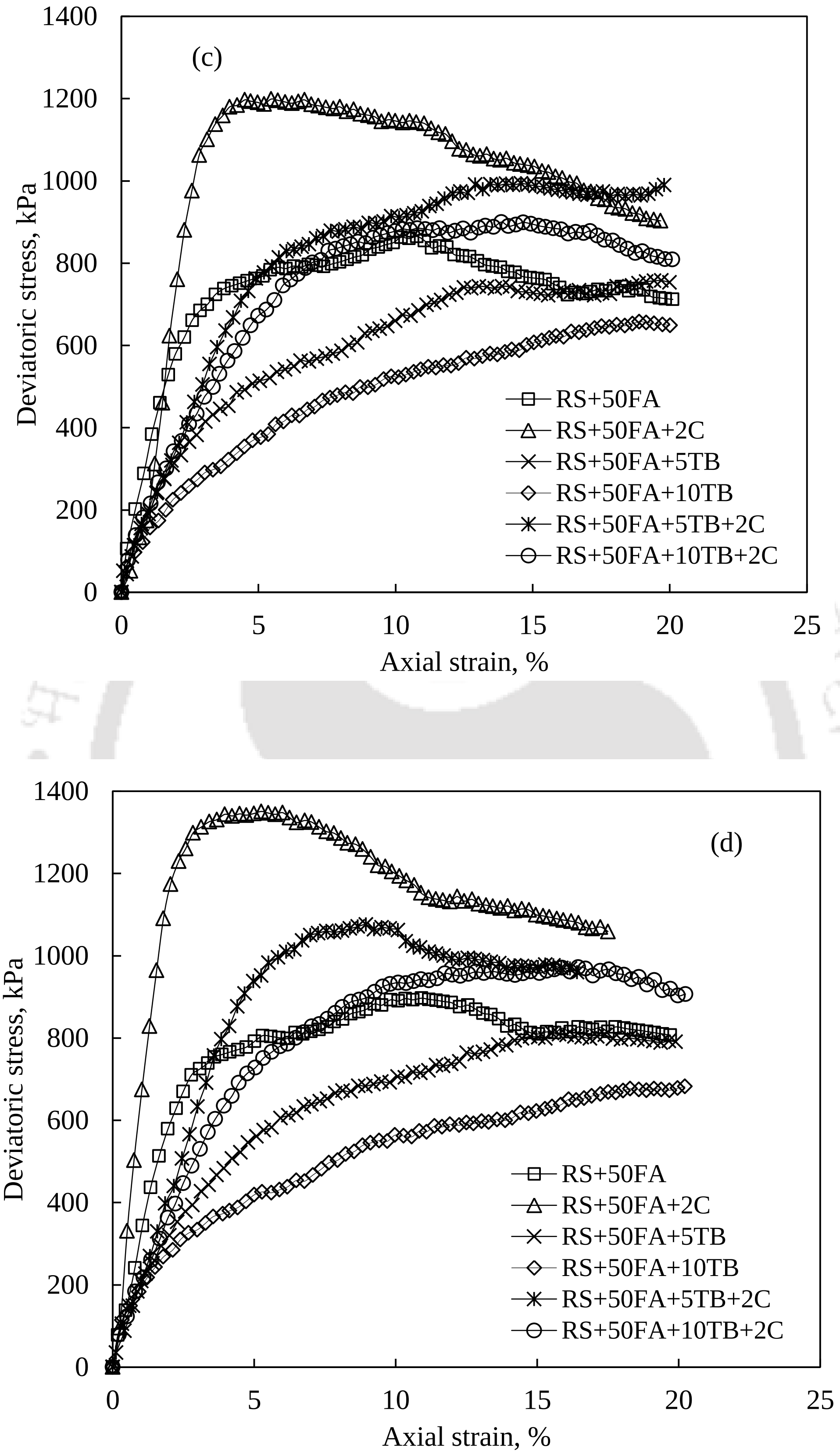


Fig. 6.26 Stress-strain behaviour of RS+50FA+TB+C mixes at 300 kPa confining pressure for (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing period

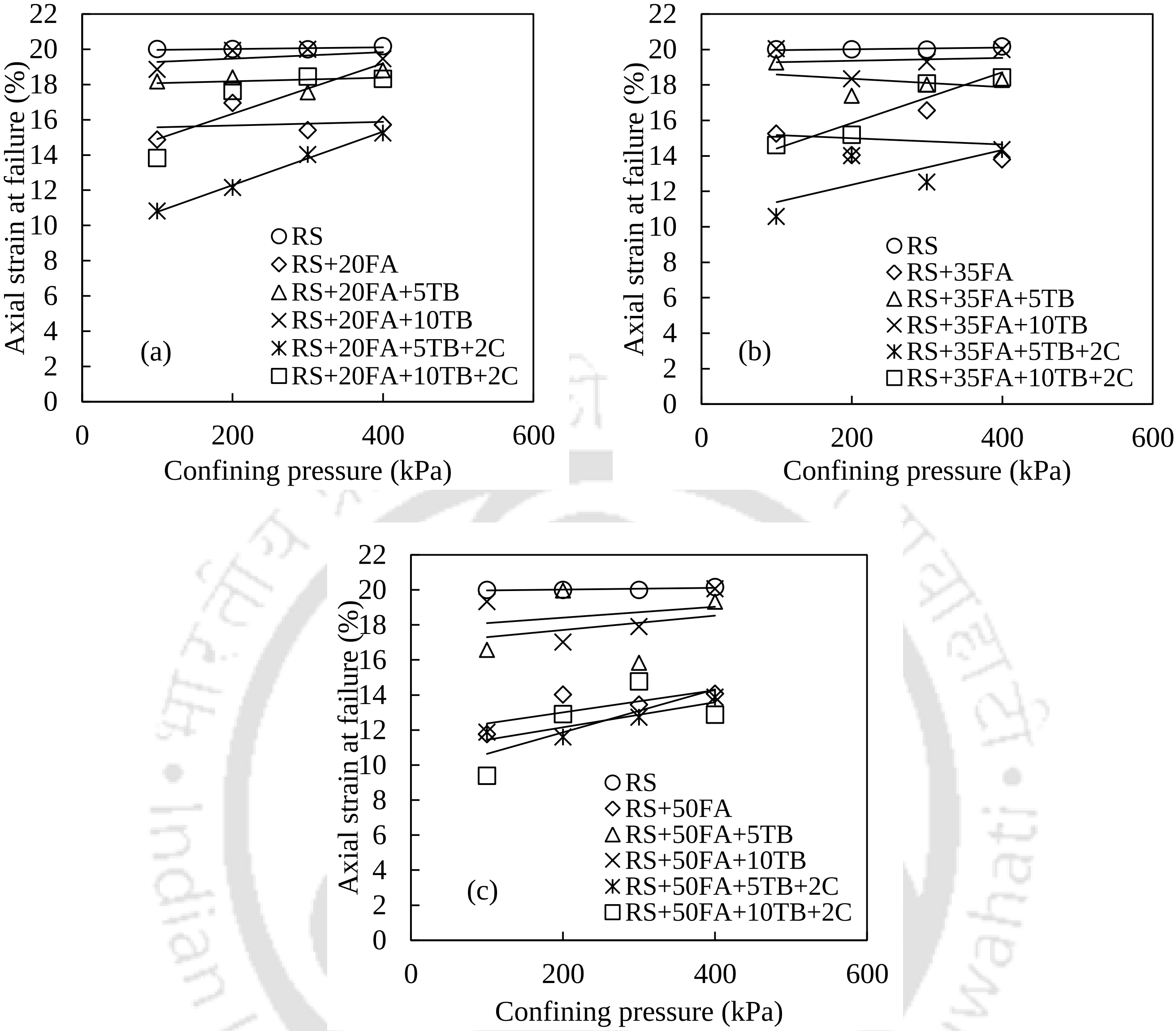


Fig. 6.27 Variation of failure axial strain of RS+FA, RS+FA+TB and RS+FA+TB+2C mixes at (a) 20%, (b) 35% and (c) 50% fly ash content

Table 6.8: Failure patterns of RS+FA+TB+2C mixes tested at 300 kPa confining pressure

Curing	Mix			
	RS	RS+20FA+5TB+2C	RS+35FA+5TB+2C	RS+50FA+5TB+2C
0 Day				
7 Days				
14 Days				
28 Days				
	Mix			
	RS	RS+20FA+10TB+2C	RS+35FA+10TB+2C	RS+50FA+10TB+2C

0 Day				
7 Days				
14 Days				
28 Days				

6.3.6.2 Shear Strength Characteristics

From Figs. 6.28 to 6.30, it is seen that addition of 2% cement content causes improvement in peak strength of RS+FA+TB mixes. It is also observed that the peak strength increases with increase in fly ash content in RS+FA+TB+2C mixes and this is due to the pozzolanic reaction that has occurred within the specimen.

Table 6.16 shows the shear strength parameters of different cemented

RS+FA+TB mix at different curing periods. In most of the cases, it is seen that addition of 2% cement to RS+FA+TB samples increases the cohesion component, but variation of internal friction angle is non-linear.

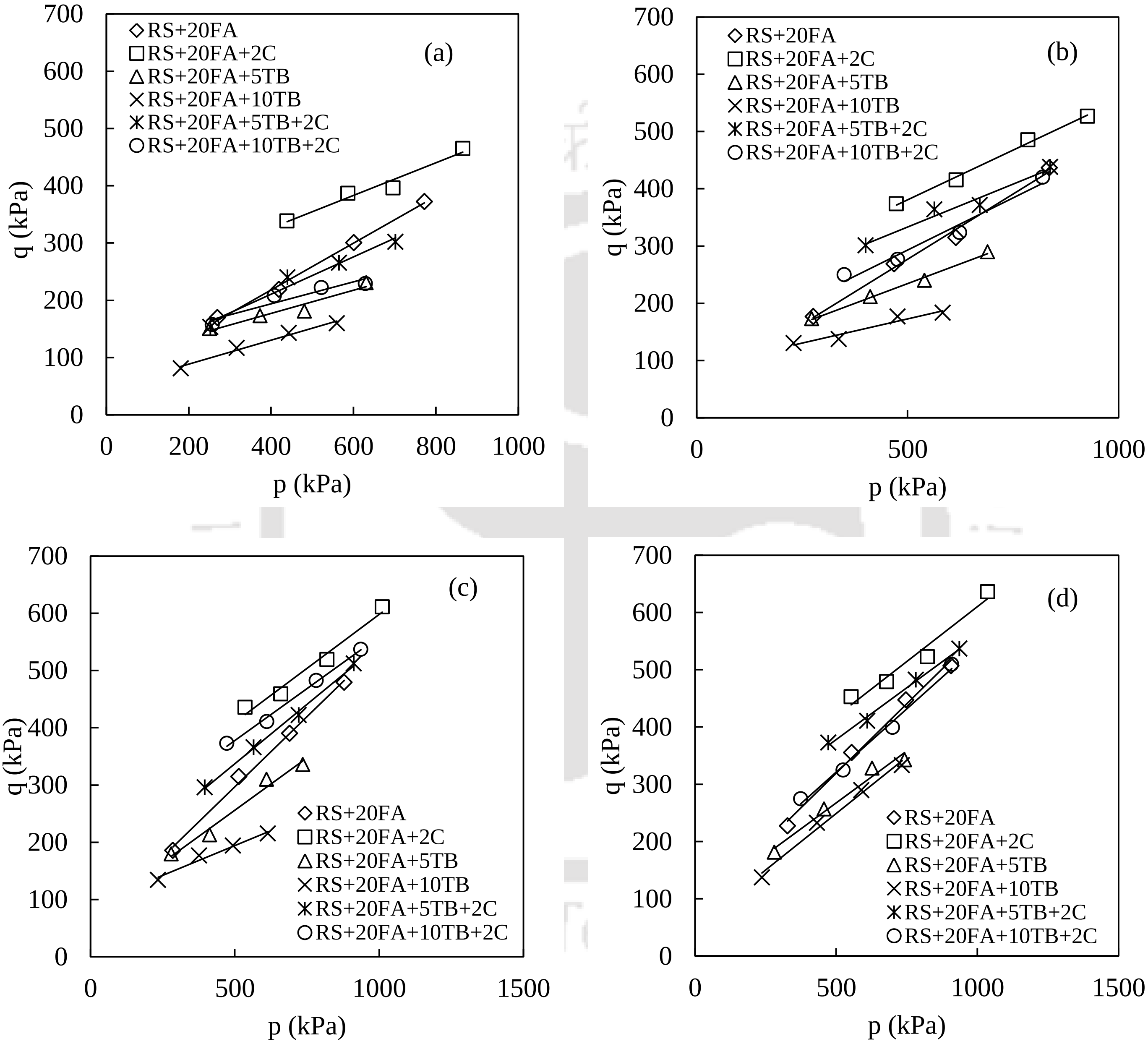


Fig. 6.28 p-q plots of RS+20FA, RS+20FA+TB and RS+20FA+TB+2C mixes for (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing

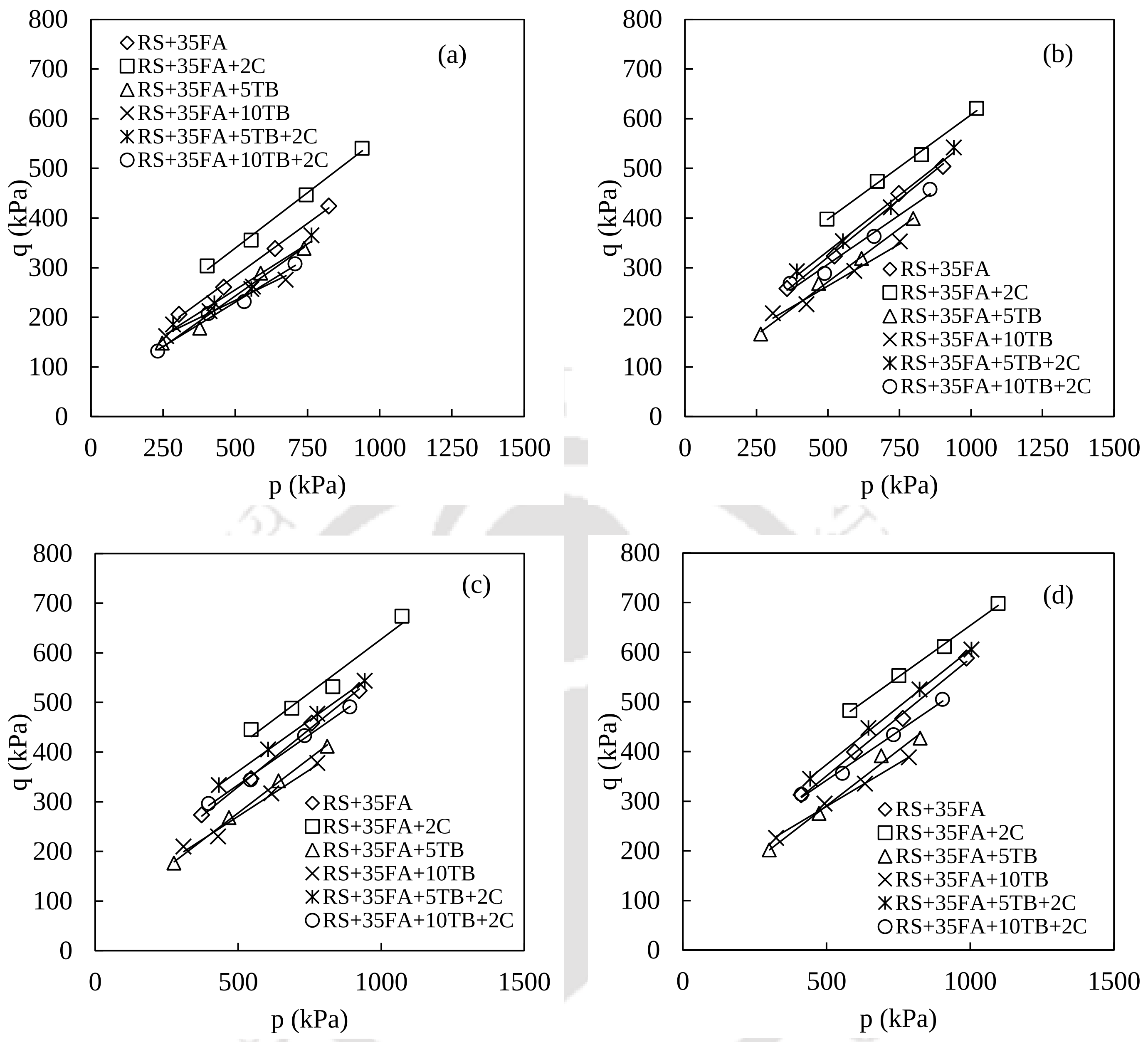


Fig. 6.29 p-q plots of RS+35FA, RS+35FA+TB and RS+35FA+TB+2C mixes for (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing

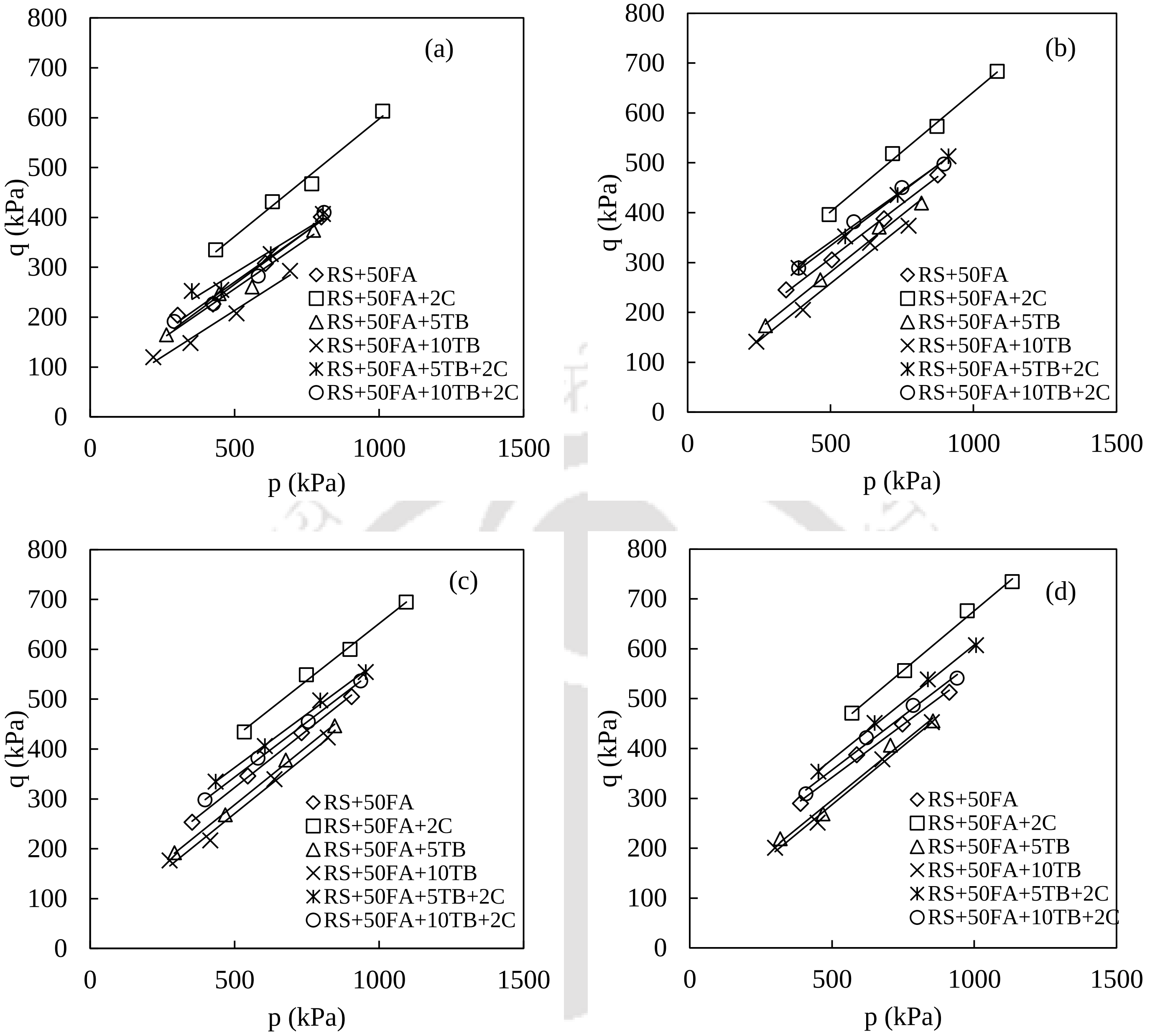


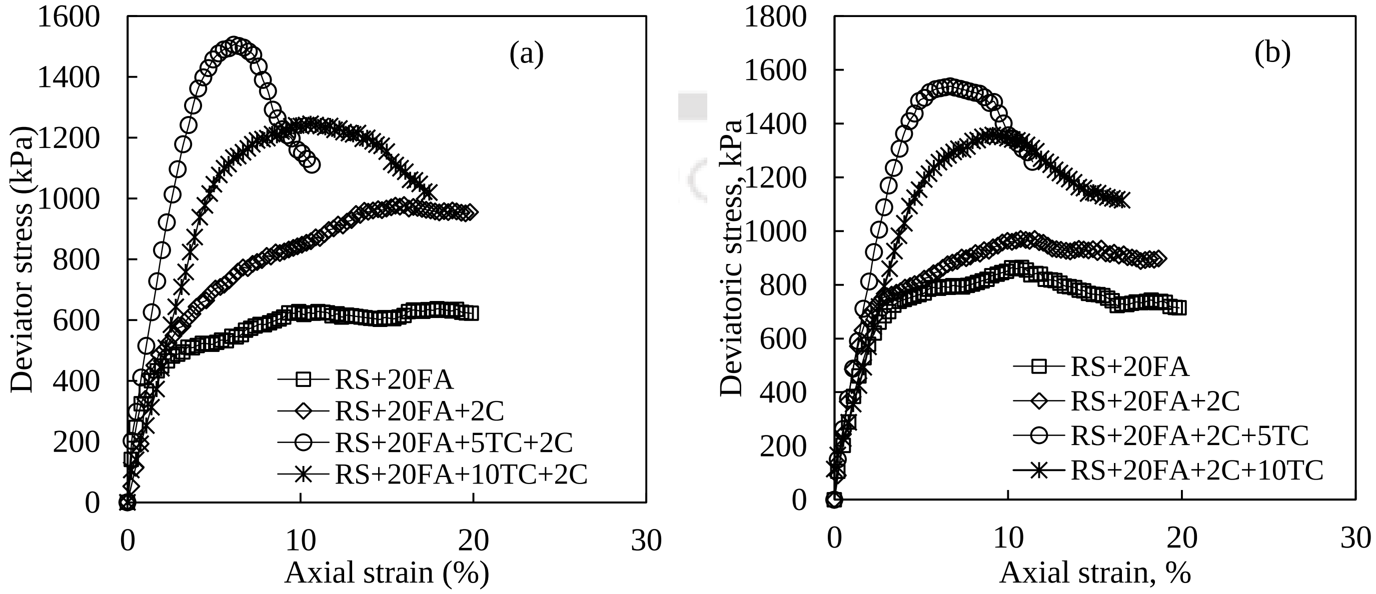
Fig. 6.30 p-q plots of RS+50FA, RS+50FA+TB and RS+50FA+TB+2C mixes for (a) 0 day, (b) 7 days, (c) 14 days and (d) 28 days curing

6.3.7 Effect of Tyre Crumb (TC) Addition on Behaviour of Red Soil-Fly Ash-Cement Mixes

6.3.7.1 Stress-Strain Behaviour

From Figs. 6.31 to 6.33, it is observed that inclusion of tyre crumb to RS+FA+2C mixes shows significant improvement in strength compared to other mixes. It evident that addition of 10% TC reduces the stiffness of the RS+FA+2C mixes as well as the failure strain. A clear peak has been observed in stress-strain plots of RS+FA+TC +2C mixes. It is also seen that addition of 5% TC to RS+FA+2C mixes increases the peak deviator stress but as the percentage of tyre crumb in the mixes increases, the peak deviator stress decreases (Table 6.13).

Fig. 6.34 reveals that addition of tyre crumb and 2% cement to red soil-fly ash mixes decreases the failure strain of the mixes. In each case, brittle failure has been observed in TC added specimens as shown in Table 6.9. This is due to addition of granular shaped tyre crumb and cement to red soil-fly ash mixes. Inclusion of tyre crumb reduces the stiffness of soil mixes.



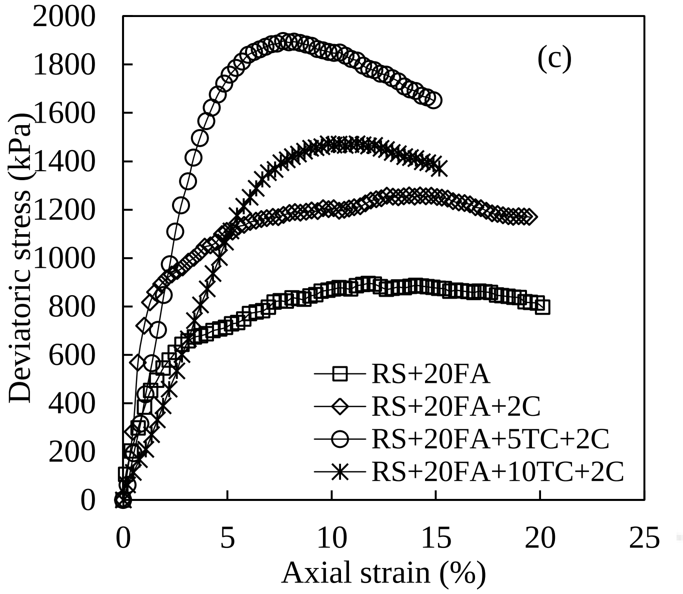
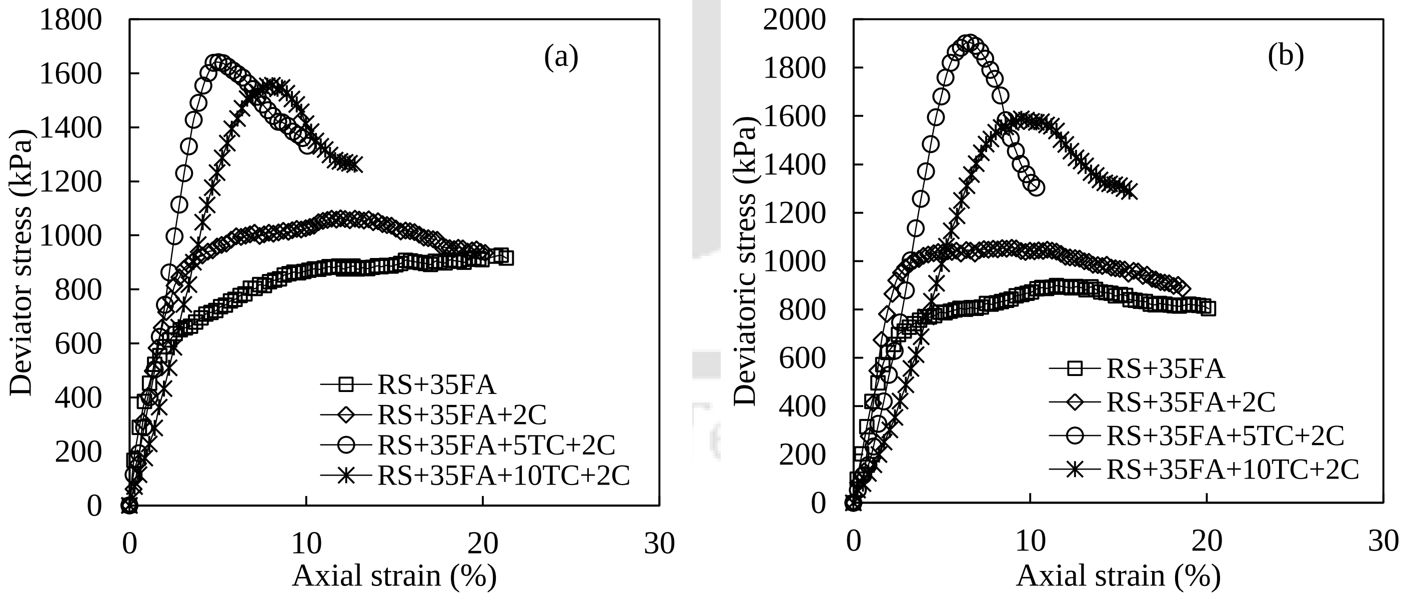


Fig. 6.31 Stress-strain plots of RS+20FA+TC+C mixes at 300 kPa confining pressure for (a) 7 days, (b) 14 days and (c) 28 days curing



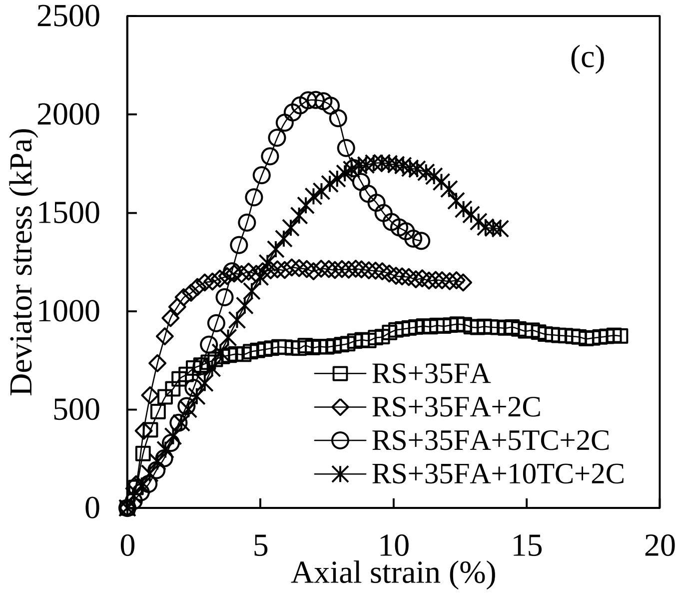
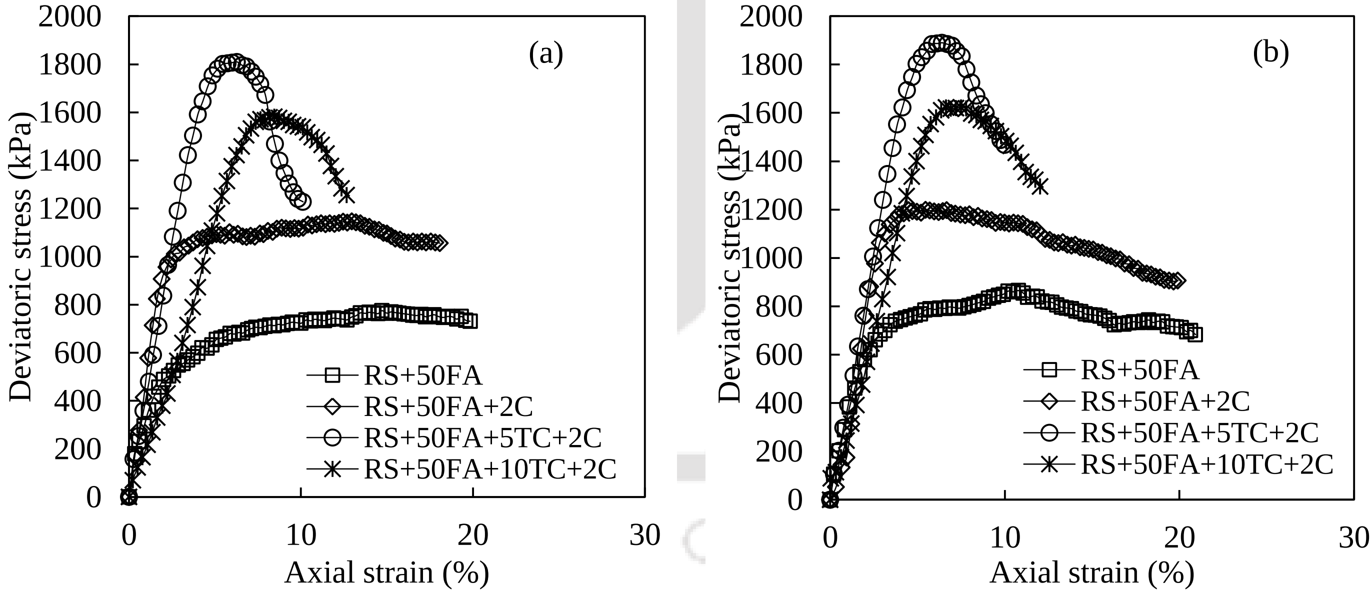


Fig. 6.32 Stress-strain plots of RS+35FA+TC+C mixes at 300 kPa confining pressure for (a) 7 days, (b) 14 days and (c) 28 days curing



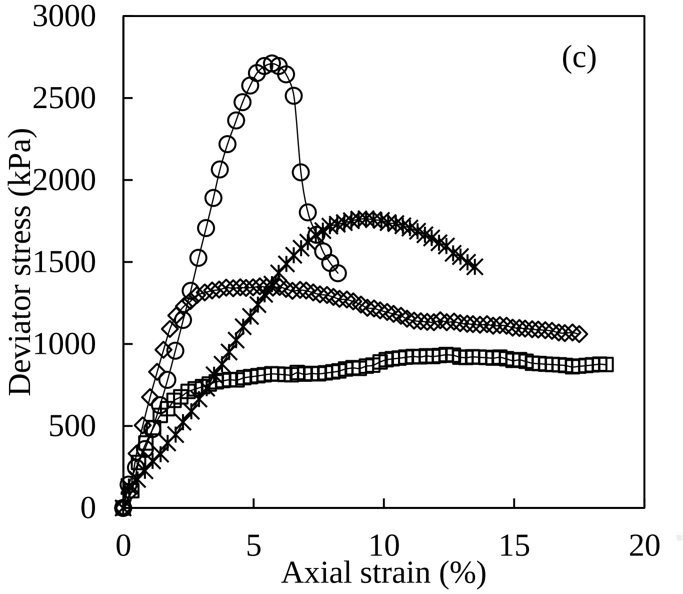
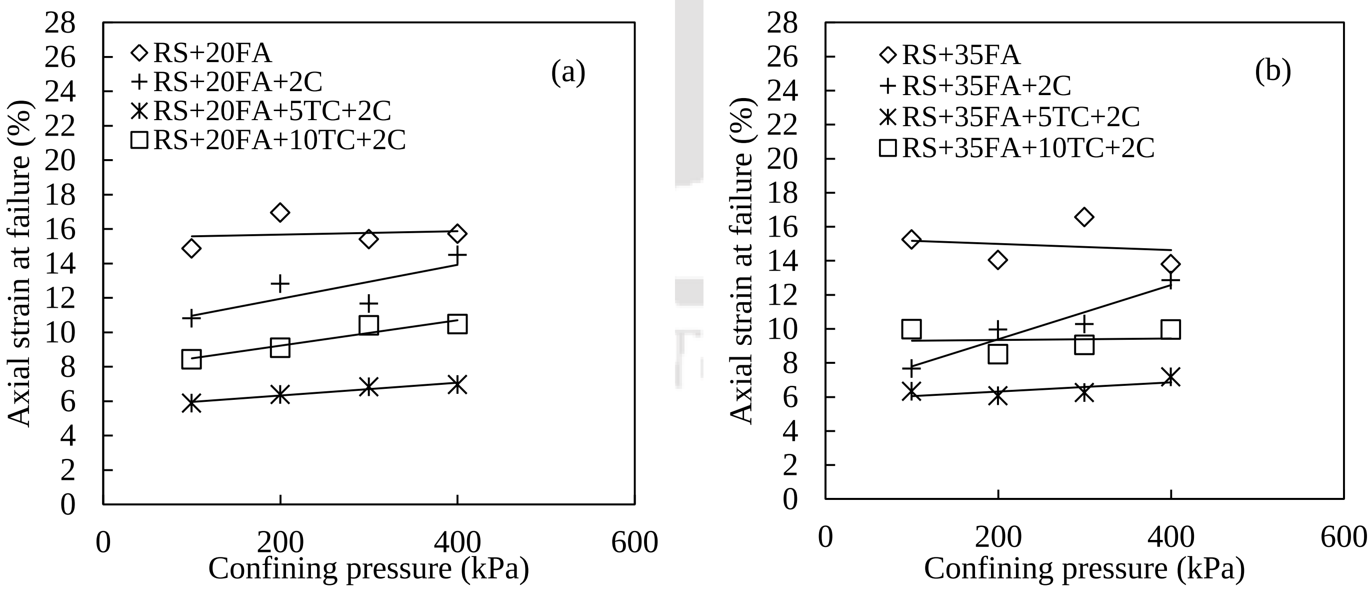


Fig. 6.33 Stress-strain plots of RS+50FA+TC+C mixes at 300 kPa confining pressure for (a) 7 days, (b) 14 days and (c) 28 days curing



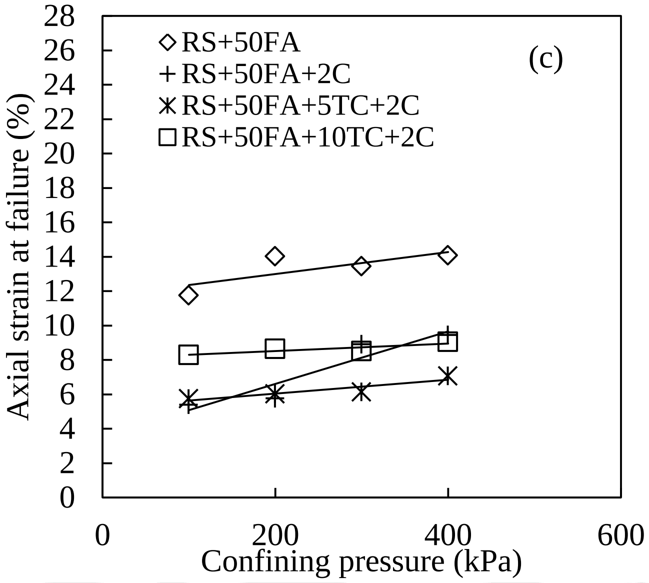


Fig. 6.34 Variation of failure axial strain of RS+FA, RS+FA+2C and RS+FA+TC+2C mixes at (a) 20%, (b) 35% and (c) 50% fly ash content

Table 6.9: Failure patterns of RS+FA+TC+2C mixes tested at 300 kPa confining pressure

Curing	Mix			
	RS	RS+20FA+5TC+2C	RS+35FA+5TC+2C	RS+50FA+5TC+2C
7 Days				
14 Days				

28 Days				
	Mix			
	RS	RS+20FA+10TC+2C	RS+35FA+10TC+2C	RS+50FA+10TC+2C
7 Days				
14 Days				
28 Days				

6.3.7.2 Shear-strength characteristics

Figs. 6.35 to 6.37 clearly show that addition of tyre crumb to soil-fly ash-cement mixes increases the strength of the specimens. In this case the granular shape of the tyre crumb plays the main role as per as increase in shear strength is concerned. In most of the cases, increase in strength of RS+FA+2C+TC mixes has been observed with the increase in FA content up to 35%.

Addition of 5% TC to cemented RS+35FA mix increases the cohesion and internal friction angle of the specimen as shown in Table 6.17.

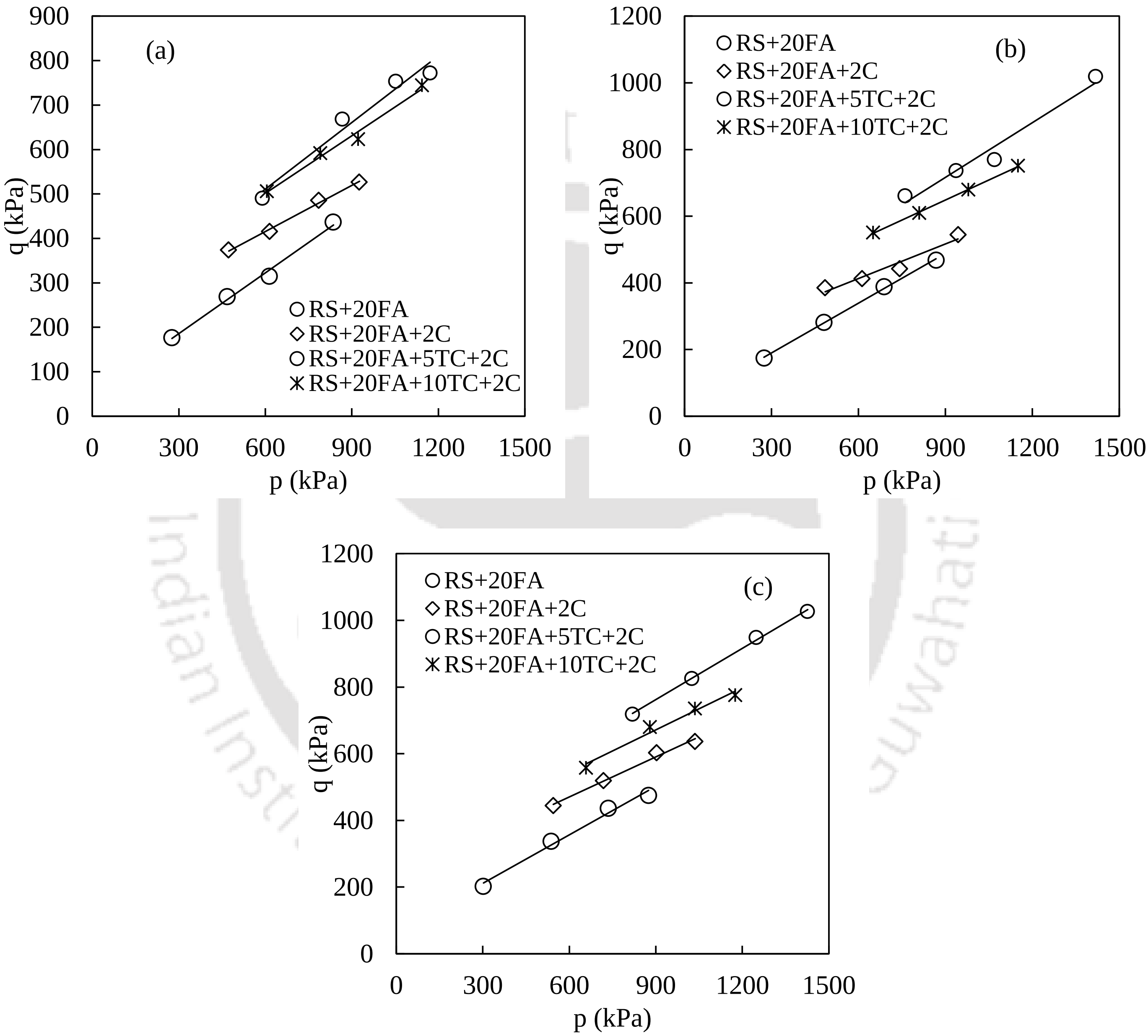


Fig. 6.35 p-q plots of RS+20FA, RS+20FA+TB and RS+20FA+TB+2C mixes for (a) 7 days, (b) 14 days and (c) 28 days curing

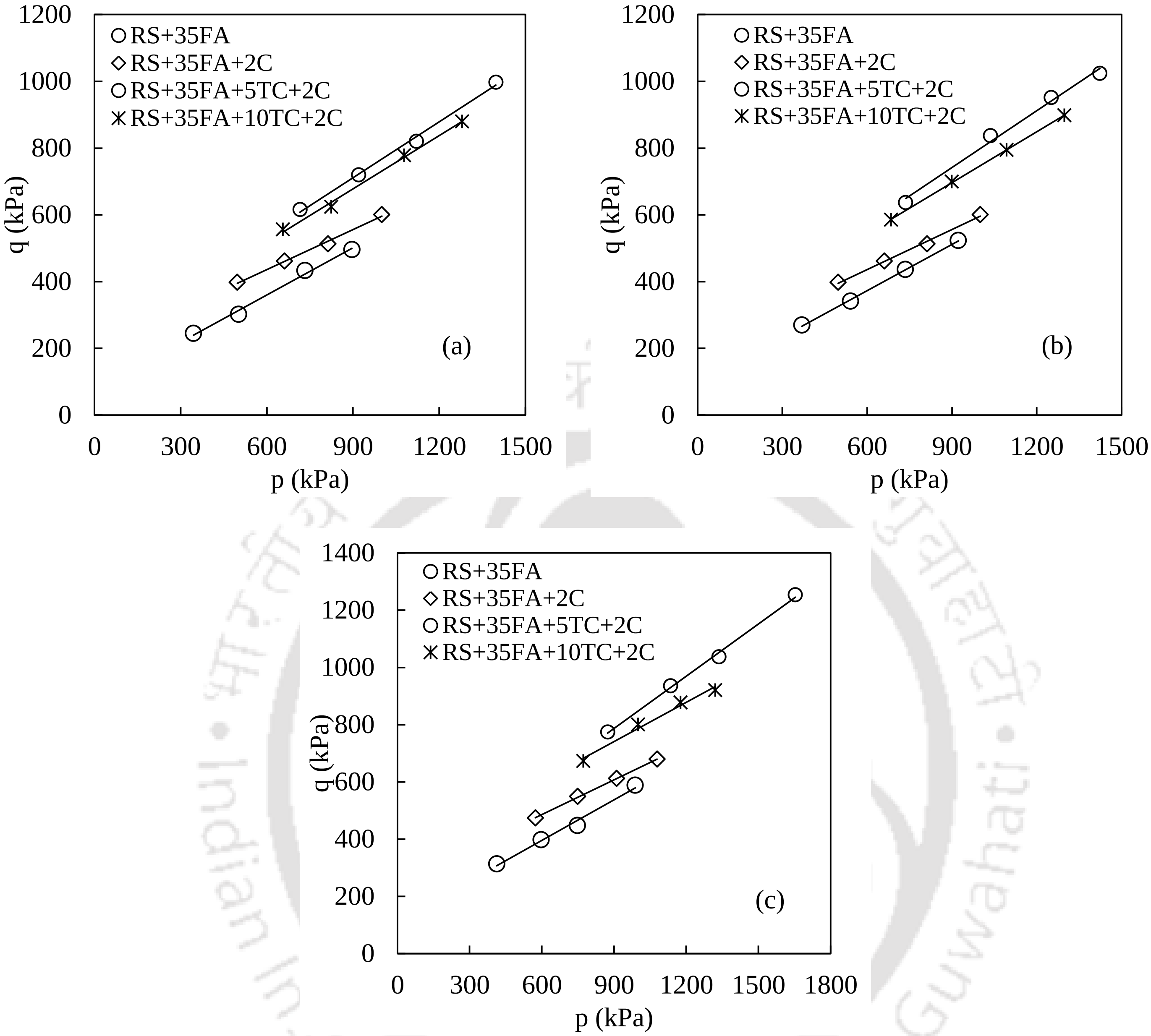


Fig. 6.36 p-q plots of RS+35FA, RS+35FA+TB and RS+35FA+TB+2C mixes for (a) 7 days, (b) 14 days and (c) 28 days curing

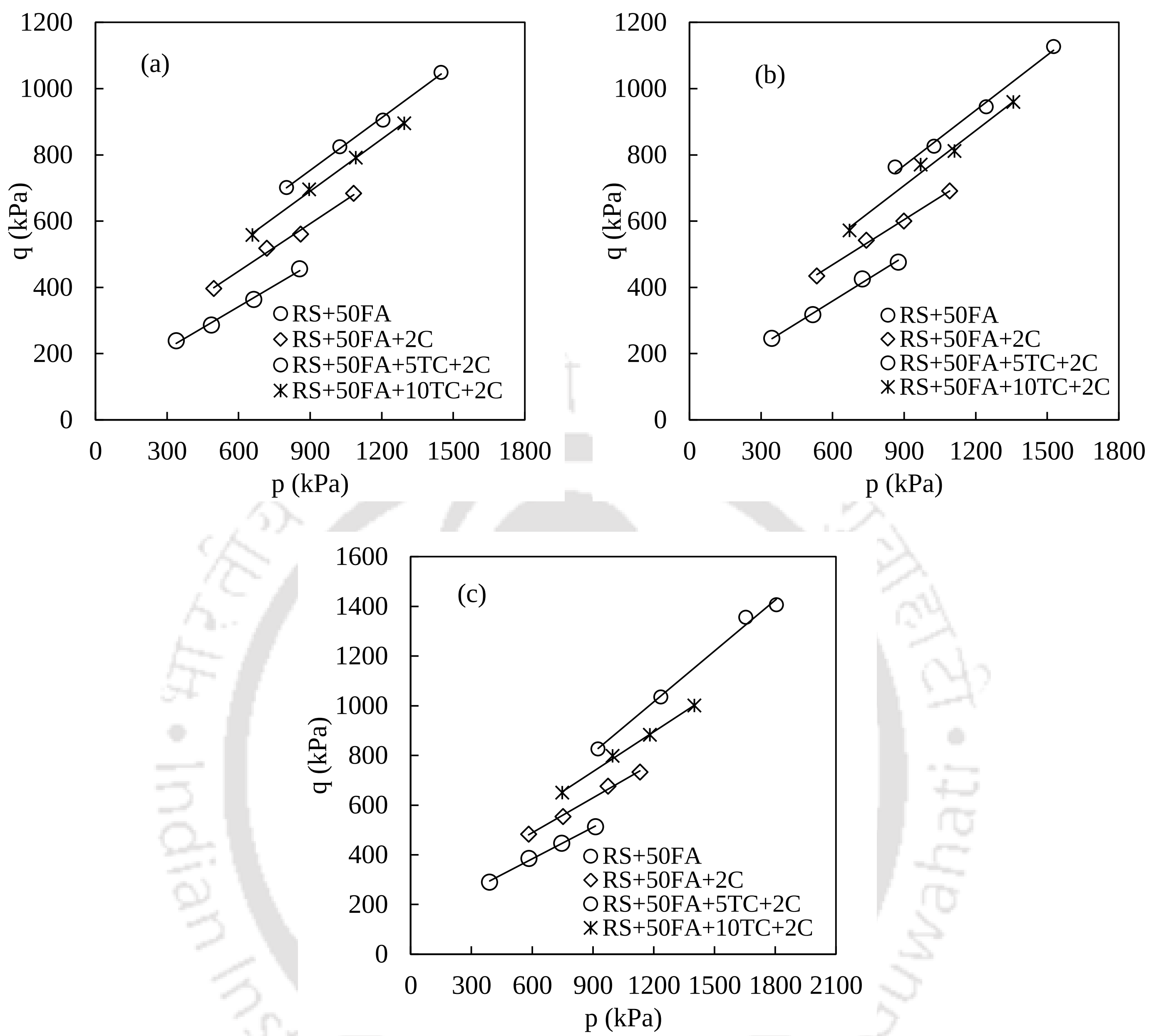


Fig. 6.37 p-q plots of RS+50FA, RS+50FA+TB and RS+50FA+TB+2C mixes for (a) 7 days, (b) 14 days and (c) 28 days curing

6.3.8 Stiffness of Red Soil Mixes

Secant elastic modulus (E_s) is used to characterize stiffness of different red soil mixes. The secant elastic modulus is the slope of a straight line drawn from the origin to a specified stress on the stress-strain curve. The value of E_s is expressed as:

$$E_s = q_{50}/\varepsilon_{50} \quad (6.1)$$

where,

q_{50} = half of the peak deviator stress, and

ε_{50} = the strain corresponding to q_{50}

Figs. 6.38 to 6.40 depict the effect of fly ash, tyre buffings and cement on secant elastic modulus (E_s) values of RS mixes. It is seen that increase in fly ash content in red soil-fly ash mixes increases the value of E_s. Again inclusion of tyre buffing to red soil-fly ash mixes reduces the E_s value of RS+FA mix. Further addition of cement mixes increases the secant elastic modulus values of RS+FA+TB mixes. As in the case of RS mixes, curing is also found to be more effective in case of cemented red soil mixes than uncemented red soil mixes. In all cases it has been seen that as confining pressure increases, secant elastic modulus of soil mixes also increases.

Jongpradist et al. (2010) investigated the strength characteristics of cement –fly ash admixed Bangkok clay by means of a series of unconfined compression tests. The fly ash used was classified as class F type of fly ash, and secant modulus was calculated corresponding to 50% of strength. It was observed that the E_s of cement-fly ash admixed clay was higher than those admixed with cement at the same strength and curing time due to the additional pozzolanic reaction from fly ash.

Kim and Kang (2013) investigated the effects of including crumb rubber and bottom ash on the geotechnical characteristics of composite geomaterial in which dredged clayey soil, crumb rubber, and bottom ash were reused for recycling. Most of the crumb rubber particles ranged from 0.1–2mm and had an irregular shape due to the cracking process. From the unconfined compression test data the relationship between the secant modulus (E_{50}) and rubber content was evaluated. The secant modulus denoted the slope of the line between the origin and the point of 50% unconfined compressive strength on the stress–strain curve. The E_{50} of composite samples tended to decrease as the rubber content increased. In the case of low rubber content, inclusion of bottom ash in mixtures yielded a higher secant modulus at a given rubber content. However, secant modulus values tended to converge to a certain value with increased rubber content in this mixing ratio.

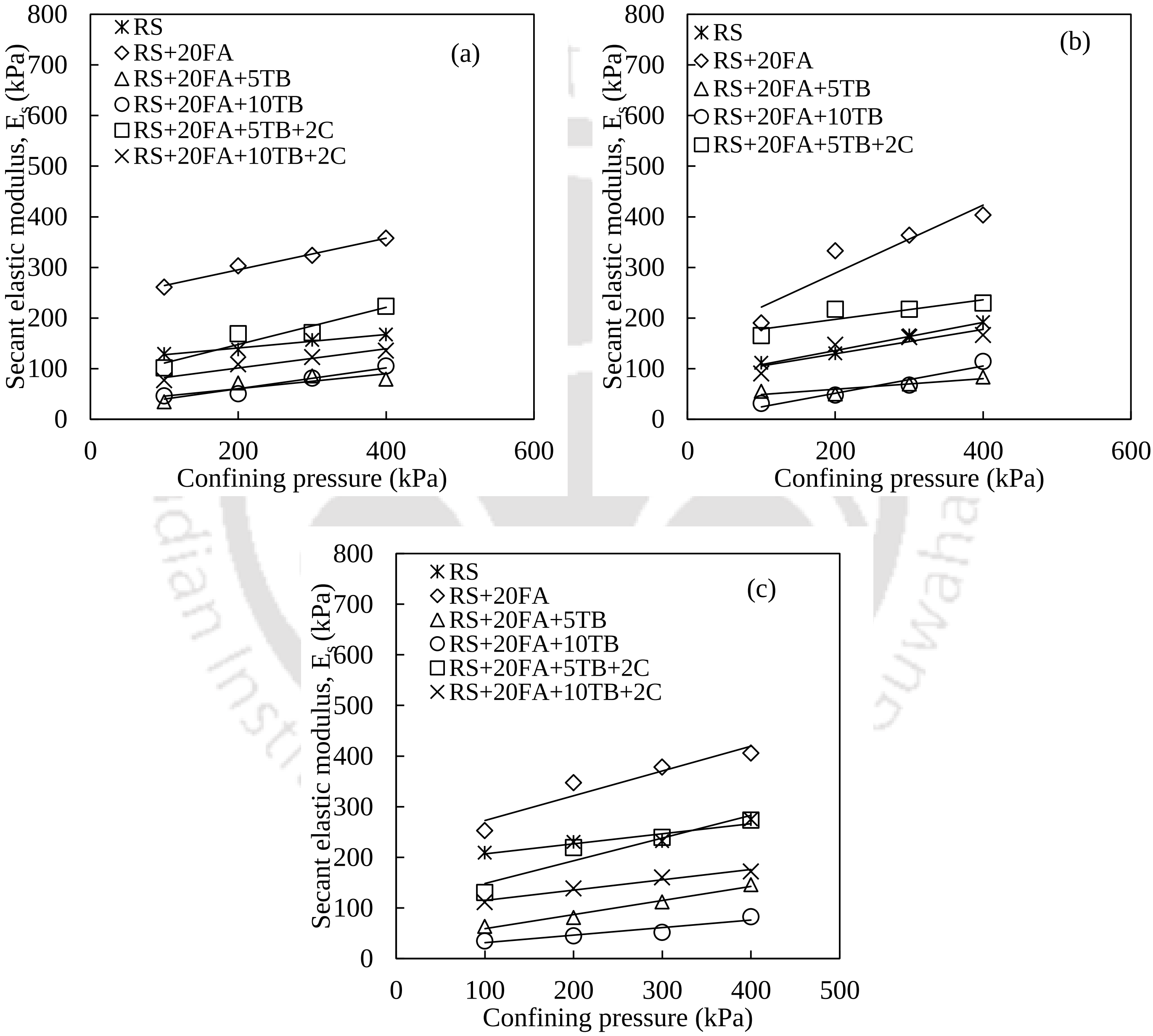


Fig. 6.38 Variation of E_s with confining pressure of RS alone and RS+20FA mixes for (a) 0 day, (b) 7 days and (c) 28 days curing period

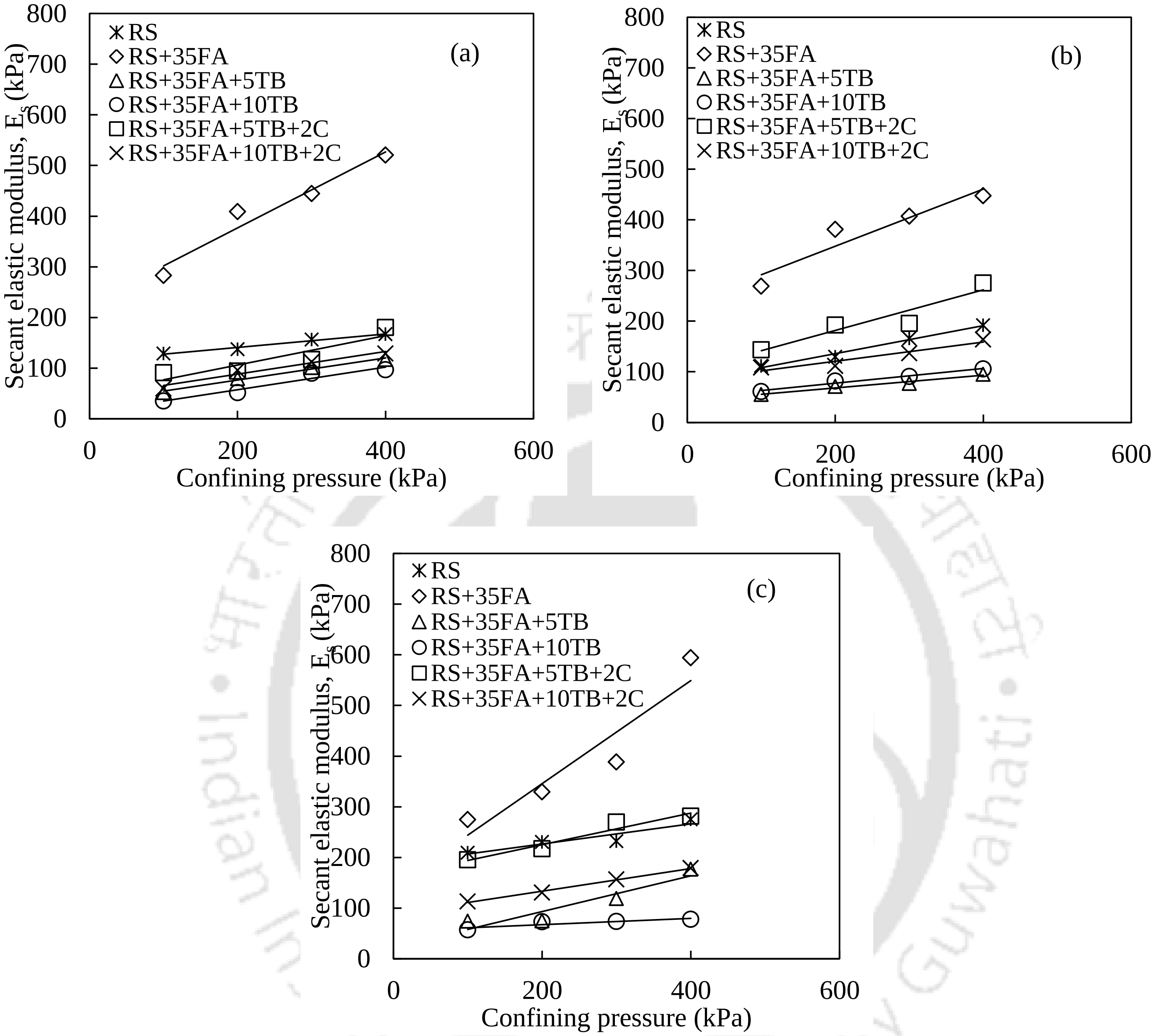


Fig. 6.39 Variation of E_s with confining pressure of RS alone and RS+35FA mixes for (a) 0 day, (b) 7 days and (c) 28 days curing period

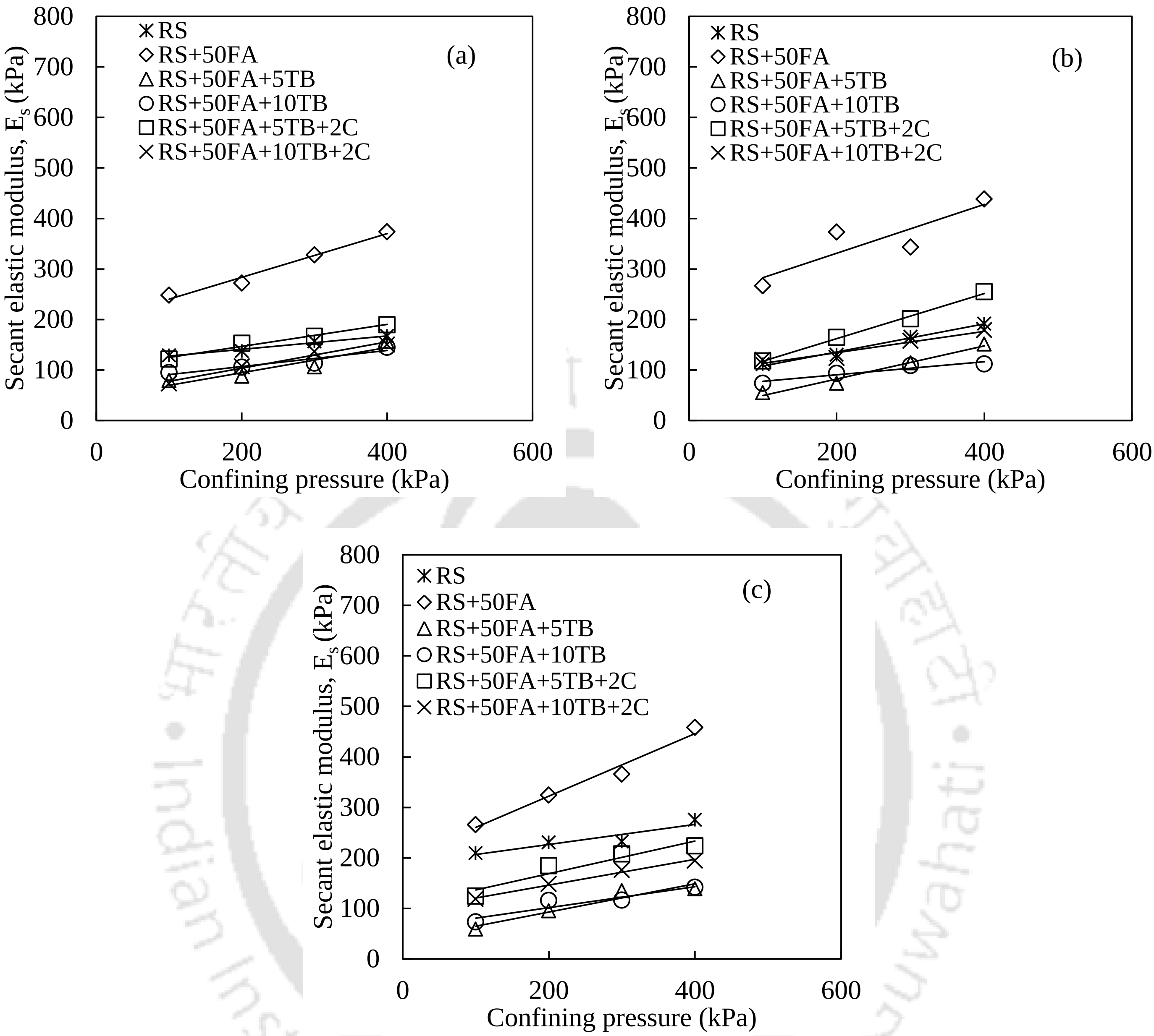


Fig. 6.40 Variation of E_s with confining pressure of RS alone and RS+50FA mixes for (a) 0 day, (b) 7 days and (c) 28 days curing period

6.3.9 Brittleness of Red Soil Mixes

The failure behaviour of different red soil mixes was examined in terms of brittleness index (I_B) as done by Muntohar et al. (2013) and Patel and Singh (2017). The brittleness index used to describe the post peak behaviour of the specimen is defined as:

$$I_B = \{(\sigma_d)_f / (\sigma_d)_{res}\} - 1 \qquad \text{...} (6.2)$$

where, $(\sigma_d)_f$ and $(\sigma_d)_{res}$ are the peak deviator stress and residual deviator stress, respectively.

The value of I_B varies from 0 to 1, where 0 and 1 represent ductile and brittle behaviour respectively. In this study, the average I_B value of the specimen for different curing periods is considered to be the I_B value of the specimen at each confining pressure.

From Fig. 6.41 it can be seen that addition of fly ash to red soil increases the I_B value of the specimen. Increase in fly ash content to red soil imparts brittleness to the specimen and it is significant up to 50% fly ash content, beyond 50% addition of fly ash affects the brittleness of the specimen marginally. Though the effect of confining pressure on I_B value of the specimen can not be evaluated clearly, still in all cases the lowest brittleness index values are found at 400 kPa.

As it can be noted from Fig. 6.42, inclusion of tyre buffings to fly ash admixed soil reduces the I_B values of mixes. This is due to the elastic behaviour of tyre buffing which imparts ductility to the mixes. For example addition of 10% tyre buffing to RS+50FA mix decreases the I_B value from 0.09 to 0.03 at 300 kPa confining pressure. At higher confining pressures of 300 and 400 kPa, TB added specimen shows more ductile behaviour compared to the specimen tested at lower confining pressure. Addition of tyre buffings to cemented mix is also effective in reducing the I_B values of the specimens as shown in Fig. 6.43. RS+FA+2C mixes shows brittle behaviour and it is also depicted in Table 6.7 where clear failure surface can be seen on those cemented specimens. Inclusion of tyre buffings to RS+50FA+2C decreases the I_B value from 0.15 to 0.079 reducing brittleness to some extent.

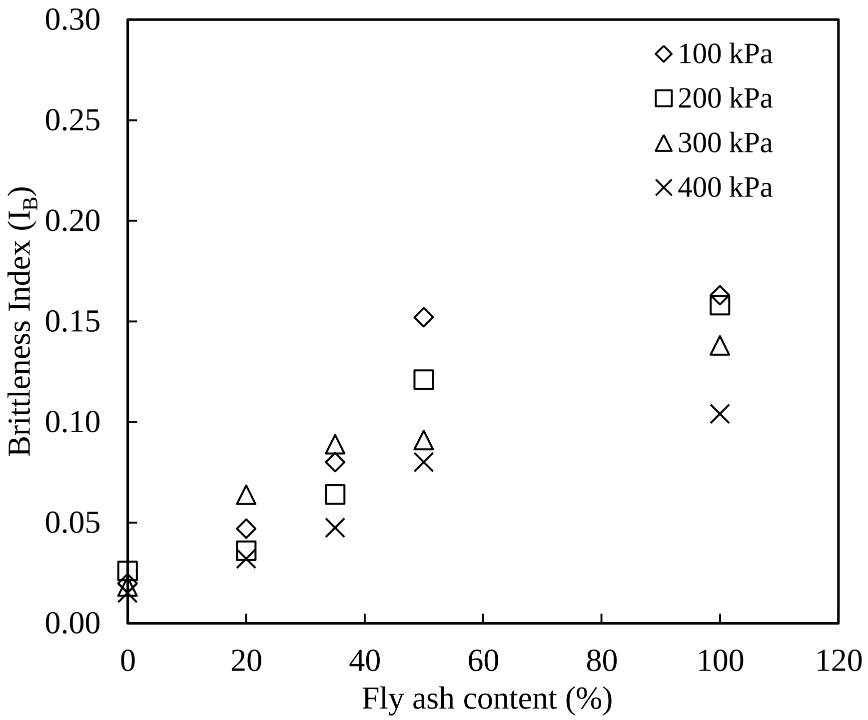
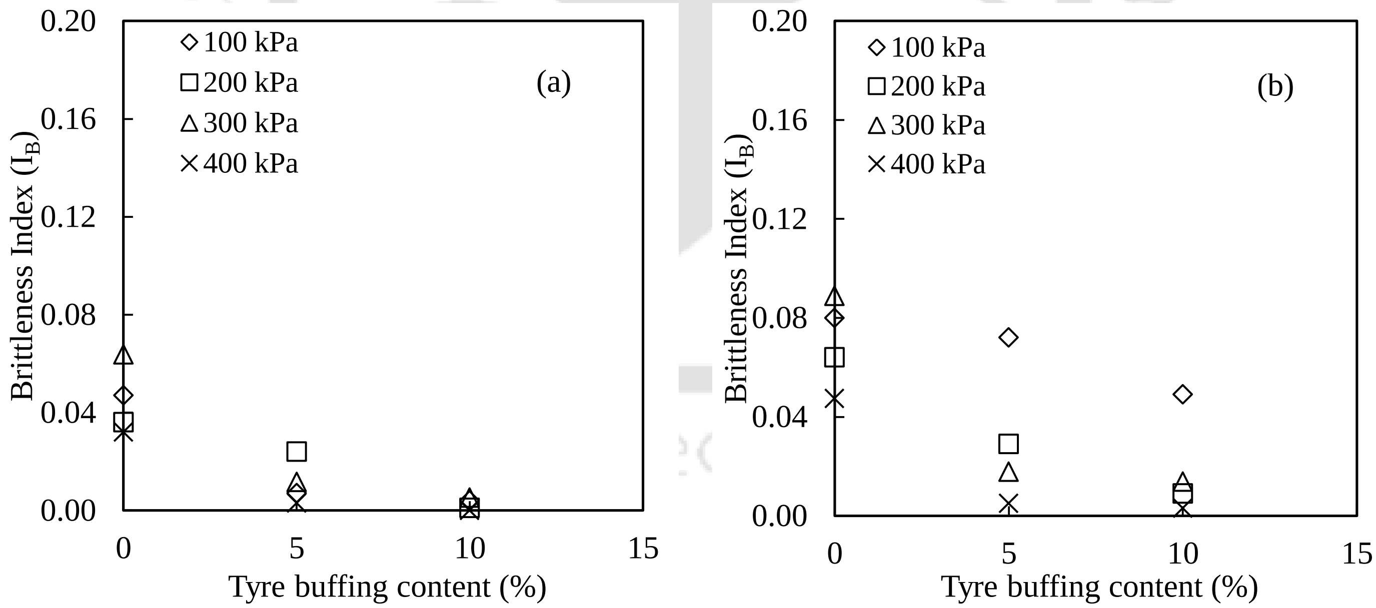


Fig. 6.41 Effect of fly ash content on brittleness of RS mixes



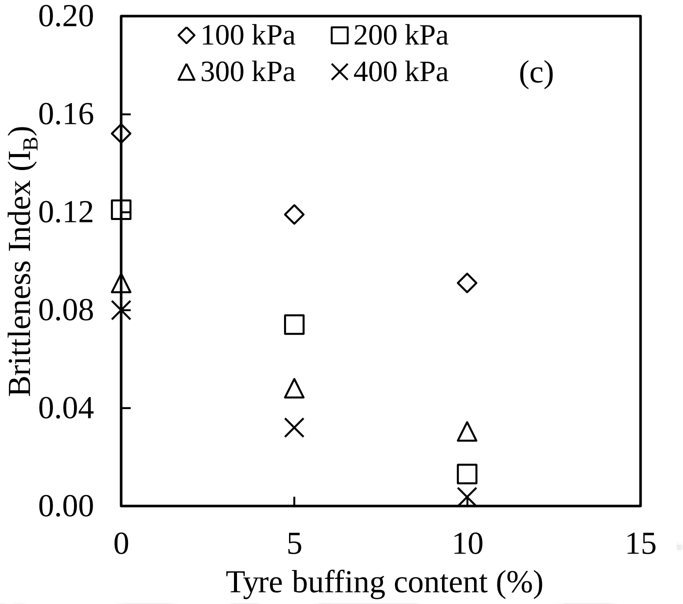
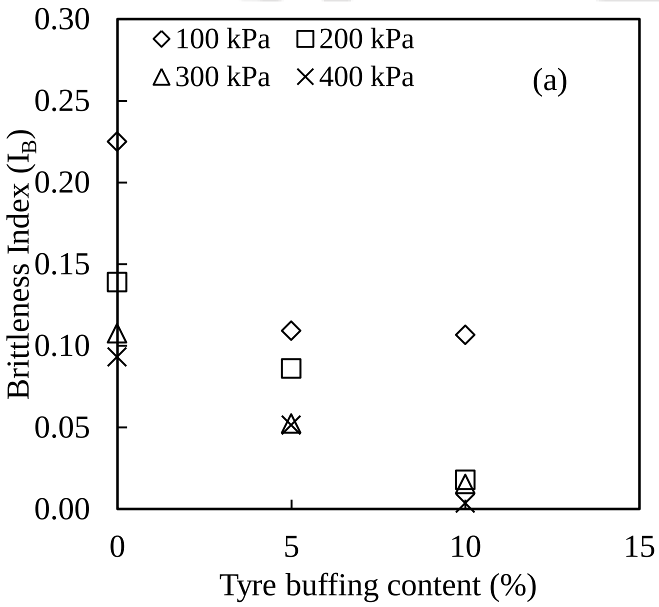
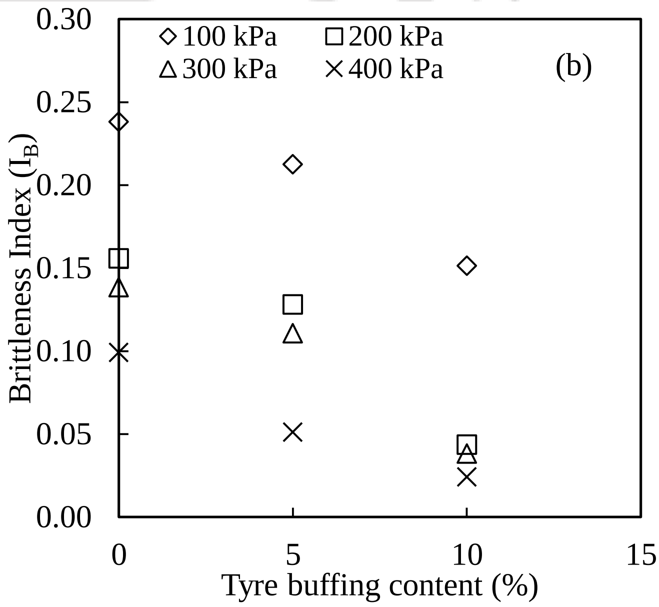


Fig. 6.42 Effect of tyre buffing content on brittleness of (a) RS+20FA, (b) RS+35FA and (c) RS+50FA mixes





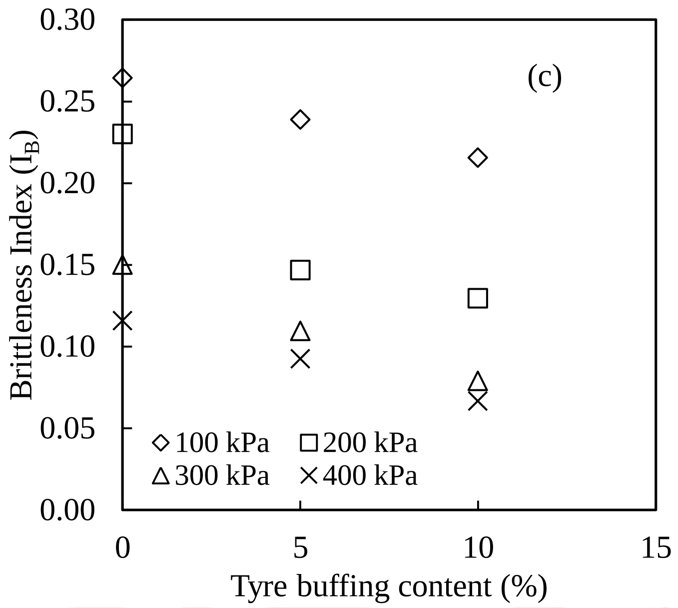


Fig. 6.43 Effect of tyre buffing content on brittleness of (a) RS+20FA+2C, (b) RS+35FA+2C and (c) RS+50FA+2C mixes

6.3.10 Energy Absorption Capacity of Red Soil Mixes

The post-peak behaviour of of different mixes was also examined in terms of energy absorption capacity (EAC) as done by Consoli et al. (2002) for fibre-reinforced cemented sand. Energy absorption capacity or toughness is the energy defined by the area under the stress-strain curve to a reference strain level (ASTM C 1018). Although the triaxial compression tests were conducted up to 20% axial strain, effect of fly ash content, tyre buffing content and curing on EAC were studied considering a reference strain level up to 15%. This is because some of the tests could not be carried out up to 20% axial strain. EAC of each specimen has been calculated at 300 kPa confining pressure.

Addition of fly ash to red soil increases the EAC values of the specimens up to 35% fly ash content (Fig. 6.44). At 50% fly ash content, reduction in EAC values is observed as compared to 35% fly ash content. At 28 days curing period, EAC values of the specimens are found to be highest.

From Fig. 6.45, it is seen that further addition of tyre buffings to red soil-fly ash mixes decreases the EAC of the mixes. For example, inclusion of 10% tyre buffings to RS+50FA mixes reduces the EAC values from 6,722 kJ/m^3 to 4,575 kJ/m^3. Effect of curing period on EAC values of the mixes are found to be effective at 28 days curing period. Increase in fly ash content also increases the EAC of the cemented red soil-fly ash mixes. Addition of 2% cement to RS+FA mixes causes improvement in EAC as shown in Fig. 6.46. At 28 days curing period, EAC values of RS+50FA and RS+50FA+2C are 6,722 kJ/m^3 and 11,792 kJ/m^3 respectively. Generally, increase in curing period increases the EAC of the mixes.

Form Fig. 6.47 it is noted that inclusion of tyre buffing to cemented mixes decreases the energy absorption capacity of the mixes. This is due to the presence of tyre buffings in the mixes which is ductile and less energy is required to induce deformation in tyre buffings.

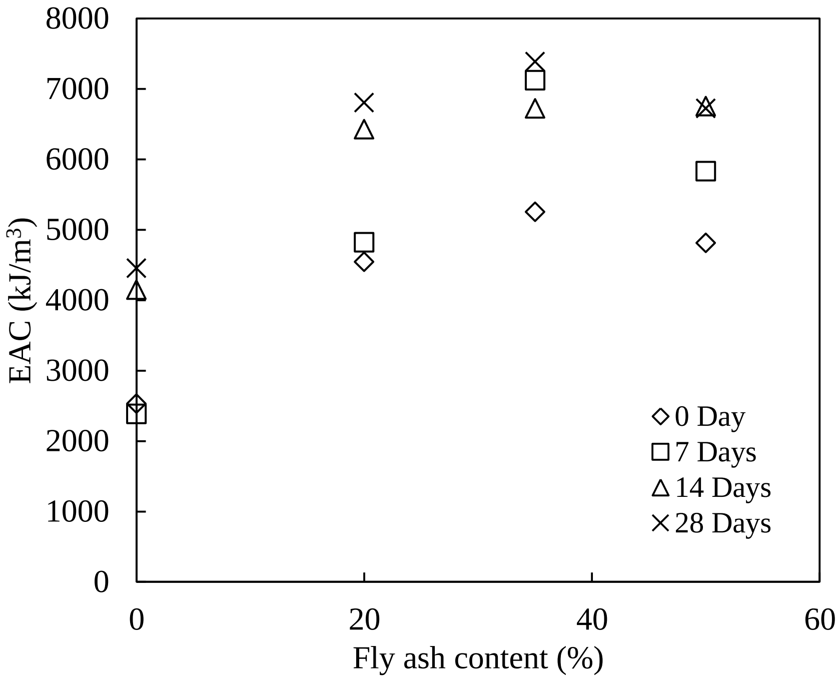


Fig. 6.44 Effect of fly ash content on EAC of RS+FA mixes

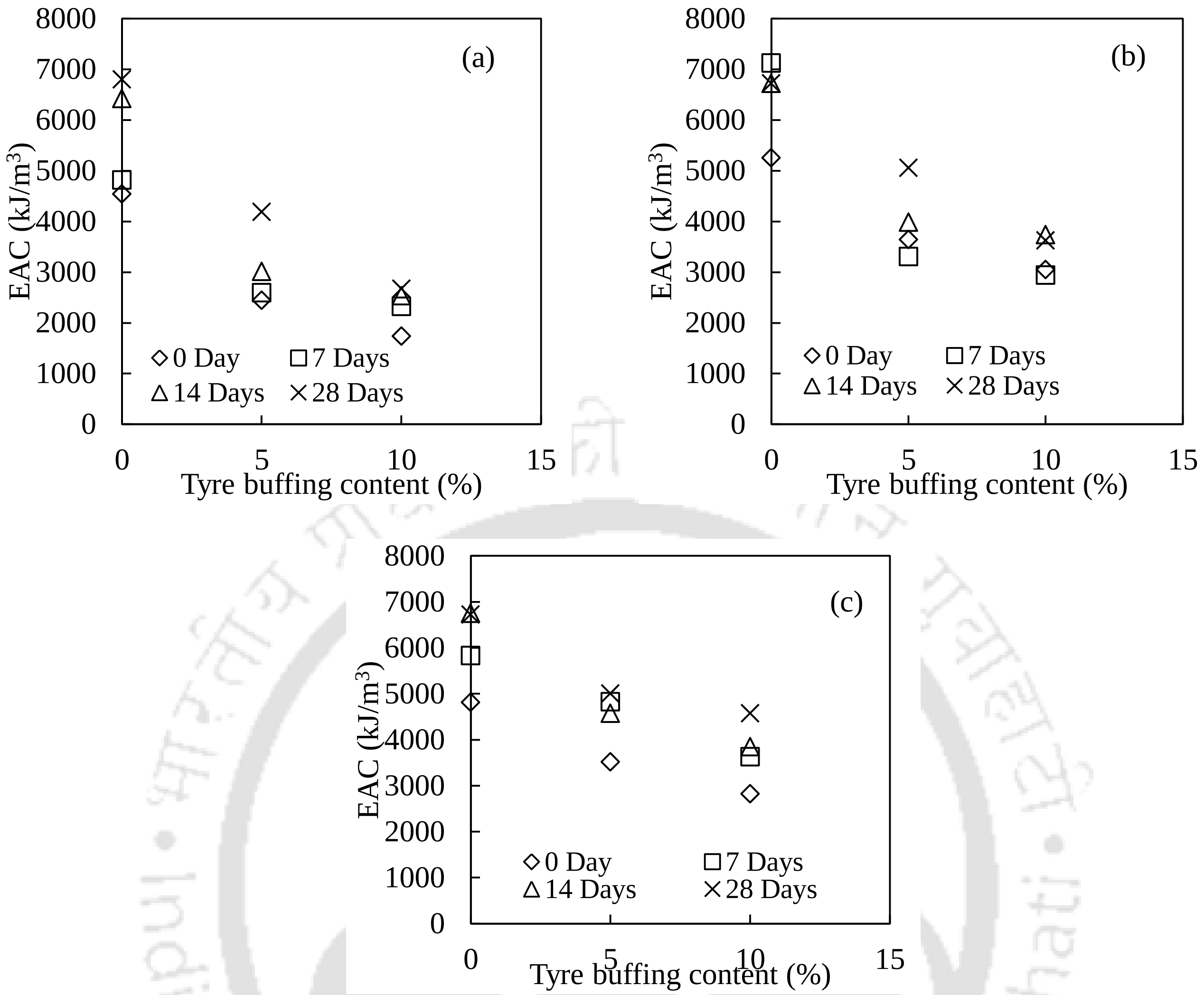


Fig. 6.45 Effect of tyre buffing content on EAC of RS+FA+TB at (a) 20%, (b) 35% and (c) 50% fly ash content

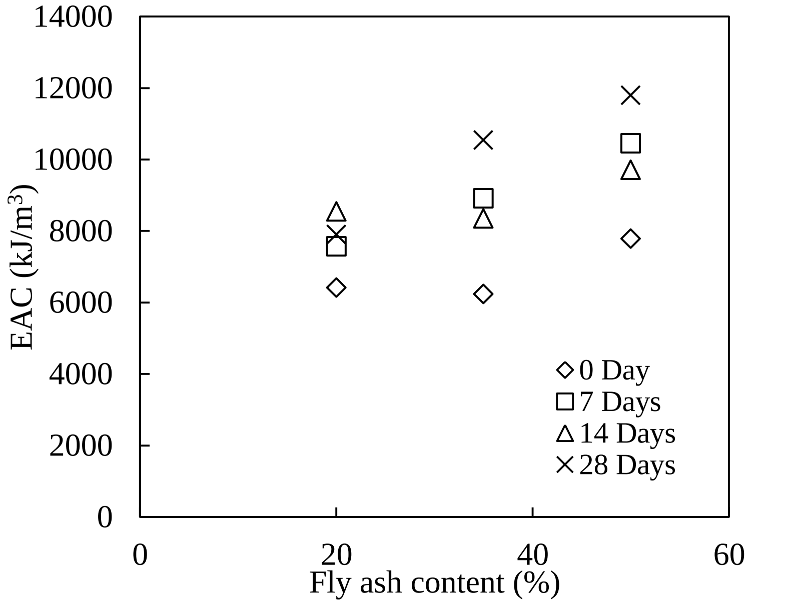


Fig. 6.46 Effect of fly ash content on EAC of RS+FA+2C mixes

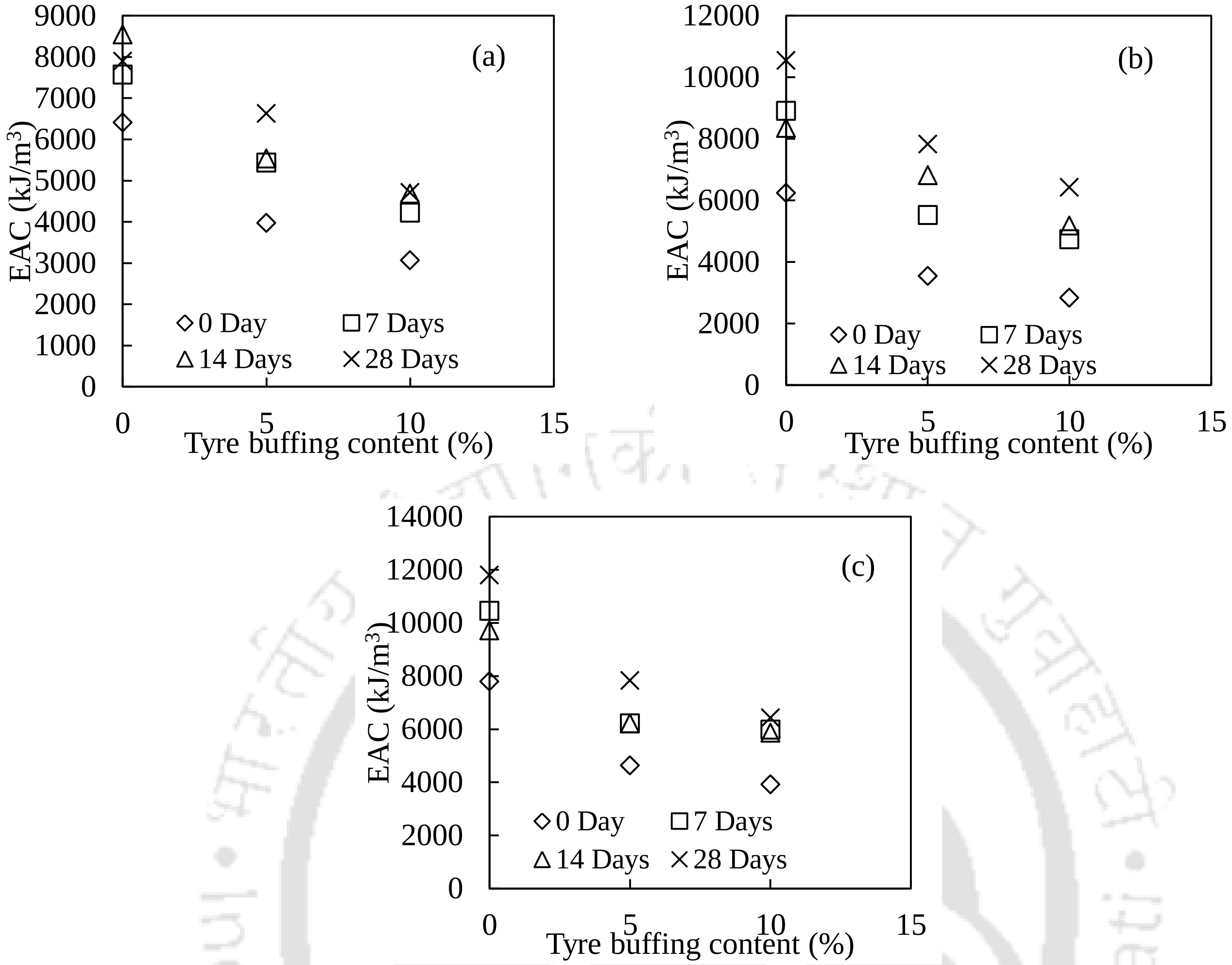


Fig. 6.47 Effect of tyre buffing content on EAC of RS+FA+TB+2C at (a) 20%, (b) 35% and (c) 50% fly ash content

Table 6.10: Peak deviator stress (in kPa) of red soil mixes using TB

Sl No.	Mix designation	Curing period																			
		0 Days				3 Days				7 Days				14 Days				28 Days			
		Confining Pressure (kPa)																			
		100	200	300	400	100	200	300	400	100	200	300	400	100	200	300	400	100	200	300	400
1	FA	227	356	456	671	256	377	643	770	279	407	643	809	294	504	672	922	315	583	888	1059
2	RS	261	310	353	367	290	346	355	373	295	349	366	501	467	521	582	609	468	525	599	659
3	RS+5TB	163	183	212	247	169	191	232	276	189	205	240	303	197	219	261	311	226	247	288	367
4	RS+10TB	146	169	190	225	155	183	212	232	184	202	218	240	191	212	219	254	204	223	240	276
5	RS+20FA	339	438	601	744	352	487	613	813	353	537	629	873	371	629	780	958	455	711	895	1014
6	RS+20FA+5TB	301	346	362	461	332	366	455	472	346	423	480	579	359	426	620	671	363	514	656	685
7	RS+20FA+10TB	162	233	286	319	218	240	317	361	261	275	353	367	268	353	388	430	275	465	579	667
8	RS+35FA	411	521	676	848	447	593	743	989	515	646	898	1007	546	692	916	1047	625	797	932	1176
9	RS+35FA+5TB	296	356	578	677	328	480	591	745	332	536	636	797	352	536	684	823	403	550	782	853
10	RS+35FA+10TB	324	424	523	555	395	430	564	606	416	452	586	705	419	460	633	755	451	589	670	776
11	RS+50FA	407	452	615	801	429	523	637	891	490	610	775	951	506	691	865	1010	579	774	916	1118
12	RS+50FA+5TB	329	494	521	747	342	522	600	762	346	530	742	838	384	536	755	893	437	537	812	910
13	RS+50FA+10TB	239	296	414	585	247	360	472	705	282	409	678	748	352	433	678	846	401	501	755	904

Table 6.11 Peak deviator stress of red soil, red soil-cement and red soil-fly ash-cement mixes

Sl. No.	Mix Designation	Peak deviator stress in different curing period (kPa)																			
		0 Days				3 Days				7 Days				14 Days				28 Days			
		Confining Pressure (kg/cm^2)																			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	RS	261	310	339	367	282	325	353	373	290	346	366	501	467	521	582	609	468	525	599	659
2	RS+1C	368	431	446	455	515	577	585	751	591	642	743	881	582	713	854	960	587	799	947	1097
3	RS+2C	482	555	576	601	587	707	744	796	709	803	968	1024	846	965	977	1071	891	973	1058	1216
6	RS+20FA	339	438	601	744	352	487	613	813	353	537	629	873	371	629	780	958	455	711	895	1014
7	RS+20FA+1C	548	639	820	896	595	648	868	908	607	771	886	936	770	834	953	1100	823	907	954	1241
8	RS+20FA+2C	677	773	792	930	692	821	958	978	747	831	971	1053	810	870	971	1222	906	918	1046	1273
11	RS+35FA	411	521	676	848	447	593	743	989	515	646	898	1007	546	692	916	1047	625	797	932	1176
12	RS+35FA+1C	538	674	805	908	563	731	835	940	659	834	845	1115	756	892	906	1264	760	906	995	1273
13	RS+35FA+2C	607	711	893	1080	742	900	939	1227	795	947	1055	1241	891	976	1063	1347	965	1105	1222	1395
16	RS+50FA	407	452	615	801	429	523	637	891	490	610	652	951	506	691	865	1010	579	774	897	1025
17	RS+50FA+1C	555	721	882	1076	592	799	968	1177	708	829	1064	1269	868	933	1069	1303	901	1057	1140	1319
18	RS+50FA+2C	670	862	934	1226	777	1035	1146	1334	792	1036	1174	1366	886	1097	1199	1389	941	1124	1351	1468

Table 6.12: Peak deviator stress (in kPa) of RS+FA+TB+2C mixes

Sl No.	Mix designation	Curing period																			
		0 Days				3 Days				7 Days				14 Days				28 Days			
		Confining Pressure (kPa)																			
		100	200	300	400	100	200	300	400	100	200	300	400	100	200	300	400	100	200	300	400
1	RS+20FA+5TB+2C	315	480	530	604	375	548	563	774	602	728	743	876	592	731	844	1024	745	821	965	1074
2	RS+20FA+10TB+2C	306	416	444	458	358	512	549	565	500	553	647	840	518	648	733	887	549	650	799	1019
3	RS+35FA+5TB+2C	371	456	513	730	457	642	718	852	585	706	842	1083	667	810	954	1087	689	894	1049	1210
4	RS+35FA+10TB+2C	264	415	463	615	316	431	519	693	537	577	725	915	593	688	866	982	627	712	867	1009
5	RS+50FA+5TB+2C	505	509	652	826	550	600	748	941	578	704	870	1026	669	811	994	1108	706	901	1076	1213
6	RS+50FA+10TB+2C	382	453	565	813	497	531	568	868	578	763	900	994	596	763	910	1073	617	842	972	1081

Table 6.13: Peak deviator stress (in kPa) of red soil mixes using TC

Serial no	Mixtures	Curing period															
		3 Days				7 Days				14 Days				28 Days			
		Confining Pressure (kPa)															
		100	**200**	**300**	**400**	**100**	**200**	**300**	**400**	**100**	**200**	**300**	**400**	**100**	**200**	**300**	**400**
1	**RS+20FA+5TC+2C**	846	1269	1305	1457	981	1336	1506	1544	1322	1473	1539	2037	1438	1651	1897	2053
2	**RS+20FA+10TC+2C**	835	1085	1219	1482	1012	1183	1246	1488	1102	1219	1358	1502	1116	1360	1472	1551
3	**RS+35FA+5TC+2C**	1100	1369	1641	1766	1231	1439	1641	1995	1273	1674	1903	2047	1547	1871	2073	2507
4	**RS+35FA+10TC+2C**	1031	1171	1399	1707	1112	1248	1556	1760	1155	1391	1588	1796	1344	1601	1754	1841
5	**RS+50FA+5TC+2C**	1006	1596	1695	2089	1402	1649	1810	2098	1526	1651	1890	2254	1651	2070	2710	2812
6	**RS+50FA+10TC+2C**	1053	1184	1449	1688	1116	1385	1582	1790	1143	1540	1623	1918	1298	1594	1764	2001

Table 6.14: Shear strength parameters of red soil mixes at different curing periods using TB

Sr. No.	Mixtures	Cohesion, C (kPa) and Angle of friction, φ (Degree)									
		0 Days		3 Days		7 Days		14 Days		28 Days	
		C	ϕ	C	ϕ	C	ϕ	C	ϕ	C	ϕ
1	RS	99.24	8.85	112.80	7.59	80.17	14.59	173.55	11.74	156.17	14.15
2	FA	20.86	24.84	16.11	28.54	6.53	31.18	11.39	31.21	19.31	34.11
3	RS+5TB	57.81	7.09	54.05	8.84	59.05	9.22	63.96	9.31	67.72	10.99
4	RS+10TB	46.55	7.37	58.10	6.61	75.78	4.86	77.55	5.13	79.80	6.01
5	RS+20FA	59.84	24.13	58.94	25.55	54.95	27.10	59.44	29.37	87.55	29.03
6	RS+20FA+5TB	69.64	14.92	112.58	11.84	94.45	16.61	73.62	21.92	92.60	21.23
7	RS+20FA+10TB	32.03	13.83	63.67	11.72	90.04	9.65	92.39	12.02	55.92	23.27
8	RS+35FA	78.25	25.08	73.36	28.20	99.45	27.79	110.79	27.68	129.22	28.29
9	RS+35FA+5TB	32.04	24.58	63.40	23.92	62.83	25.44	64.87	26.03	75.95	26.46
10	RS+35FA+10TB	96.29	16.46	113.80	16.30	100.54	19.69	89.73	22.05	124.21	2027
11	RS+50FA	72.77	24.07	73.66	25.79	99.62	25.92	105.49	27.24	122.17	27.93
12	RS+50FA+5TB	63.15	23.44	71.54	23.75	57.15	27.39	61.48	27.84	73.30	27.61
13	RS+50FA+10TB	28.08	21.49	12.98	25.73	3.47	27.38	41.91	27.85	58.21	28.13

Table 6.15: Shear strength parameters of RS, RS+C and RS+FA+C mixes

Sr. No.	Mixtures	Cohesion, c (kPa) and Angle of internal friction, ϕ (Degree)									
		0 Days		3 Days		7 Days		14 Days		28 Days	
		c	ϕ	c	ϕ	c	ϕ	c	ϕ	c	ϕ
1	RS	99.24	8.85	112.80	7.59	80.17	14.59	173.55	11.74	156.17	14.15
2	RS+1C	156.35	7.12	158.22	15.87	166.25	19.25	189.19	19.93	193.41	22.48
3	RS+2C	194.41	9.27	208.32	14.64	206.38	20.71	232.66	19.66	214.27	22.53
6	RS+20FA	59.84	24.13	58.94	25.55	54.95	27.10	59.44	29.37	87.55	29.03
7	RS+20FA+1C	139.22	22.47	153.61	21.99	178.18	21.08	217.71	20.76	205.38	24.17
8	RS+20FA+2C	221.77	16.52	213.61	19.74	221.07	20.30	239.73	22.06	234.24	23.21
11	RS+35FA	78.25	25.08	73.36	28.20	99.45	27.79	110.79	27.68	129.22	28.29
12	RS+35FA+1C	140.40	22.54	152.47	22.53	122.51	29.69	164.43	27.06	173.33	27.05
13	RS+35FA+2C	129.86	26.51	175.97	25.96	206.43	24.87	216.70	25.62	262.52	23.80
16	RS+50FA	72.77	24.07	73.66	25.79	99.62	25.92	105.49	27.24	122.17	27.93
17	RS+50FA+1C	114.16	27.54	117.69	29.37	141.45	29.43	220.31	24.73	250.09	23.76
18	RS+50FA+2C	18.65	35.89	55.36	35.62	184.55	28.70	219.41	27.16	228.07	28.45

Table 6.16: Shear strength parameters of RS and RS+FA+TB+2C mixes at different curing periods using

Sr. No.	Mixtures	Cohesion, C (kPa) and Angle of internal friction, ϕ (Degree)									
		0 Days		3 Days		7 Days		14 Days		28 Days	
		C	ϕ	C	ϕ	C	ϕ	C	ϕ	C	ϕ
1	RS	99.24	8.85	112.80	7.59	80.17	14.59	173.55	11.74	156.17	14.15
2	RS+20FA+5TB+2C	89.0	18.61	83.83	22.66	192.10	17.43	142.97	24.47	211.16	21.24
3	RS+20FA+10TB+2C	114.10	11.62	123.46	14.98	118.88	21.37	134.01	21.99	111.92	26.18
4	RS+35FA+5TB+2C	76.06	21.70	115.68	22.89	120.05	26.90	170.41	24.36	160.68	27.56
5	RS+35FA+10TB+2C	55.20	20.97	61.18	22.36	117.94	23.40	144.84	23.78	156.91	23.29
6	RS+50FA+5TB+2C	107.33	21.14	110.36	23.77	131.99	25.5	164.08	25.42	166.99	27.36
7	RS+50FA+10TB+2C	60.60	24.89	97.62	23.01	137.29	26.17	100.50	31.06	154.38	25.82

Table 6.17: Shear strength parameters of RS+FA+TC+2C mixes at different curing periods

Sr. No.	Mixtures	Curing period							
		3 Days		7 Days		14 Days		28 Days	
		C	ϕ	C	ϕ	C	ϕ	C	ϕ
1	RS+20FA+5TC+2C	204.52	30.24	244.12	29.91	267.32	33.18	350.81	30.80
2	RS+20FA+10TC+2C	179.98	30.73	268.19	25.60	313.84	23.68	324.20	21.45
3	RS+35FA+5TC+2C	246.10	32.33	251.90	33.90	280.46	34.58	300.55	37.54
4	RS+35FA+10TC+2C	208.07	32.26	234.88	32.15	269.43	30.98	370.50	27.20
5	RS+50FA+5TC+2C	155.20	32.28	325.12	32.10	323.51	33.66	268.46	43.04
6	RS+50FA+10TC+2C	222.82	31.51	253.91	31.78	250.61	33.63	300.75	32.28

5.3.11 Effect of Fly Ash on Behaviour of Sand Mixes

5.3.11.1 Stress-Strain Behaviour

Fig. 6.48 shows the stress-strain plots of BS and BS+FA mixes at 0, 7, 14 and 28 days of curing obtained at confining pressure of 300 kPa. Marginal change in stress-strain behaviour of the sand mixes is observed due to the addition of fly ash. Increase in fly ash content in soil- fly ash mixes has imparted strain-softening behaviour which is distinctly exhibited in BS+50FA mixes. At a confining pressure of 100 kPa, improvement in peak deviator stress occurred on addition of fly ash to sand as shown in Table 6.24. But reduction in peak deviator stress was observed as the fly ash content in the mixes is increased. This kind of behaviour can be seen only at higher confining pressures i.e. from 200 kPa to 400 kPa which is also depicted in Table 6.24. This may be attributed to the change in texture within the soil matrix after addition of fly ash to sand. Reduction of peak strength occurred due to decreased frictional resistance by the addition of fly ash within the specimens which is evident from Table 6.27. It is also seen that curing increased the peak deviator stress of the sand mixes.

The failure strain obtained for each specimen is the average failure strain value of the specimens for the range of curing periods considered in this study. It is seen that addition of fly ash to sand reduces the failure strain values of the mixes; hence BS+50FA mix shows the minimum value of failure strain among BS+FA mixes, whereas increase in confining pressure has made the specimen to fail in larger strain (Fig. 6.49). From Table 6.18, it is seen that sand specimen shows a bulging kind of failure, whereas a clear failure surface is observed in fly ash added sand specimens irrespective of any curing period.

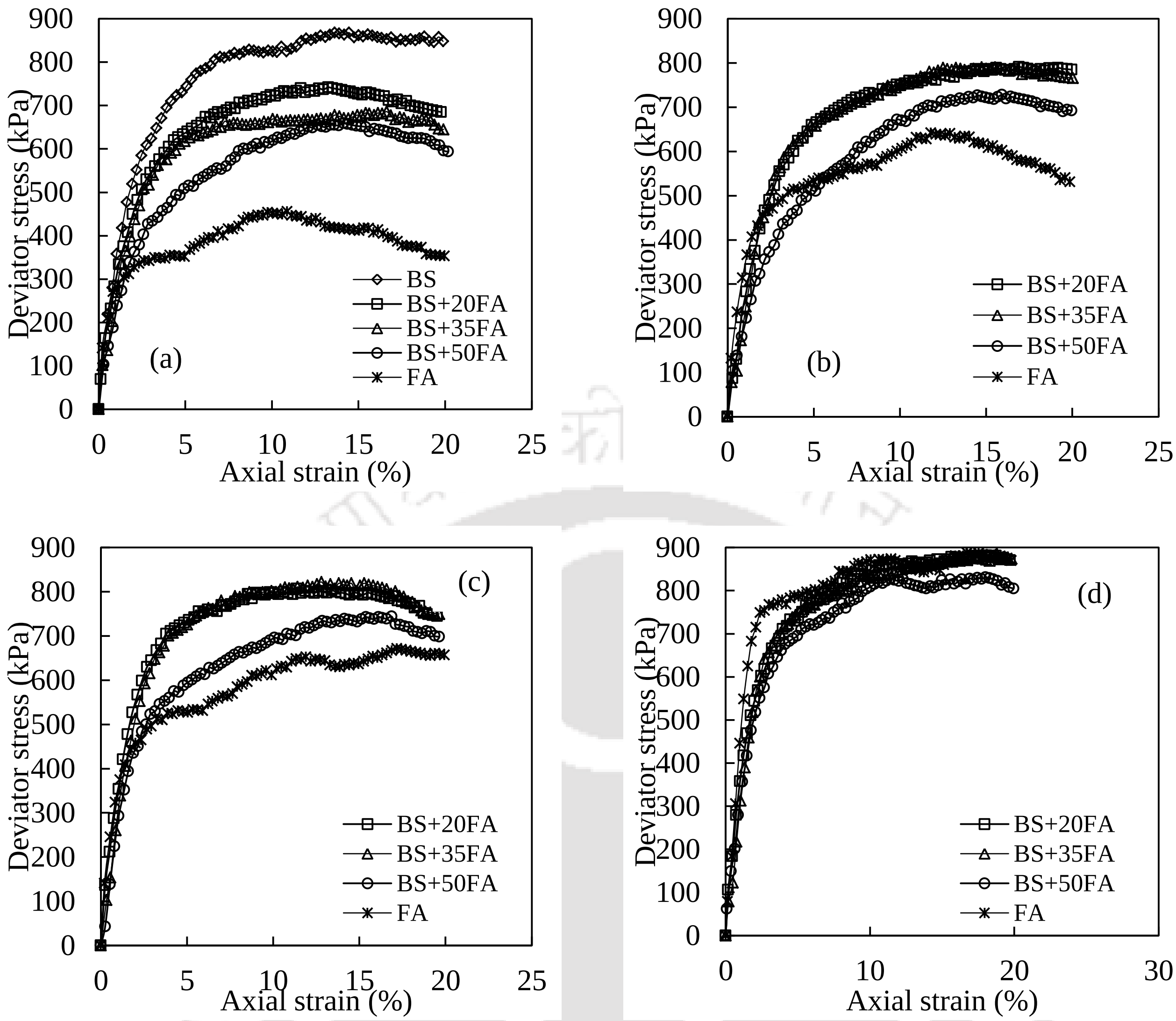


Fig. 6.48 Stress-strain behaviour of BS+FA at 300 kPa confining pressure at (a) 0, (b) 7 days, (c) 14 days and (d) 28 days curing

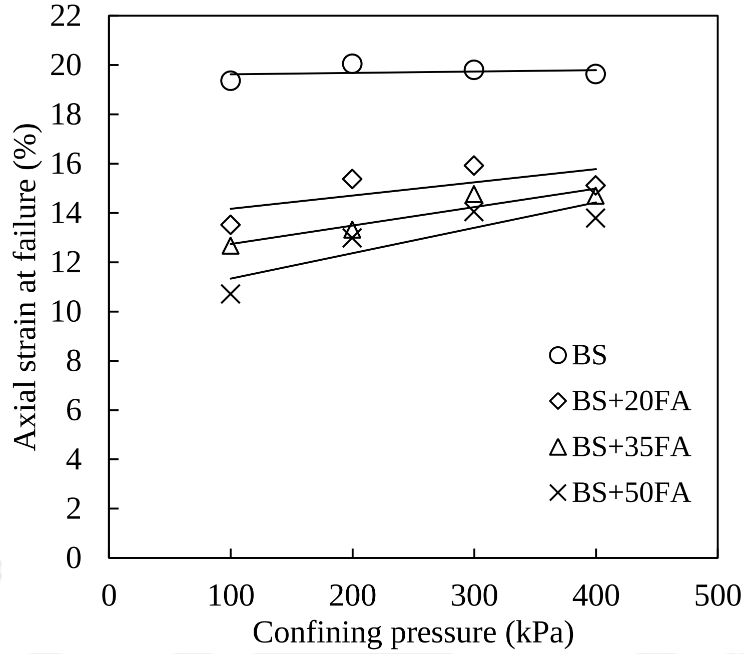


Fig. 6.49 Variation of failure axial strain of BS alone and BS+FA mix with confining pressure

Table 6.18: Failure patterns of BS+FA mixes tested at 300 kPa confining pressure

Curing	Mix			
	BS	BS+20FA	BS+35FA	BS+50FA
0 Day				
7 Days				

14 Days				
28 Days				

5.3.11.2 Shear Strength Characteristics

Fig. 6.50 shows the p-q plots for BS+FA mixes. It is observed that increase in fly ash content in sand-fly ash mixes has made the mixes weaker. BS+FA mix has exhibited strength between sand and fly ash. As the curing period is increased, improvement in peak strength is observed to some extent.

Table 6.27 shows the values of cohesion and internal friction angle for BS+FA mixes. Cohesion values of BS+FA mixes are increased with the increase in fly ash content in mixes, and this is due to cementations between sand and fly ash particles. Again increase in fly ash content in mixes has reduced the internal friction angle values due to the replacement of angular sand particles with spherical fly ash particles. BS+20FA mixes show greater value of internal friction angle among all other BS+FA mixes. It is observed that the effect of curing on variation of cohesion and friction angle is marginal.

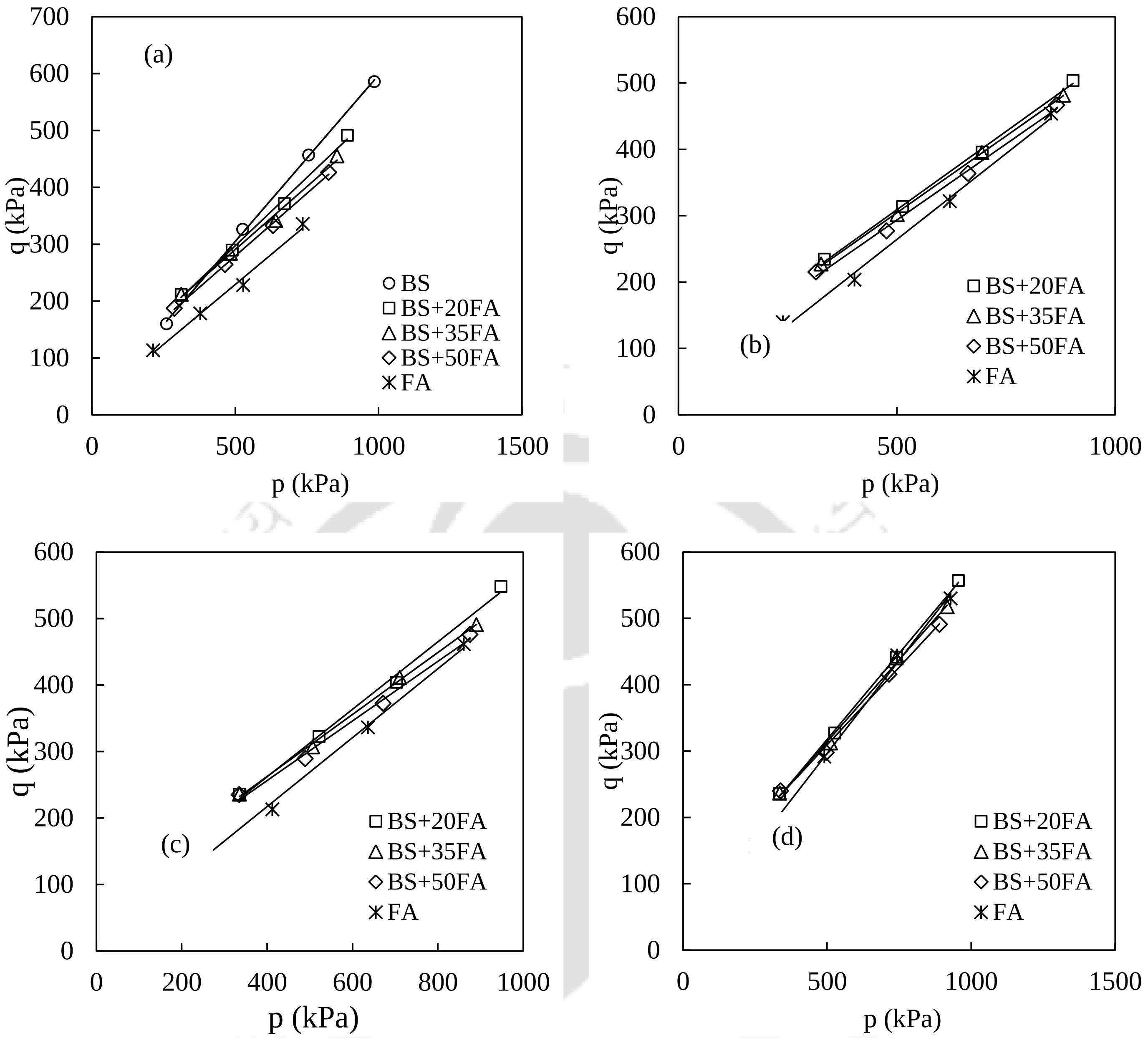


Fig. 6.50 p-q plots for BS+FA mixes at (a) 0, (b) 7 days, (c) 14 days and (d) 28 days curing

To understand the mechanism affecting the shearing behaviour of sand-fly ash mixes, the interaction between the particles of various textures within the assemblage should be taken into account. The distribution of sand and fly ash particles in sand-fly ash mixes is shown in Fig. 6.51. The spherical fly ash particle can easily roll over another particle which results in weaker resistance during shearing within the specimen. Therefore, replacement of angular sand particles by fly ash particles reduces the shear strength of sand-fly ash mixes. Here angularity of the particles plays an important role.

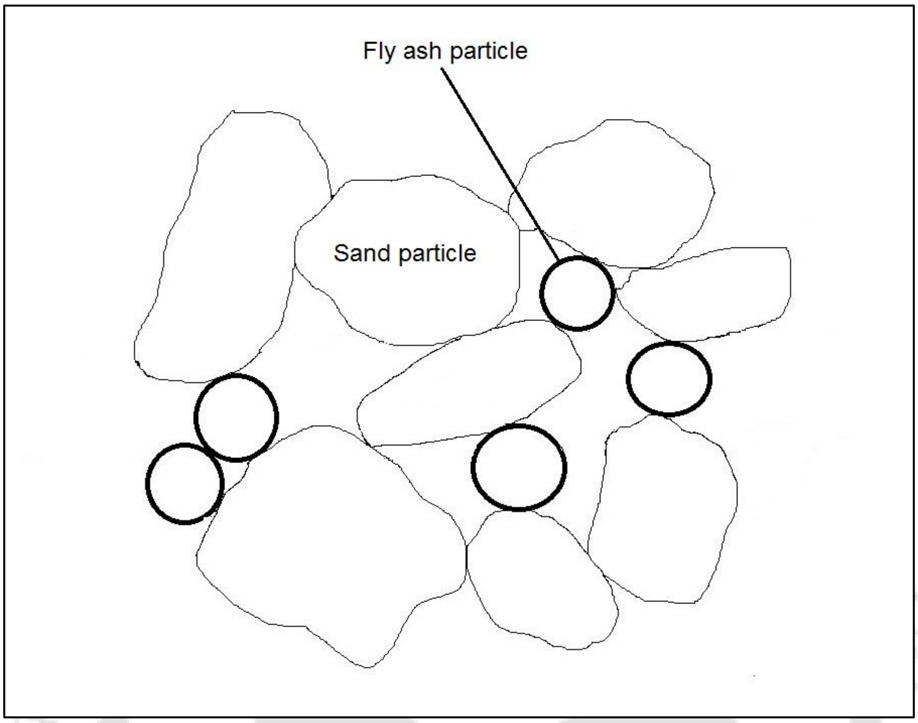


Fig. 6.51 Schematic diagram of interfacial interactions of sand and fly ash particles

5.3.12 Effect of Tyre Buffing (TB) Inclusion on Behaviour of Sand Mixes

6.3.12.1 Stress-Strain Behaviour

Fig. 6.52 shows the variation of the deviator stress (σ_1-σ_3), with axial strain (ε) for the BS and BS+TB specimens at 300 kPa confining pressure for 0 curing period. In some of the sand-tyre buffing mix specimens, no peak deviator stress is reached even at 20% axial strain. This is a manifestation of the ductile behaviour induced by both the confining pressure and the tyre buffing inclusion. Generally, inclusion of tyre buffing reduces the peak deviator stress and stiffness of soil mixes. Lee et al. (1999) reported that mixes of sand and tyre chips present a response intermediate between those of pure sand and pure tyre chips. But at 100 kPa confining pressure, BS+TB mixes exceptionally have showed higher values of peak deviator stress values than BS alone mix (Table 6.24).

As shown in Fig. 6.53, 5% inclusion of tyre buffings to sand has reduced the failure strain and further addition of 10% tyre buffings to sand has increased the failure strain of the mixes. Table 6.14 shows no trace of failure surface in the specimen.

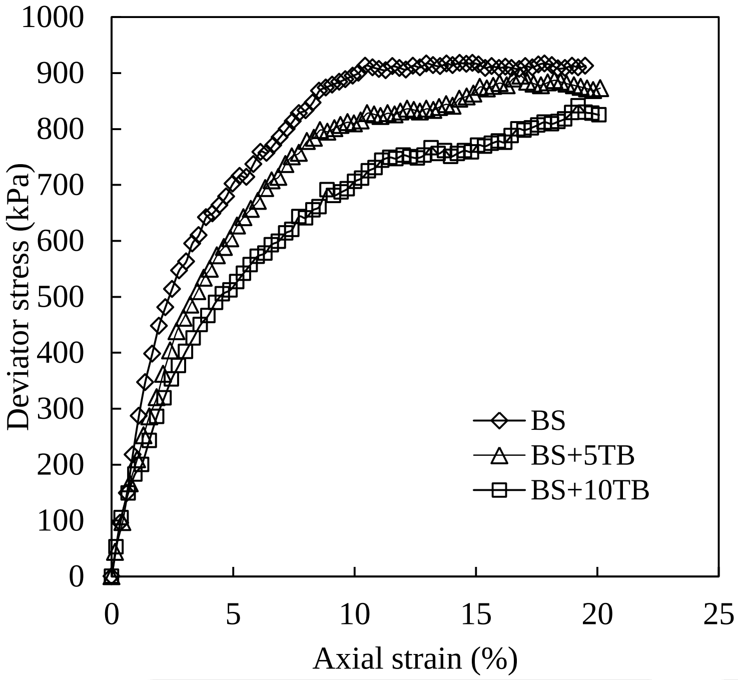


Fig. 6.52 Stress-strain behaviour of BS alone and BS+TB mixes at 300 kPa confining pressure with 0 day of curing

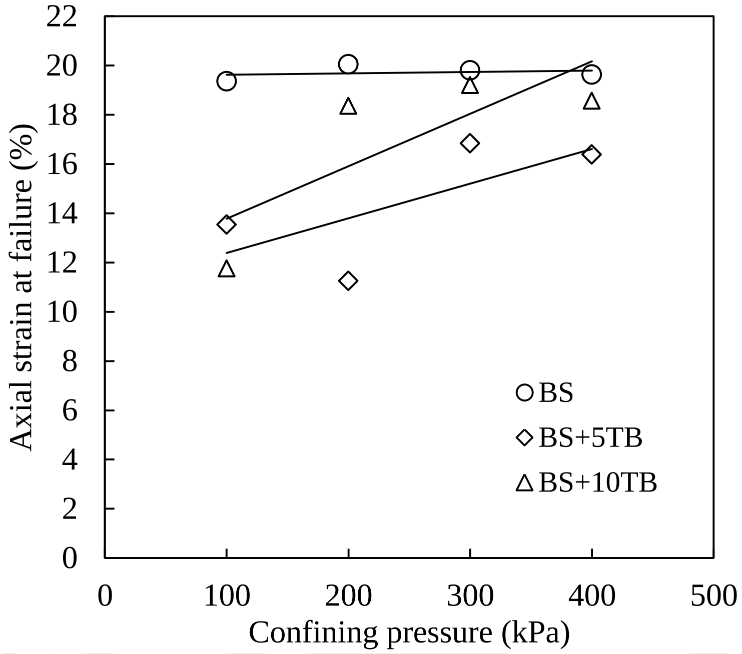


Fig. 6.53 Variation of faliure axial strain of BS alone and BS+TB mix with confining pressure

Table 6.19: Failure patterns of BS+TB mixes tested at 300 kPa confining pressure

Curing	Mix		
	BS	BS+5TB	BS+10TB
0 Day			

6.3.12.2 Shear Strength Characteristics

The p-q plots of BS and BS+TB specimens at 0 day curing period have been shown in Fig. 6.54. Except for specimens tested in 100 kPa confining pressure, the peak strength of the tyre buffings added specimens is found to be lower than the BS alone mixes. No improvement in peak strength is observed on further addition of tyre buffings.

Significant contribution of tyre shred to the sand-tyre shred mixes was also reported by Zornberg et al. (2004). Youwai et al. (2003) reported that the strength of the shredded rubber tire – sand mixture increased linearly with increasing confining pressure from 50 to 200 kPa. The strength of the mixed material increased with increasing amounts of sand 50% to 80% in the mix because the shear strength of sand was higher than that of the shredded rubber tires. Reduction in shear strength with increase in tyre buffings content in the sand-tyre mixes was also reported by Edincliler et al. (2012). Tyre buffings retained between the sieve of sizes 2 mm and 0.425 mm were used in their study.

It has been seen that inclusion of tyre buffing to sand mixes has increased the cohesion as shown in the Table 6.27. This kind of behavior is attributed to the development of apparent cohesion in BS+TB mixes. However sand- tyre buffing mixes have showed lower value of internal friction angle than sand alone mixes. This kind of behaviour resembles the findings by Youwai et al. (2003). The peak internal friction angle is found to vary from 30^0 to 34° with increasing proportions of sand in the mix. There is also an apparent cohesion intercept resulting from the compaction effort.

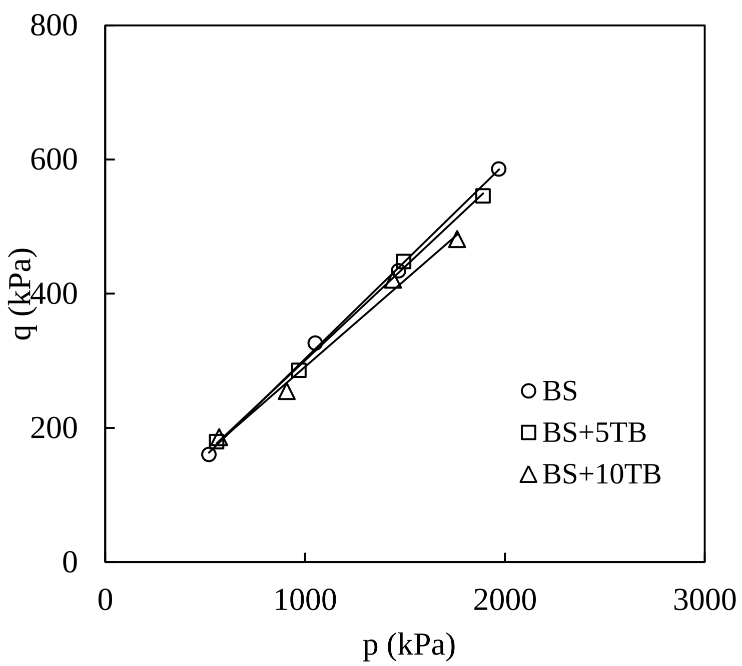


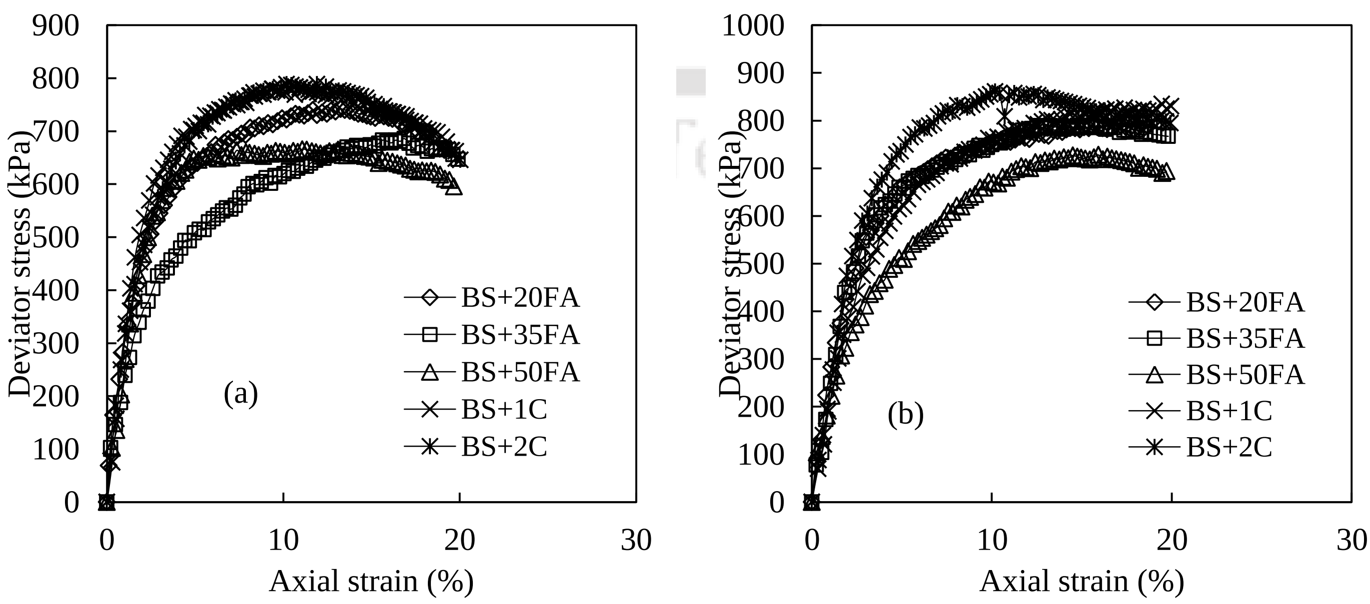
Fig. 6.54 p-q plots of BS alone and BS+TB mixes with 0 day of curing

5.3.13 Effect of Cement Addition on Behaviour of Sand Mixes

5.3.13.1 Stress-Strain Behaviour

From Figs 6.55, effect of cement addition on stress-strain plots obtained at confining pressure of 300 kPa can be observed for curing period of 0, 7, 14 and 28 days. It is seen that addition of cement has increased the peak deviator stress and stiffness of the soil matrix. It is seen that addition of cement to sand mixes is more effective in higher curing period, as far as increase in peak deviator stress is concerned. Without curing, increase in cement content has shown no significant improvement in strength as compared to cemented specimens tested after longer curing days. The peak deviator stress values of BS+C mixes are higher than the BS+FA mixes. It is evident that as the curing increased the peak deviator stress of the sand-cement mixes has also increased (Table 6.25).

From Fig. 6.56, it is seen that addition of cement to sand has made the specimen to fail in a lower axial strain. Table 6.20 reveals that cemented sand mixes showed brittle behaviour as compared to sand alone mixes. Failure surface is visible in BS+C specimens.



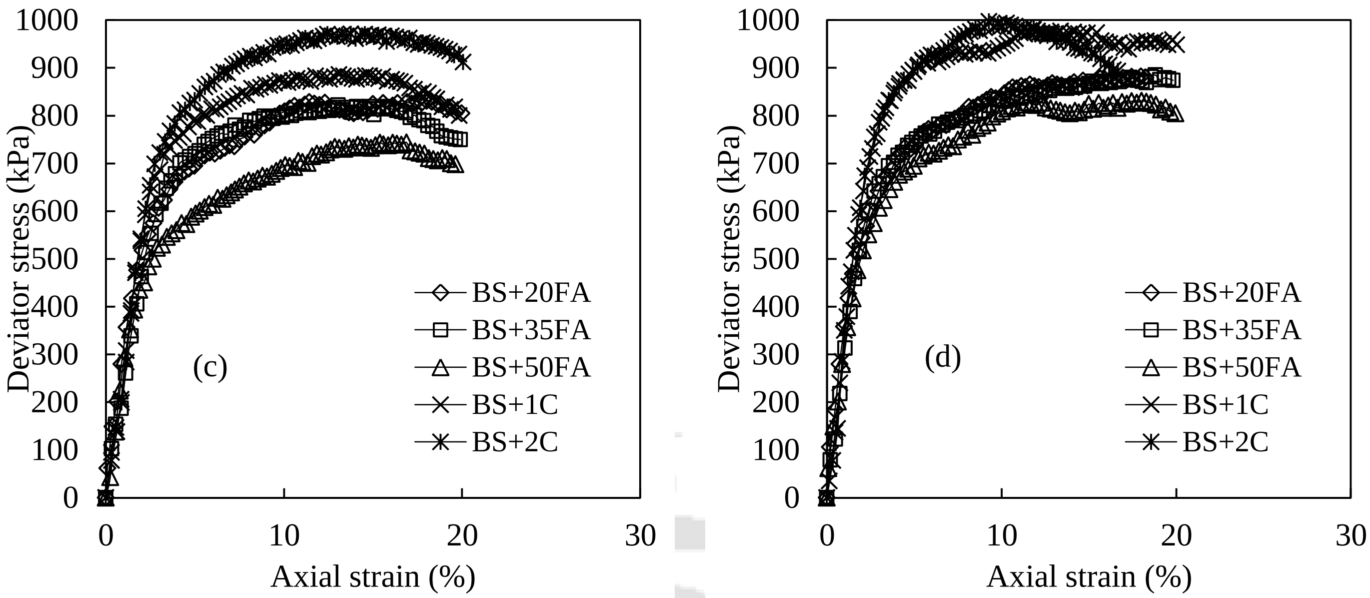


Fig. 6.55 Stress-strain behaviour of BS+C and BS+FA at 300 kPa confining pressure at (a) 0, (b) 7 days, (c) 14 days and (d) 28 days curing

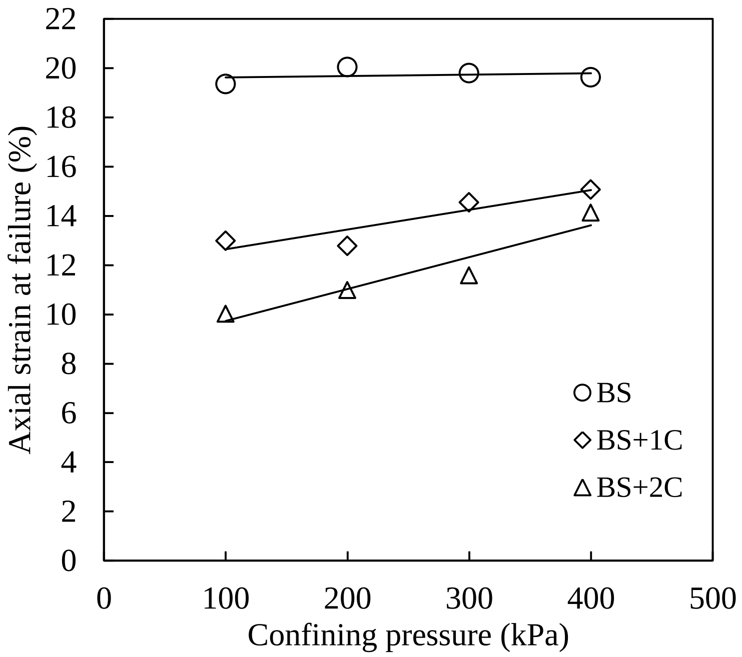


Fig. 6.56 Variation of failure axial strain of BS+C mixes with confining pressure

Table 6.20: Failure patterns of BS+C mixes tested at 300 kPa confining pressure

Curing	Mix		
	BS	BS+1C	BS+2C
0 Day			
7 Days			
14 Days			
28 Days			

5.3.13.2 Shear Strength Characteristics

Fig. 6.57 shows the p-q plots for BS+FA and BS+C mixes at 0, 7, 14 and 28 days curing periods. It is observed that on addition of cement to sand, peak strength is increased marginally with no curing as compared to BS+FA mixes. As the curing period has increased, a significant increase in peak strength is observed for cemented mixes. The effect of cement addition is more prominent in case of 28 days curing periods.

It is evident from Table 6.28 that with the increase in curing period and cement content in BS+C mixes, the cohesion parameter has increased significantly. Addition of cement to sand has decreased the values of internal friction angle. Marginal effect of curing on friction angle is observed for the cemented mixes.

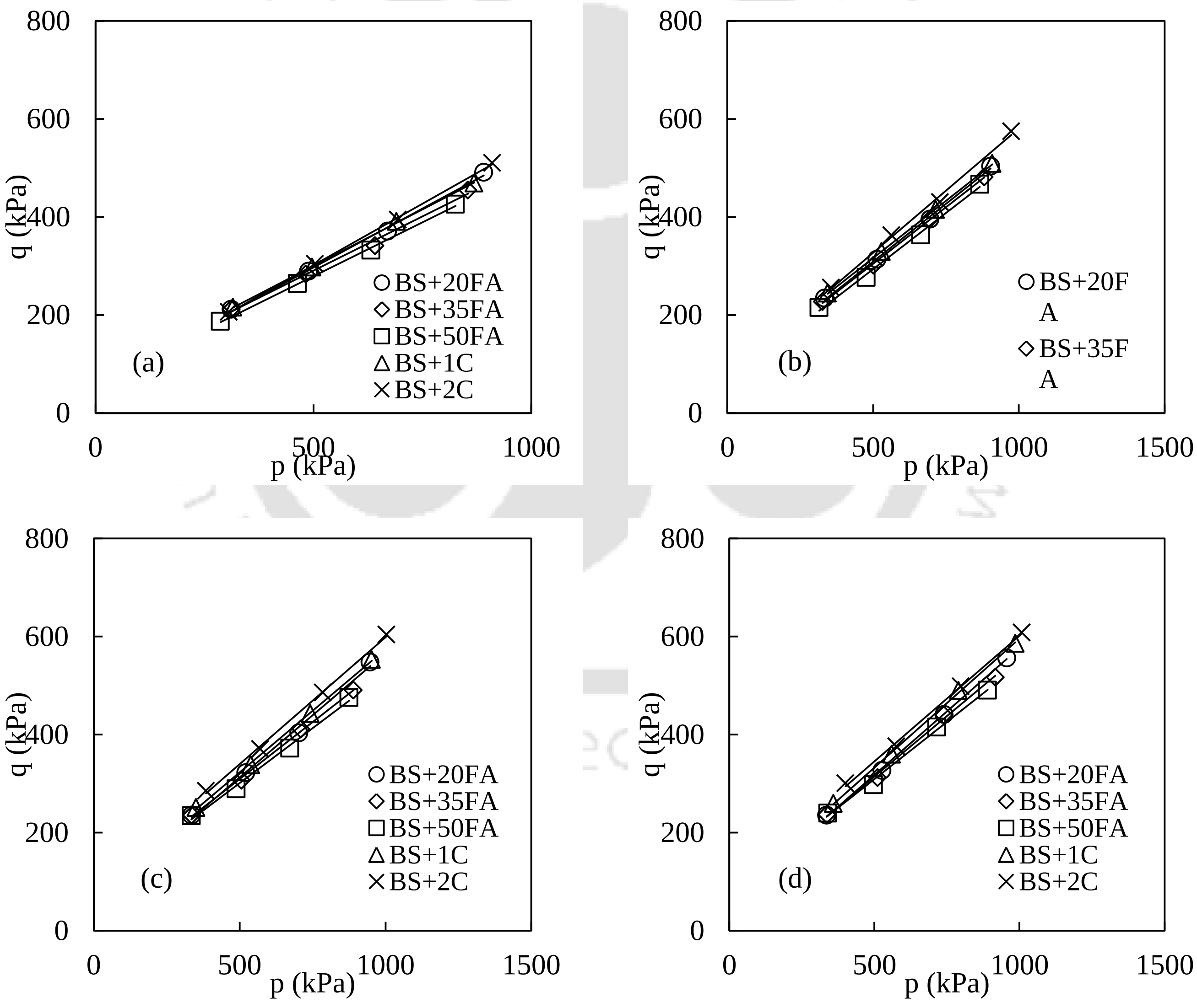


Fig. 6.57 p-q plots for BS+FA and BS+C mixes at (a) 0, (b) 7 days, (c) 14 days and (d) 28 days curing

6.3.14 Effect of Tyre Buffing Inclusion on Behaviour of Sand-Fly Ash Mixes

Triaxial compression tests were carried out on sand-fly ash tyre buffing mixes to study the effect of inclusion of tyre buffings on stress-strain-strength characteristics.

6.3.14.1 Stress-Strain Behaviour

Figs. 6.58 to 6.60 show the variation of the deviator stress (σ_1-σ_3), with axial strain (ε) for the BS, BS+FA and BS+FA+TB specimens at 300 kPa confining stress for different curing periods. The deviator stress has attained a peak value and thereafter has remained almost constant. In some of the soil-fly ash-tyre buffings mix specimens, no peak deviator stress is reached even at 20% axial strain. This is due to the ductile behaviour induced by both the confining pressure and the tyre buffing inclusion. Inclusion of tyre buffing reduced the stiffness of soil mixes. In most of the cases, it is seen that peak deviator stress values of sand-fly ash-tyre buffing mixes are comparable or greater than the sand-fly ash mixes.

Table 6.24 gives the summary of peak deviator stress values of different sand-fly ash-tyre buffing mixes at different confining pressures and curing periods. Peak deviator stress of sand-fly ash mixes is influenced by the inclusion of tyre buffing to sand-fly ash mixes. It is seen that confining pressure and fly ash content play an important role in the improvement of strength of BS+FA+TB mixes (Table 6.24). At 100 kPa confining pressure, the addition of tyre buffing to sand-fly ash mixes has reduced the peak deviator stress values of the mixes irrespective of any fly ash content. As the confining pressure is increased from 200 kPa to 400 kPa, the inclusion of tyre buffings to BS+FA mixes containing 35% and 50% fly ash contents has shown a tendency for gain in strength when compared to BS+35FA and BS+50FA mixes. At any confining pressure, peak deviator stress values of BS+20FA+TB mixes are lower than BS+20FA mixes.

Therefore, the inclusion of tyre buffings to sand-fly ash mixes can be beneficial at higher confining pressure and higher fly ash content as well. This kind of behaviour may be due to an increase in the contact area between tyre buffings and sand-fly ash matrix within the specimens at higher confining pressure and fly ash content. As such, BS+50FA+5TB mix has shown greater peak deviator stress values among any other mixes. Improvement of peak deviator stress values of the mixes has also occurred with the increase in the curing period.

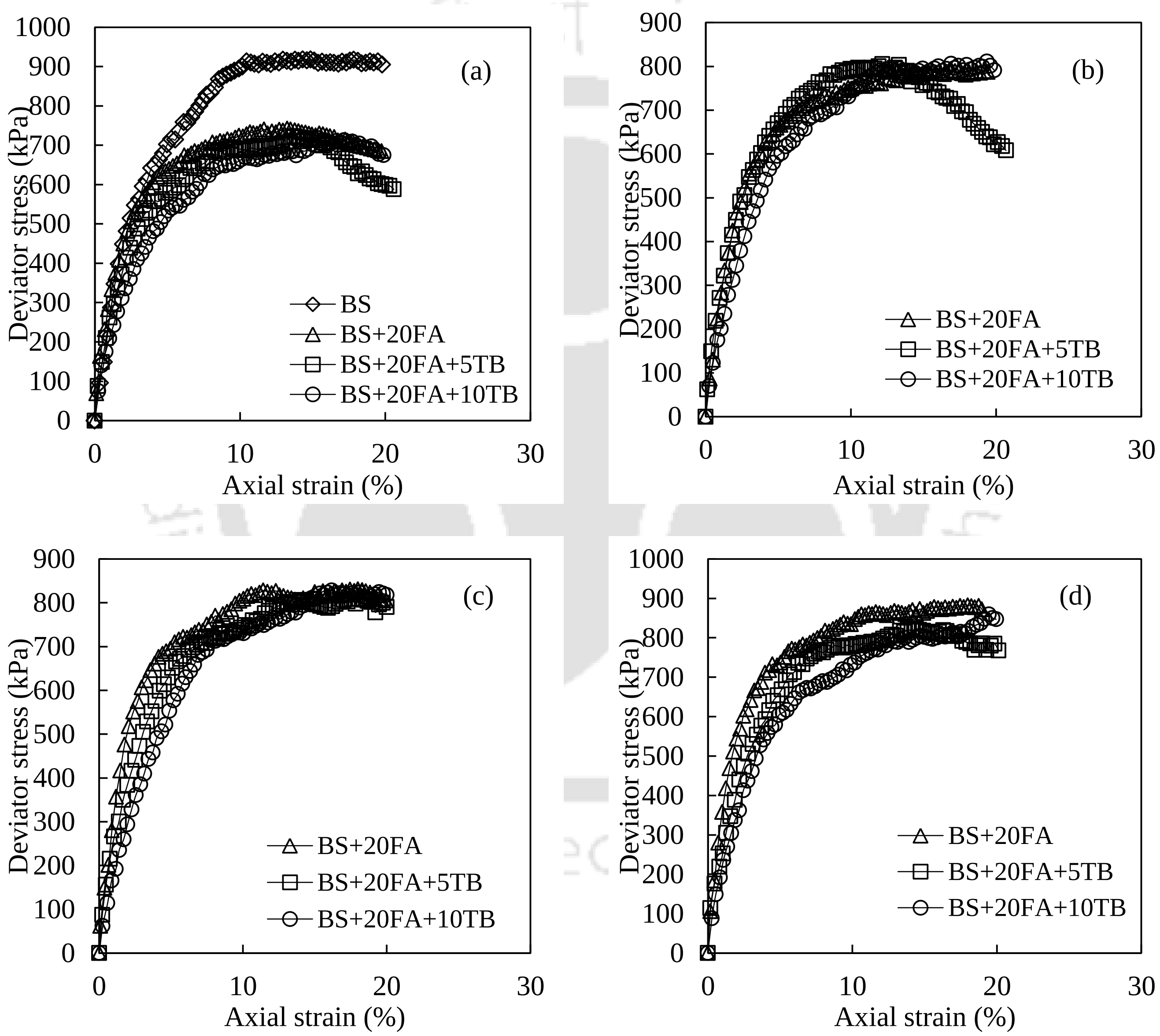


Fig. 6.58 Stress-strain behaviour of BS, BS+20FA and BS+20FA+TB at 300 kPa confining pressure for (a) 0, (b) 7 days, (c) 14 days and (d) 28 days curing

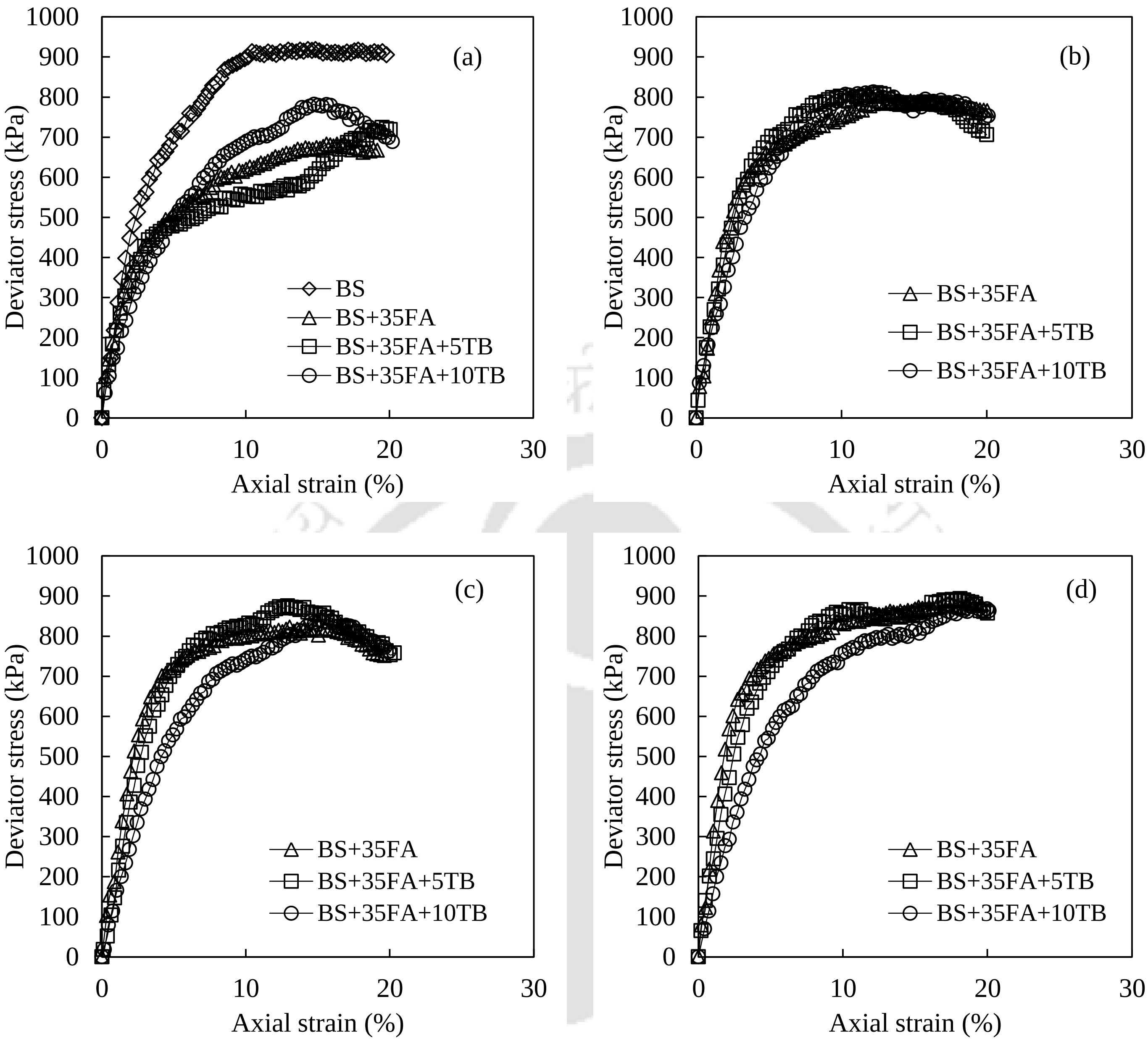


Fig. 6.59 Stress-strain behaviour of BS, BS+35FA and BS+35FA+TB at 300 kPa confining pressure for (a) 0, (b) 7 days, (c) 14 days and (d) 28 days curing

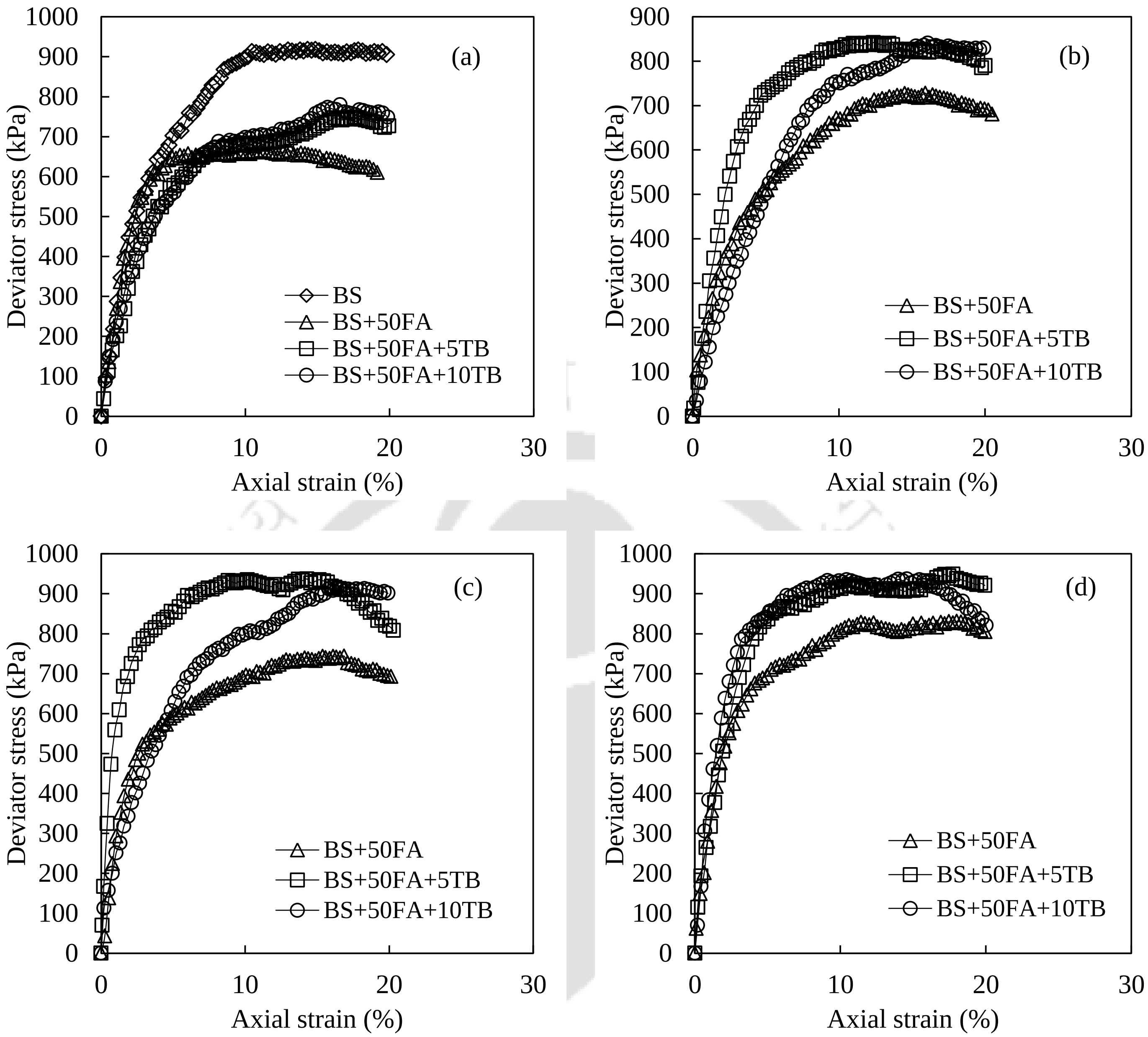


Fig. 6.60 Stress-strain behaviour of BS, BS+50FA and BS+50FA+TB at 300 kPa confining pressure for (a) 0, (b) 7 days, (c) 14 days and (d) 28 days curing

Inclusion of tyre buffings to sand-fly ash mixes generally has increased the failure strain (Fig. 6.61). This kind of behaviour is attributed to the elastic behaviour of tyre buffings. As shown in Table 6.21, addition of tyre buffings to sand-fly ash specimens alters the failure pattern and the specimen shows the tendency for undergoing bulging failure. But specimens containing 10% tyre buffings has shown no clear failure surface even at 28 days curing period and bulging failure has occurred. This behaviour indicates that an increase in tyre buffing content introduces ductility in the soil specimen, which resembles previous findings of researchers (Mukherjee and Mishra, 2019). Hazarika et al. (2010) also reported that because of the elasticity reactions exhibited by tyre chips, shearing of clay-tyre chips mixes are restrained. Therefore, increased tyre buffing content in sand-fly ash-tyre buffing mixes has resulted in no failure surface during shearing.

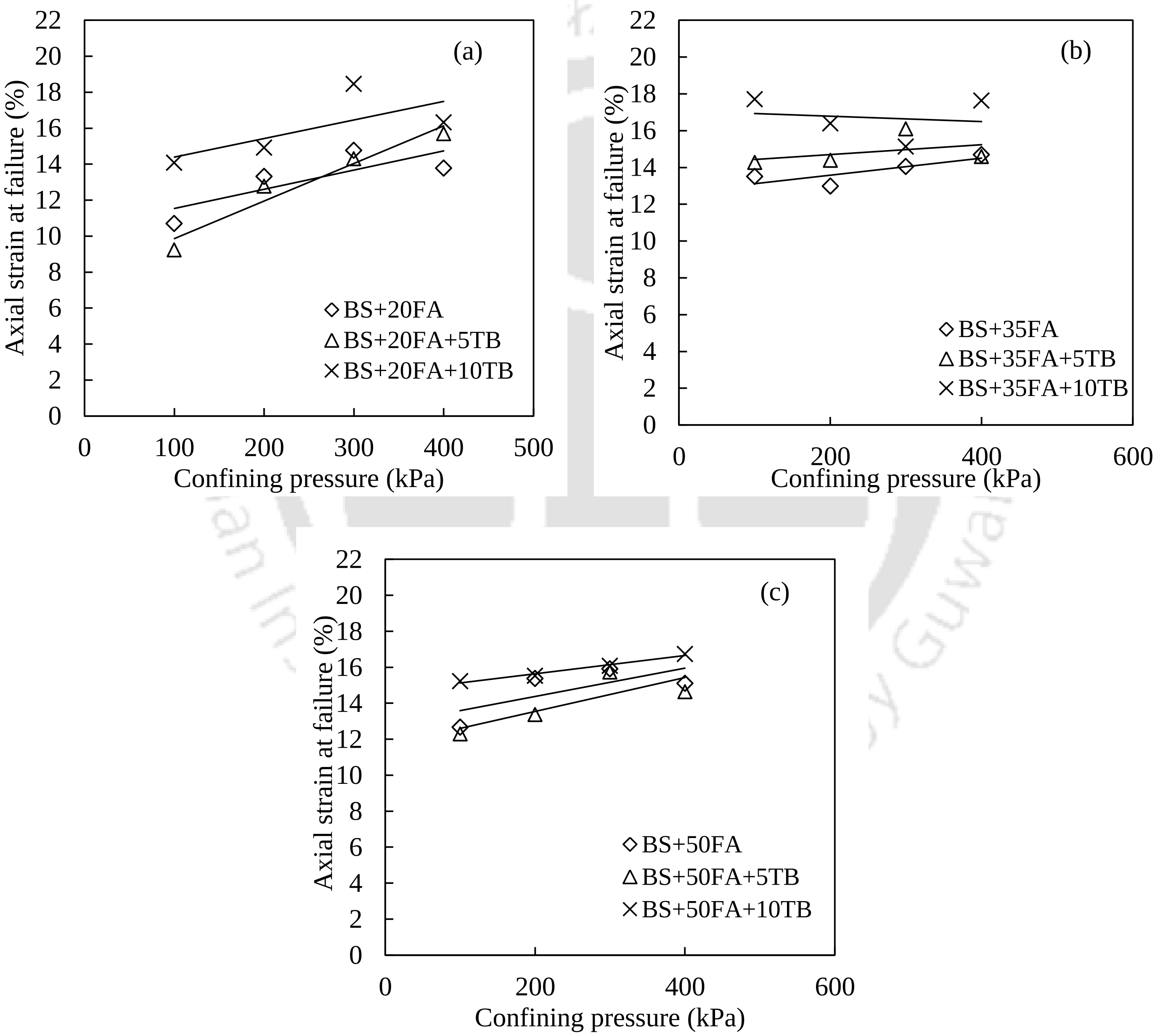


Fig. 6.61 Variation of failure axial strain of BS+FA and BS+FA+TB mixes with confining pressure for (a) 20%, (b) 35% and (c) 50% FA content

Table 6.21: Failure patterns of BS+FA+TB mixes tested at 300 kPa confining pressure

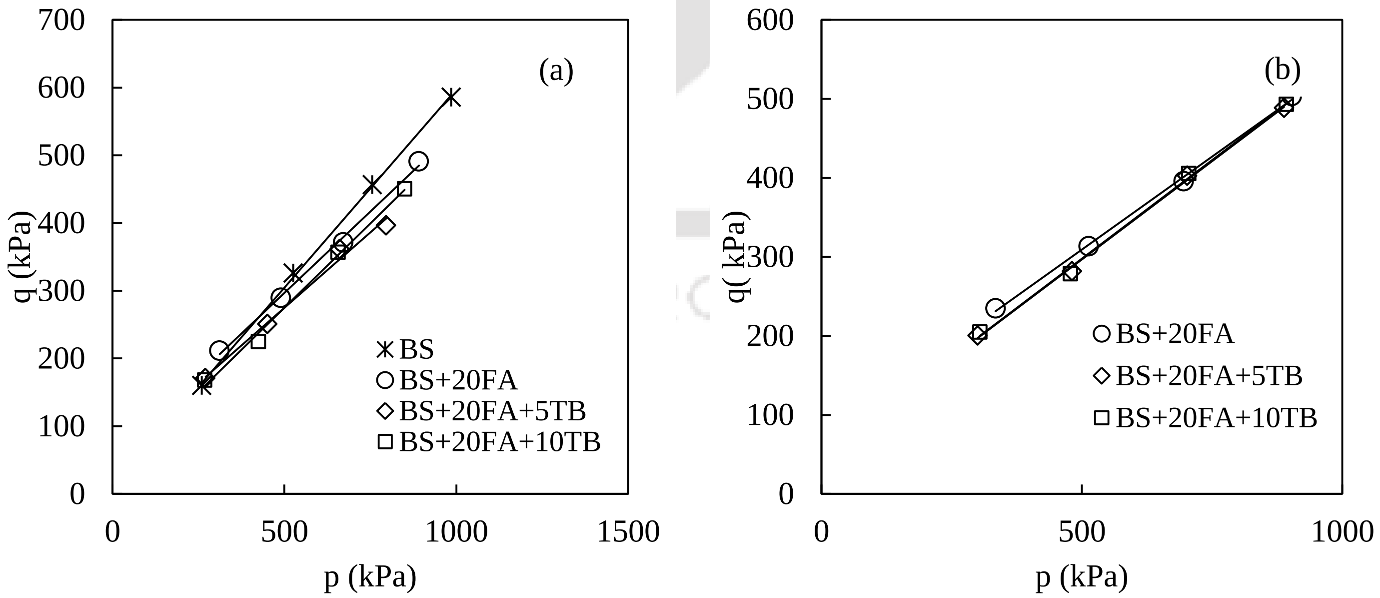
Curing	Mix			
	BS	BS+20FA+5TB	BS+35FA+5TB	BS+50FA+5TB
0 Day				
7 Days				
14 Days				
28 Days				
	Mix			
	BS	BS+20FA+10TB	BS+35FA+10TB	BS+50FA+10TB

0 Day				
7 Days				
14 Days				
28 Days				

6.3.14.2 Shear Strength Characteristics

Figs. 6.62 to 6.64 show the stress-paths in terms of p-q plots for BS, BS+FA and BS+FA+TB mixes at 0, 7, 14 and 28 days curing periods. It is seen that addition of 5% TB to sand-fly ash mix has increased the strength of mixes containing 35% and 50% fly ash contents. It is noticeable that at 100 kPa confining pressure, tyre buffing added mixes have shown lower strength as compared to sand-fly ash mixes. As such BS+50FA+5TB mix has exhibited highest strength among any other BS+FA+TB mixes. Therefore it can be stated that tyre buffing can effectively be added to sand-fly ash mixes especially with 35% and 50% fly ash content. The variation of strength of BS+FA+TB mixes with curing periods is marginal.

Table 6.27 shows the shear strength parameters of different sand-fly ash-tyre buffing mixes at different confining pressures and curing periods. Generally, the addition of tyre buffing to sand-fly ash mixes has reduced the cohesion values of the mixes. In most of the cases, BS+FA+TB mixes have shown higher values of friction angle than BS+FA mixes. The sand used in this study is poorly graded; the addition of fly ash to sand changes the texture of sand-fly ash composite. This transformation is responsible for the improvement in internal friction angle of tyre buffings added sand-fly ash mixes. Anbazhagan et al. (2016) also reported that the addition of rubber fibre to uniformly graded sand increases the friction angle of mixes.



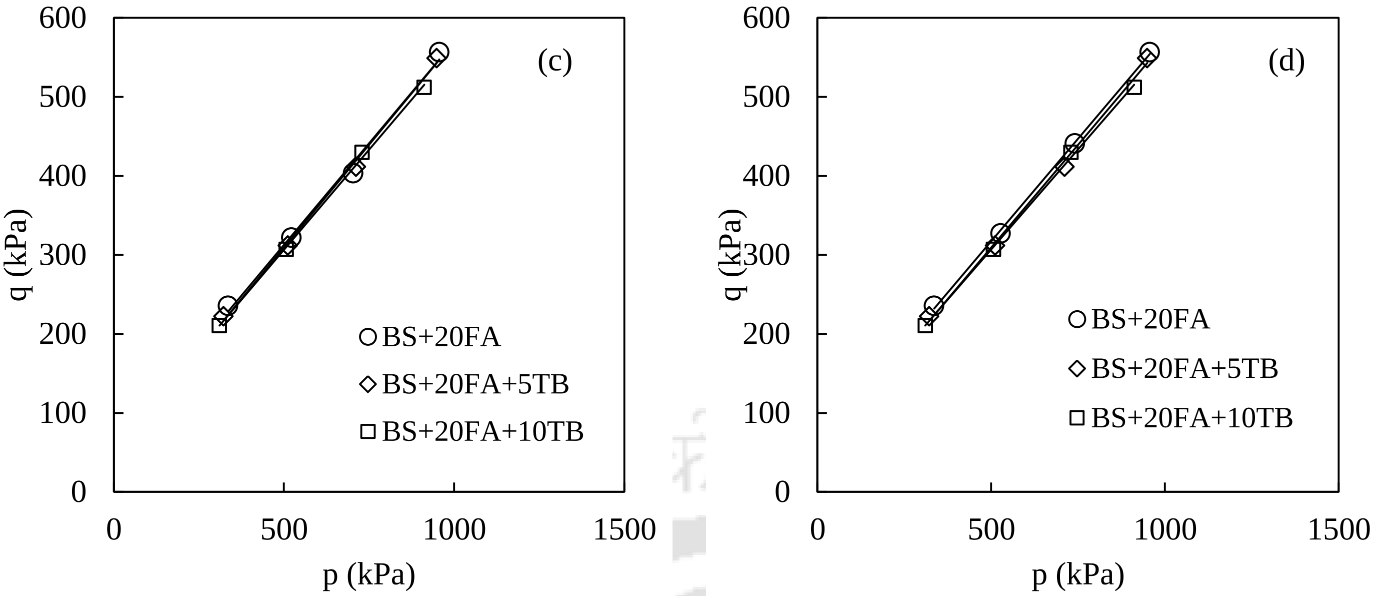
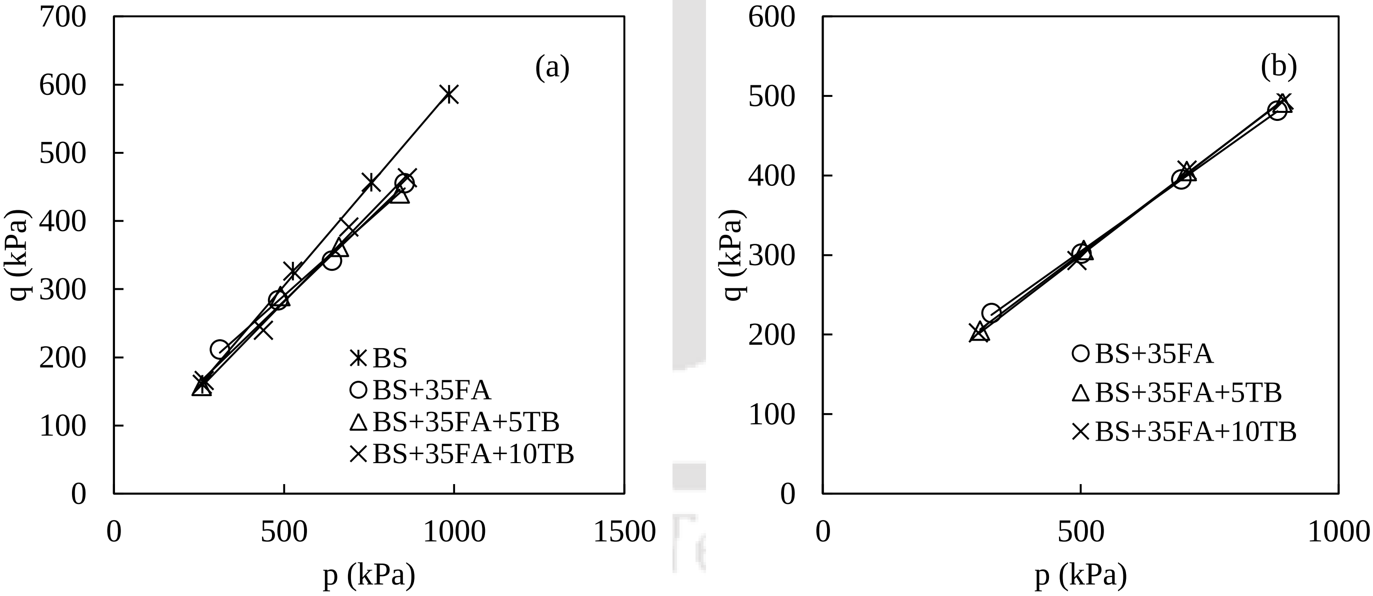


Fig. 6.62 p-q plots of BS, BS+20FA and BS+20FA+TB for (a) 0, (b) 7 days, (c) 14 days and (d) 28 days curing



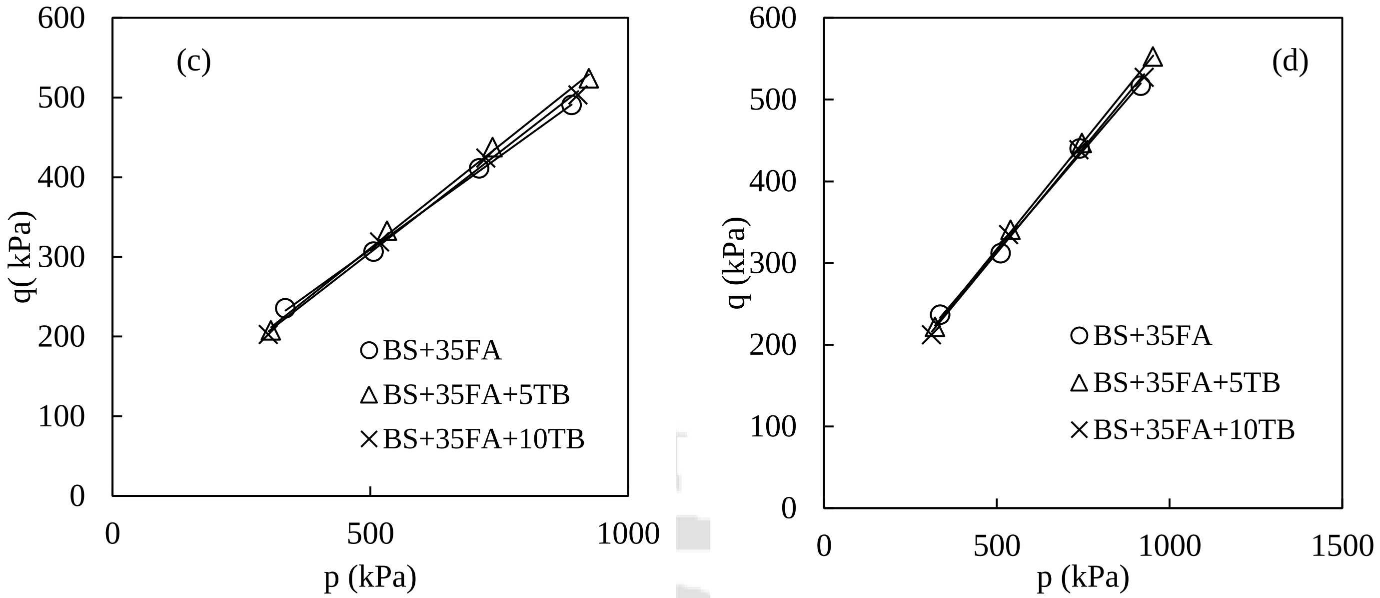
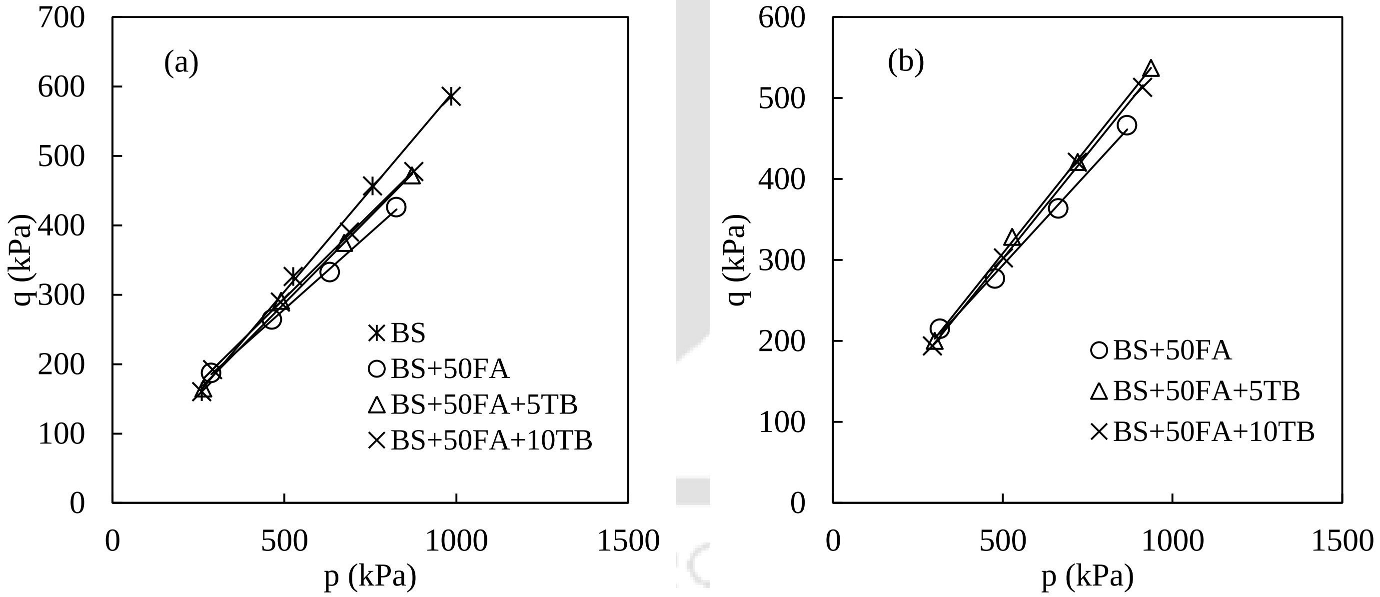
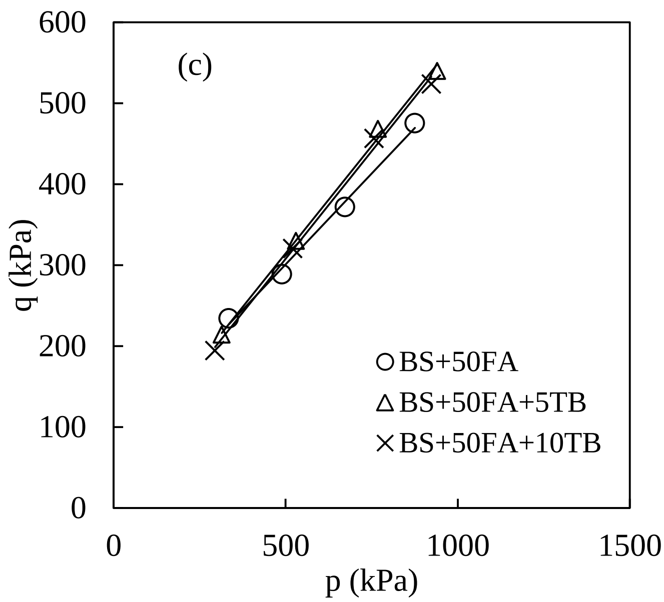


Fig. 6.63 p-q plots of BS, BS+35FA and BS+35FA+TB for (a) 0, (b) 7 days, (c) 14 days and (d) 28 days curing





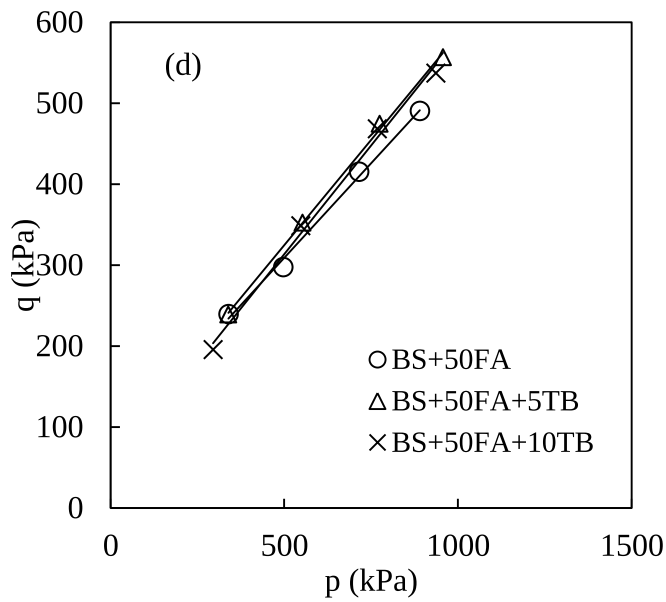


Fig. 6.64 p-q plots of BS, BS+50FA and BS+50FA+TB for (a) 0, (b) 7 days, (c) 14 days and (d) 28 days curing

Previously, the interaction mechanism of rubber fibre-soil interface was proposed by Kalkan (2013). To understand the mechanism affecting the shearing behaviour of sand-fly ash-tyre buffing mixes, the interaction between the particles of various textures within the assemblage should be taken into account. The distribution of sand, fly ash and tyre buffing particles in sand-fly ash-tyre buffing mixes is shown in Fig. 6.65. Addition of tyre buffing to sand-fly ash mixes generates skin friction resistance along the surface of the elongated tyre buffing. It increases the friction angle of the mixes. It can also be stated that the increase in fly ash content in the mixes imparts more dense packing within the matrix. Moreover, the confining pressure also plays its part as far as gain in shear strength is concerned in tyre buffing added mixes. At 100 kPa, the tyre buffing particle behaves as a weaker material compared to the other two materials in the mix. While tyre buffing particle gets interlocked with sand and fly ash particles, the interlocking force is weak. Hence shearing of the specimen can easily occur. At higher confining pressure, tyre buffings become more rigid; therefore, resistance due to friction along the surface of the tyre fibre would be increased. This results in higher shear strength.

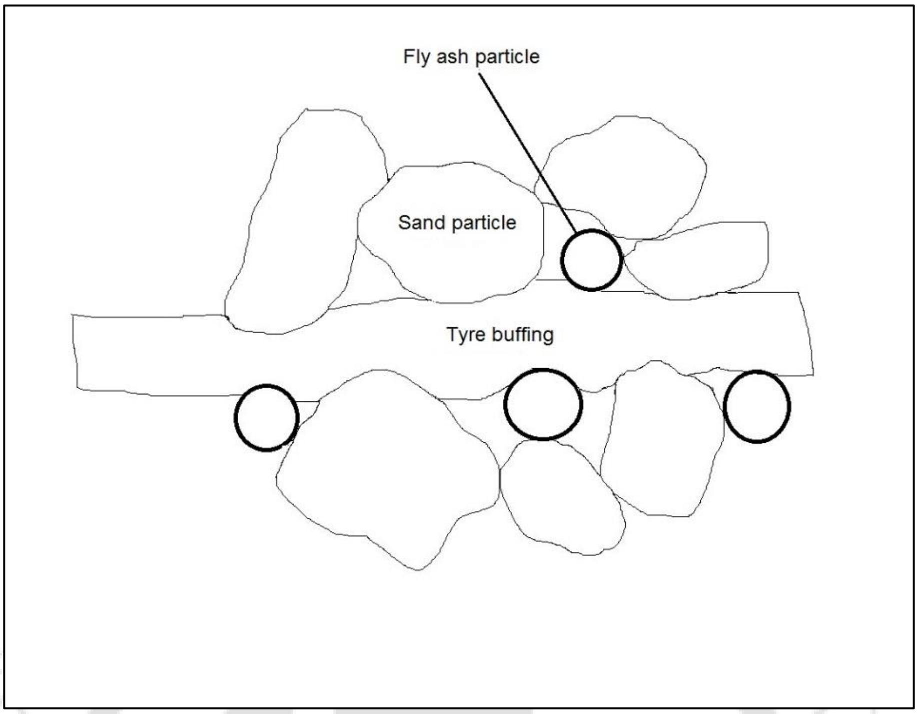


Fig. 6.65 Schematic diagram of interfacial interactions between tyre buffing, sand and fly ash particles

6.3.15 Effect of Cement Addition on Behaviour of Sand-Fly Ash Mixes

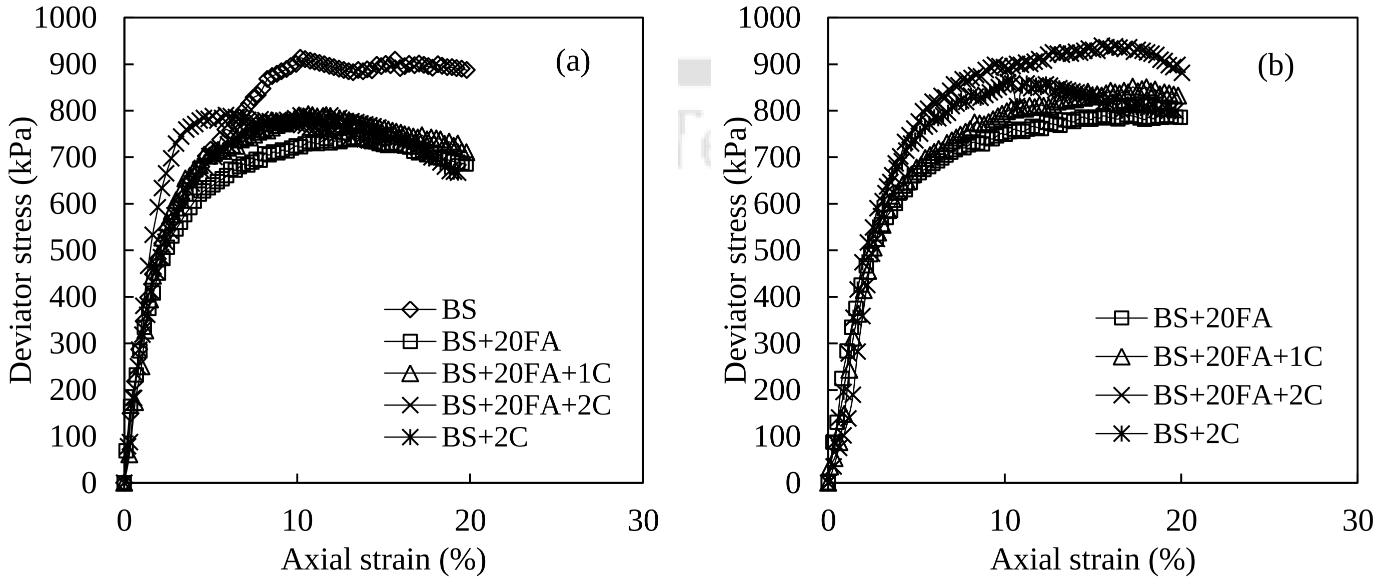
6.3.15.1 Stress-Strain Behaviour

From Figs 6.66 to 6.68, effect of cement addition in sand-fly ash mixes on stress-strain plots obtained at confining pressure of 300 kPa can be observed for curing periods of 0, 7, 14 and 28 days. It is seen that addition of cement to sand-fly ash mixes has increased the peak deviator stress and stiffness of the soil matrix. A sharp increase in peak deviator stress is observed in case of cemented mixes. Clear post peak stress drop is observed in cemented sand-fly ash specimens for curing periods of 7, 14 and 28 days. It is also seen that addition of 2% cement to sand-fly ash mixes has caused more post-peak drop as compared to other cemented mixes especially at higher curing periods (14 and 28 days). For BS+35FA+2C mix, the post-peak drop in strength is found to be 66, 214 and 439 kPa at 7, 14 and 28 days curing periods, respectively.

Similar kinds of findings were reported in research work by Consoli et al. (2009). The soil used in their study was nonplastic silty sand (SM). The fly ash was of Class F type. It was reported that addition of lime significantly improved strength and stiffness of the soil, even considering the nonplastic characteristics of the silty sand utilised. However, the presence of fly ash was fundamental to further improvement of the material behaviour, due to occurrence of a larger amount of time-dependent pozzolanic reactions.

It is seen that addition of cement to sand-fly ash mixes is more effective as far as increase in peak deviator stress was concerned (Table 6.25). As expected, addition of cement to sand-fly ash mixes immediately has shown no significant improvement in strength as compared to sand-cement mixes. In other curing days, cemented sand mixes have shown increase in peak deviator stress up to a fly ash content of 35% and decrease with 50%. Excessive increase in non-cohesive fraction in the mixes caused the reduction in strength. It is evident that as the curing has increased, the peak deviator stress of the sand mixes also has increased.

Effects of confining pressure and cement on variation of failure strain are shown in Fig. 6.69. Table 6.22 depicts the failure patterns of different sand-fly ash-cement mixes. Failure surface is seen in all cemented specimens. In 28 days curing period, failure surface is more clearly visible compared to other curing periods.



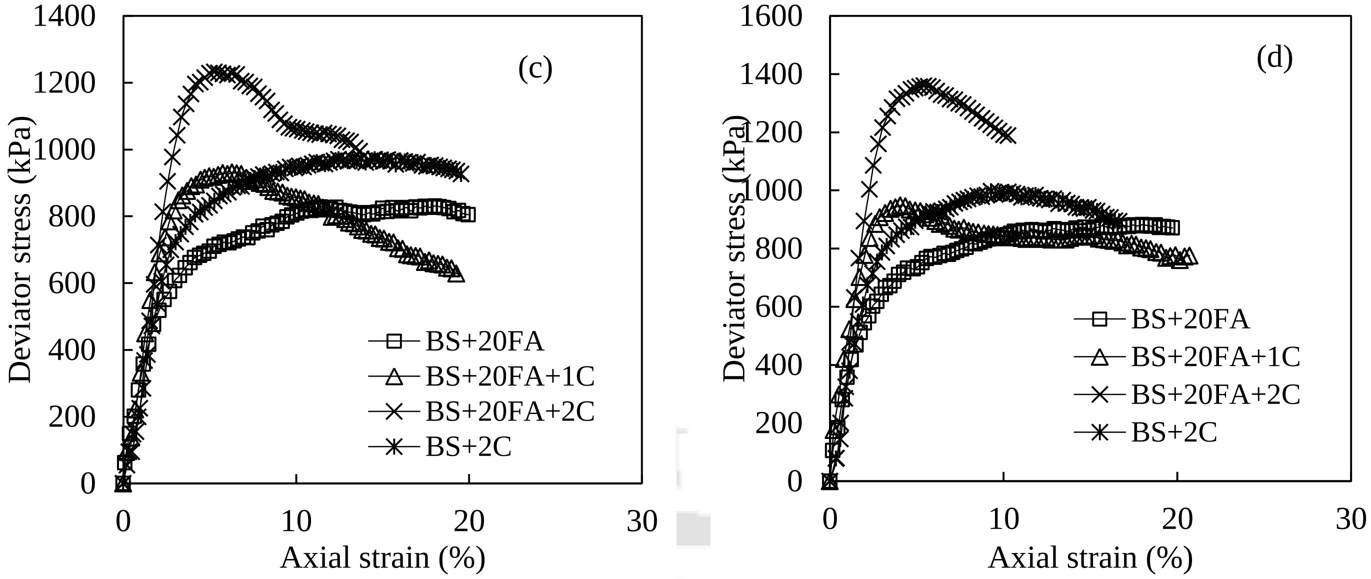
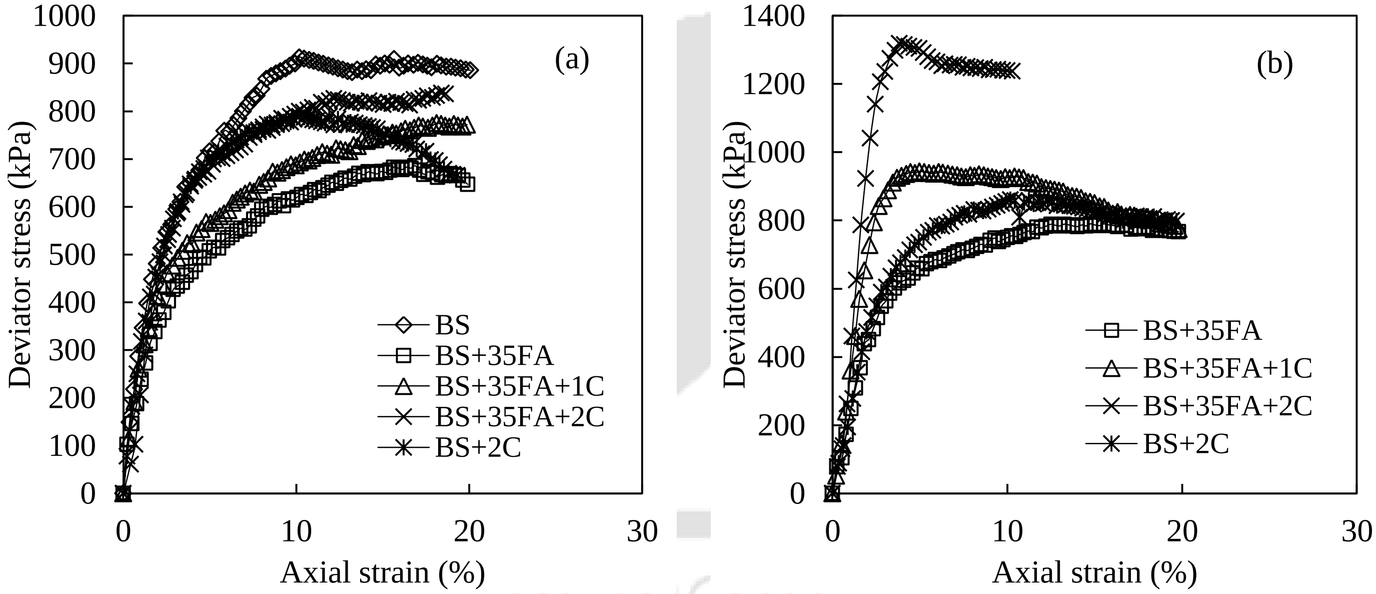


Fig. 6.66 Stress-strain behaviour of BS, BS+20FA, BS+2C and BS+20FA+C mixes at 300 kPa confining pressure for (a) 0, (b) 7 days, (c) 14 days and (d) 28 days curing



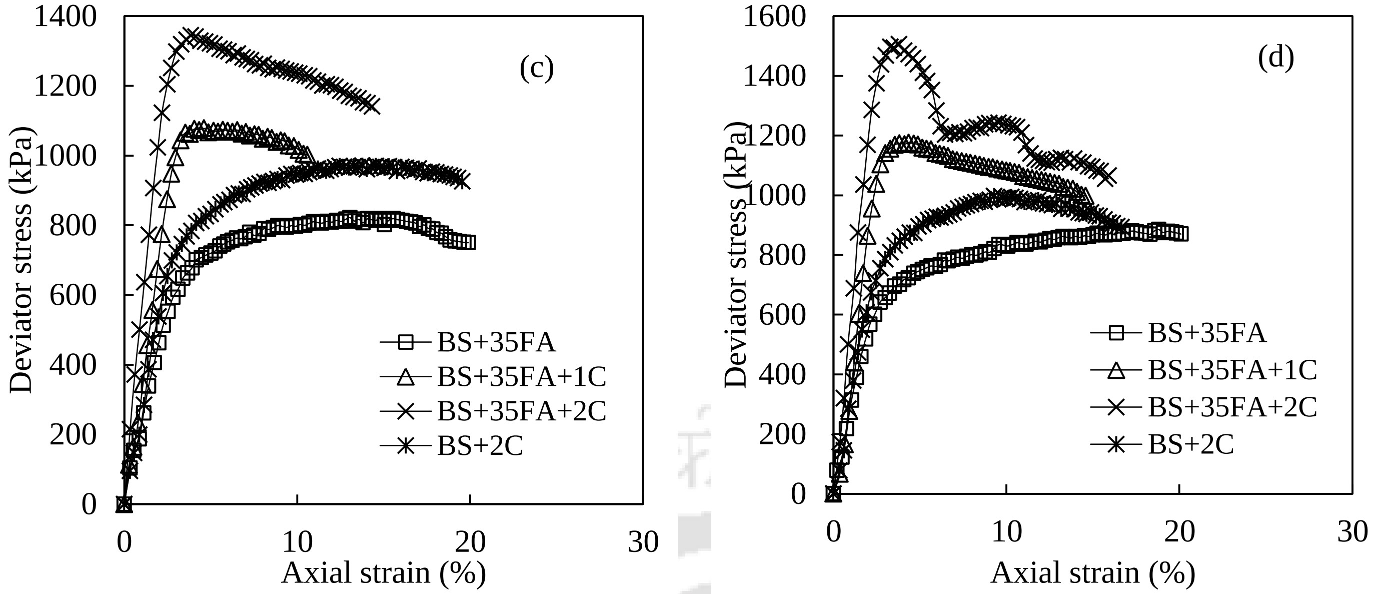
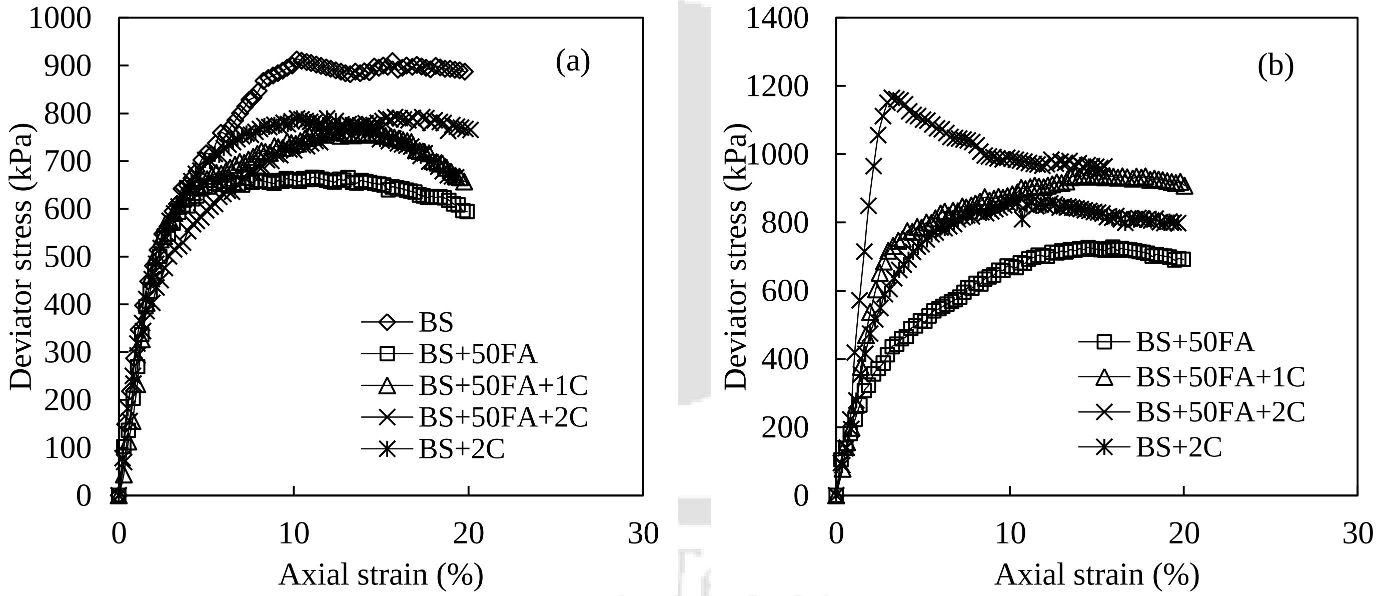


Fig. 6.67 Stress-strain behaviour of BS, BS+35FA, BS+2C and BS+35FA+C mixes at 300 kPa confining pressure for (a) 0, (b) 7 days, (c) 14 days and (d) 28 days curing



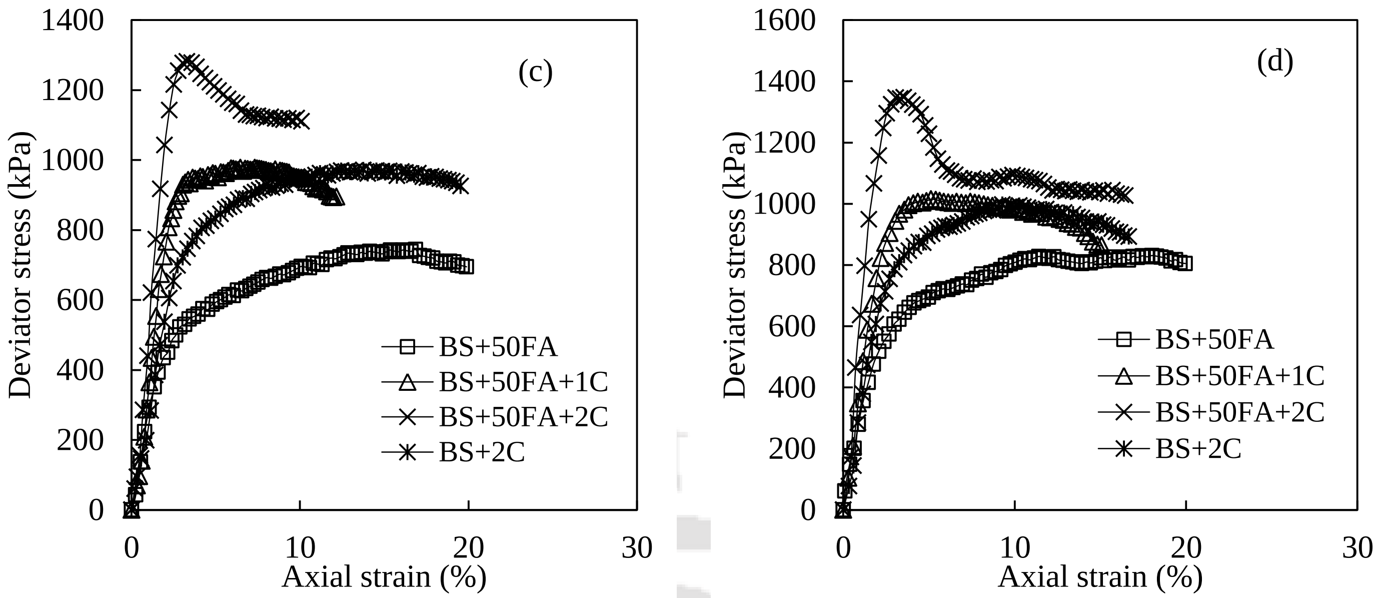
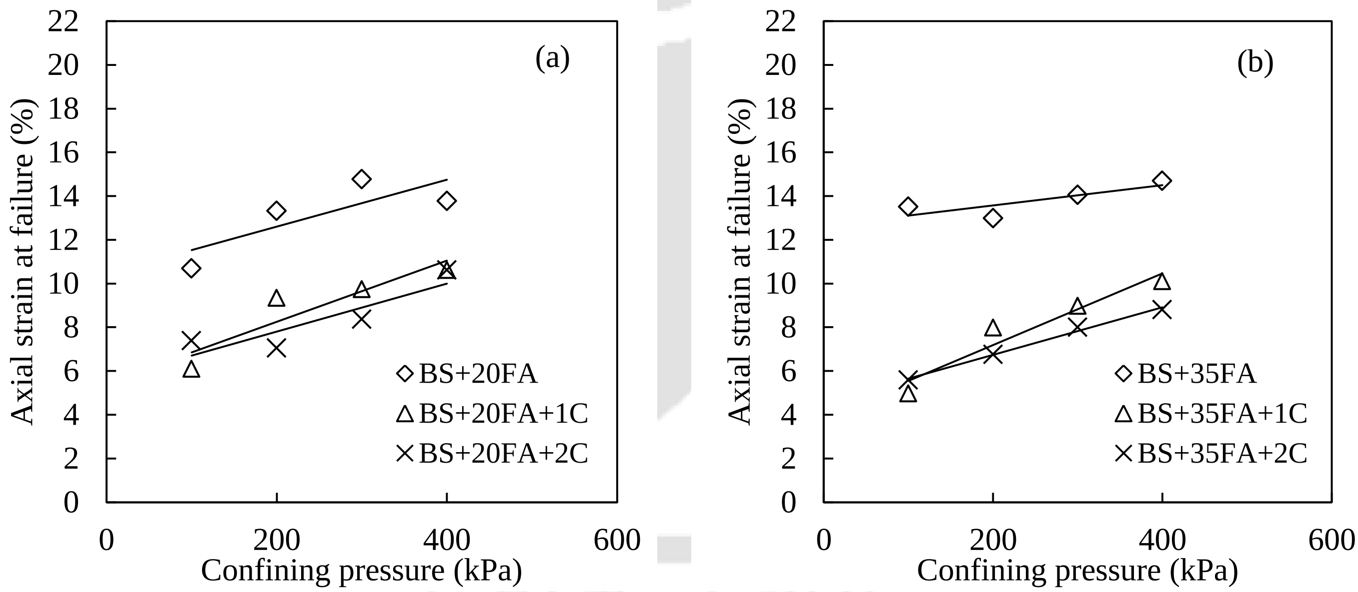


Fig. 6.68 Stress-strain behaviour of BS, BS+50FA, BS+2C and BS+50FA+C mixes at 300 kPa confining pressure for (a) 0, (b) 7 days, (c) 14 days and (d) 28 days curing



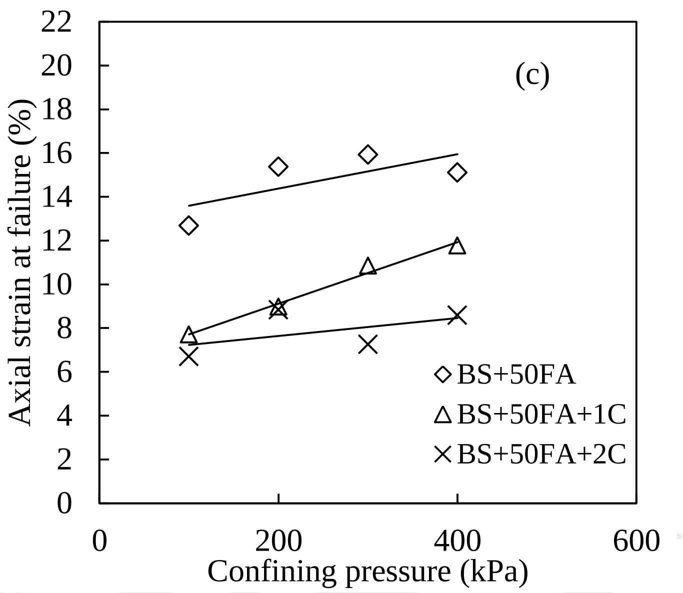


Fig. 6.69 Variation of failure axial strain of BS, BS+FA and BS+FA+C mixes with confining pressure at (a) 20%, (b) 35% and (c) 50% FA content

Table 6.22: Failure patterns of BS+FA+C mixes tested at 300 kPa confining pressure

Curing	Mix			
	BS	BS+20FA+1C	BS+35FA+1C	BS+50FA+1C
0 Day				
7 Days				

14 Days				
28 Days				
		Mix		
		BS+20FA+2C	BS+35FA+2C	BS+50FA+2C
0 Day				
7 Days				
14 Days				

28 Days				

6.3.15.2 Shear Strength Characteristics

Figs. 6.70 to 6.72 show the p-q plots for BS+FA and BS+FA+C mixes at different curing periods. It is observed that on addition of cement to sand-fly ash mixes, peak strength has increased marginally for specimens tested without curing. As the curing period has increased, a significant increase in peak strength is observed for cemented mixes. The effect of cement addition is more prominent in case of 28 days curing periods.

It is evident from Table 6.28 that as the fly ash content in sand-fly ash-cement mixes has increased the cohesion parameter of the mixes increases up to a fly ash content of 35% and then starts to decrease for the mixes with no curing. It can be stated that addition of cement to sand-fly ash mixes has improved both the shear strength parameters.

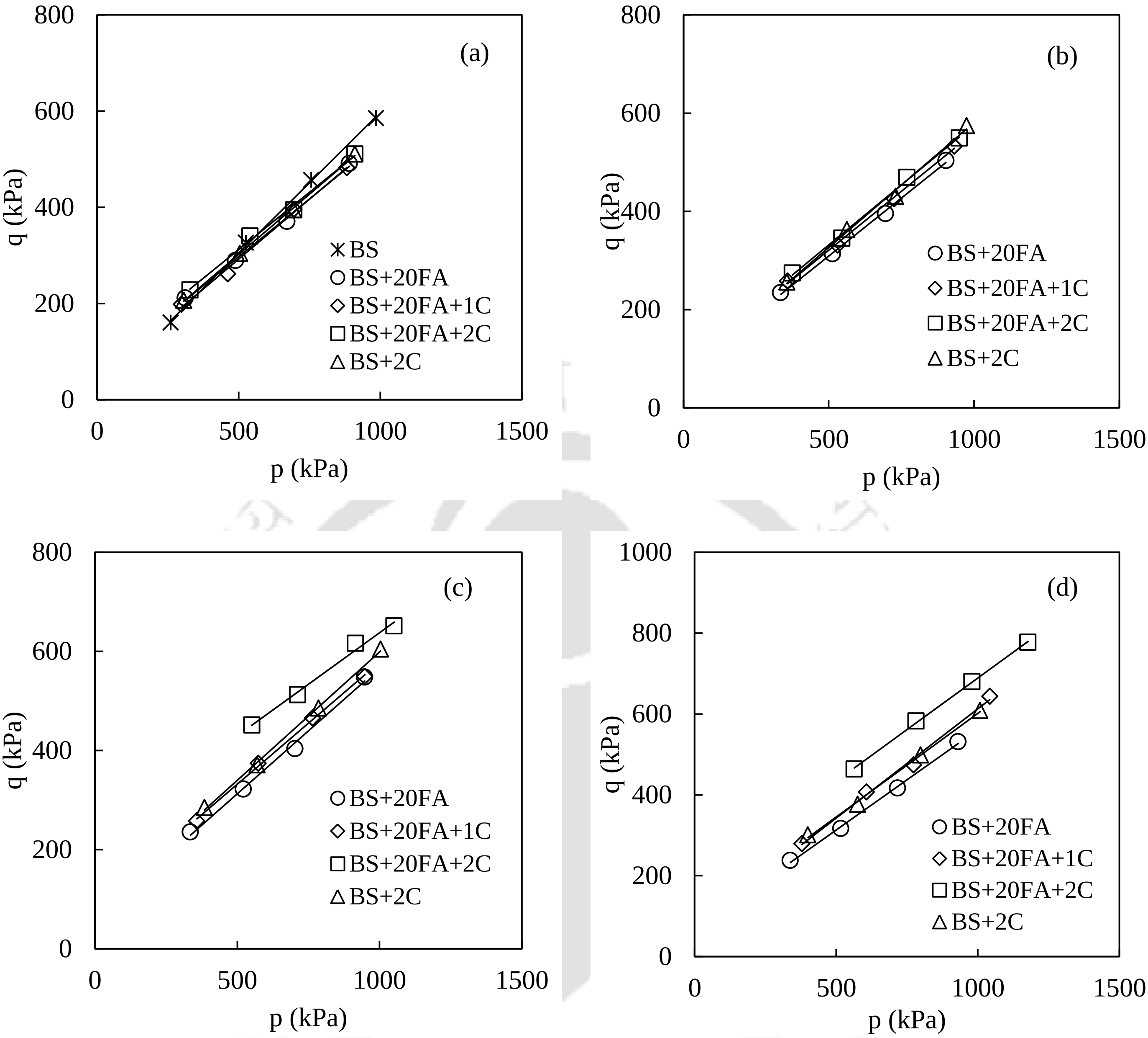


Fig. 6.70 p-q plots of BS, BS+20FA, BS+2C and BS+20FA+C mixes for (a) 0, (b) 7 days, (c) 14 days and (d) 28 days curing

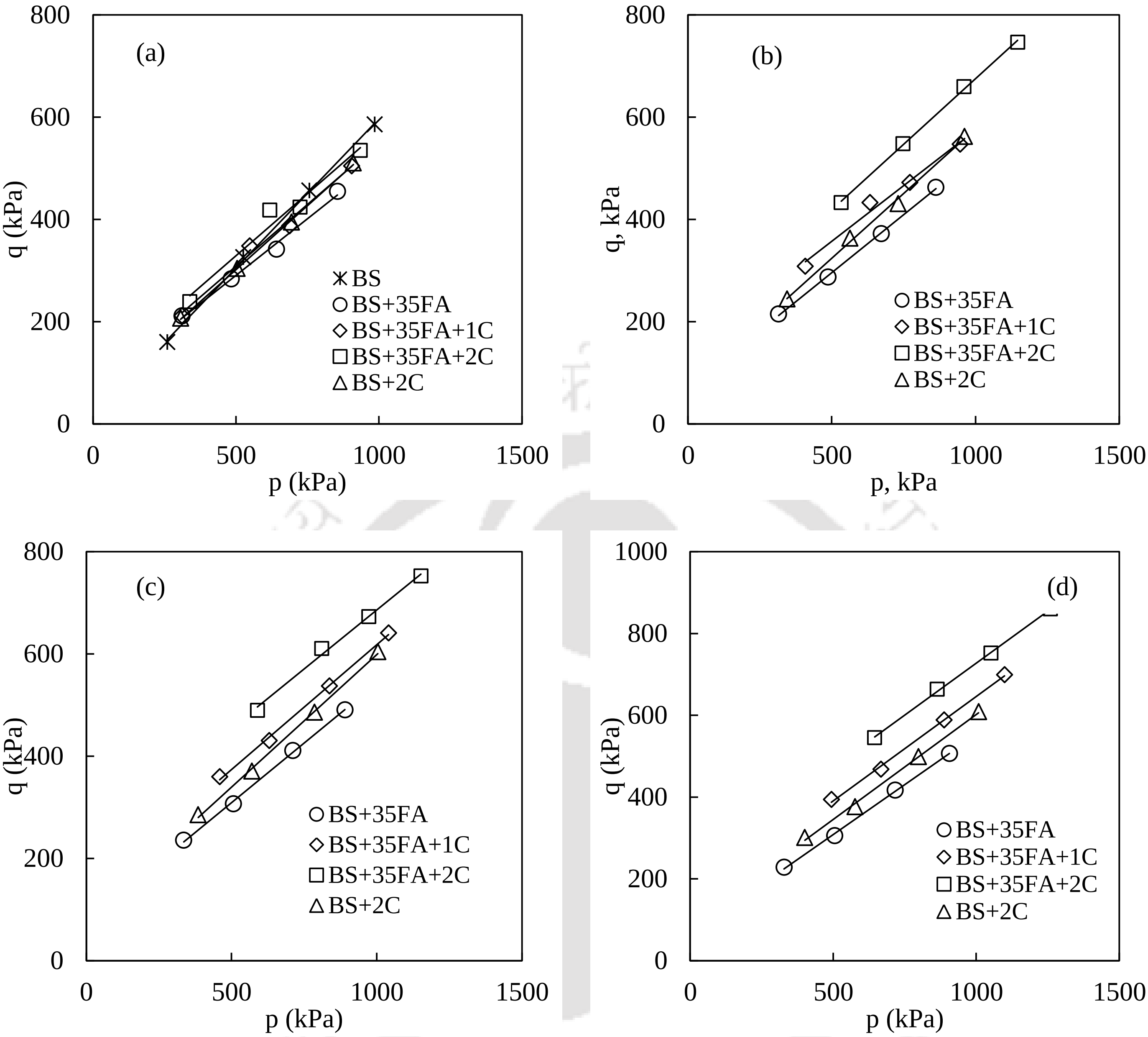


Fig. 6.71 p-q plots of BS, BS+35FA, BS+2C and BS+35FA+C mixes for (a) 0, (b) 7 days, (c) 14 days and (d) 28 days curing

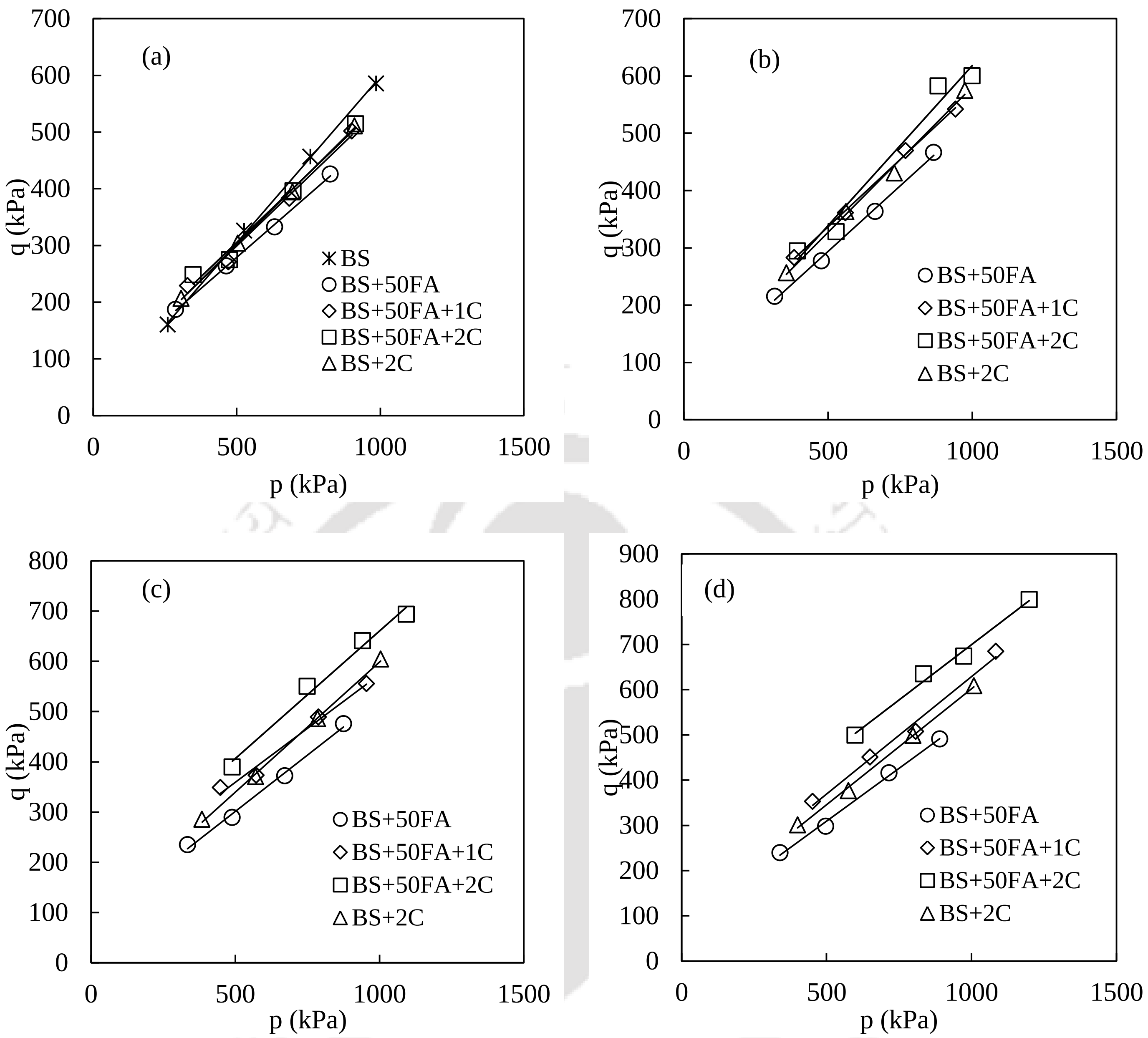


Fig. 6.72 p-q plots of BS, BS+50FA, BS+2C and BS+50FA+C mixes for (a) 0, (b) 7 days, (c) 14 days and (d) 28 days curing

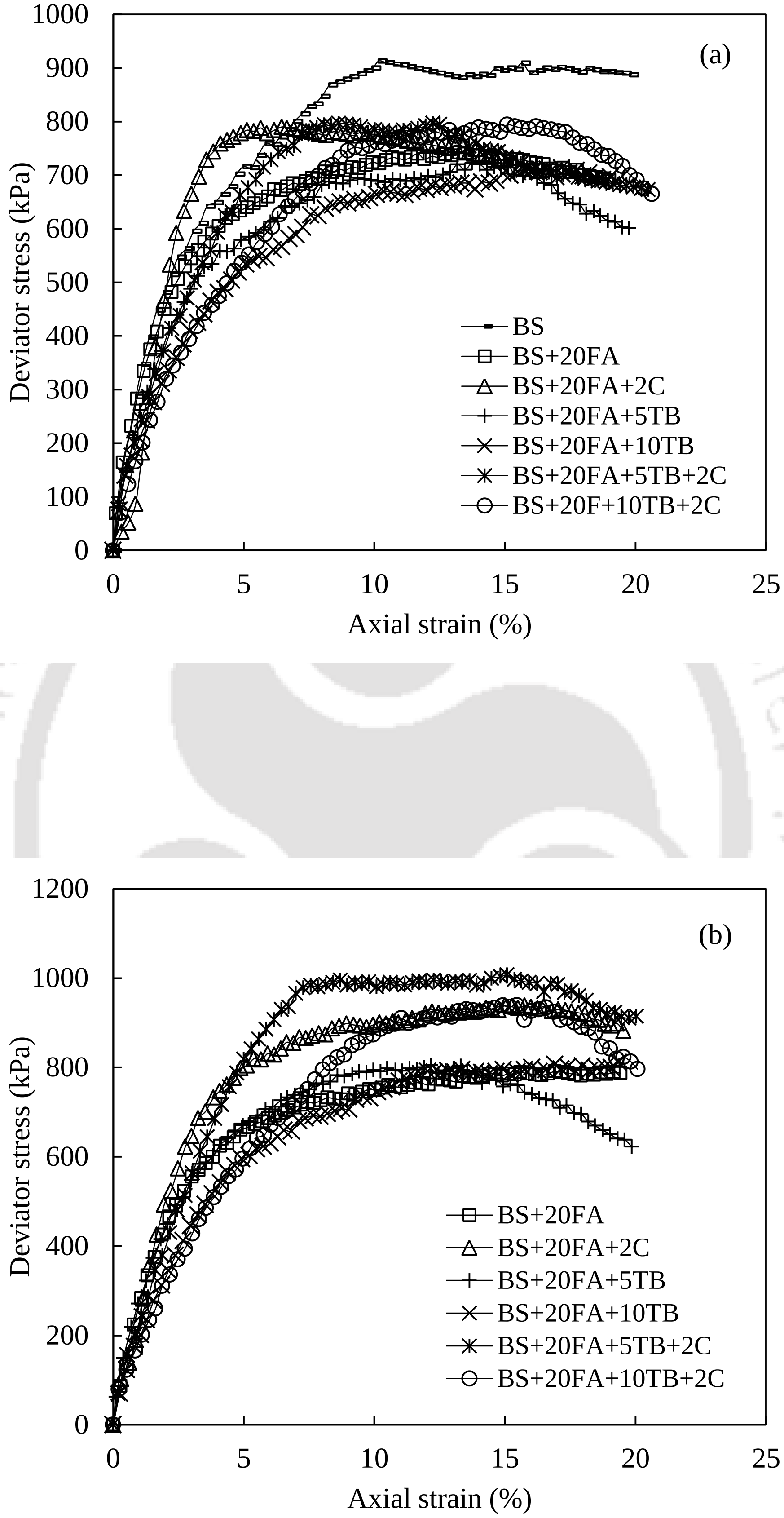
6.3.16 Effect of Cement Addition on Sand-Fly Ash-Tyre Buffing Mixes

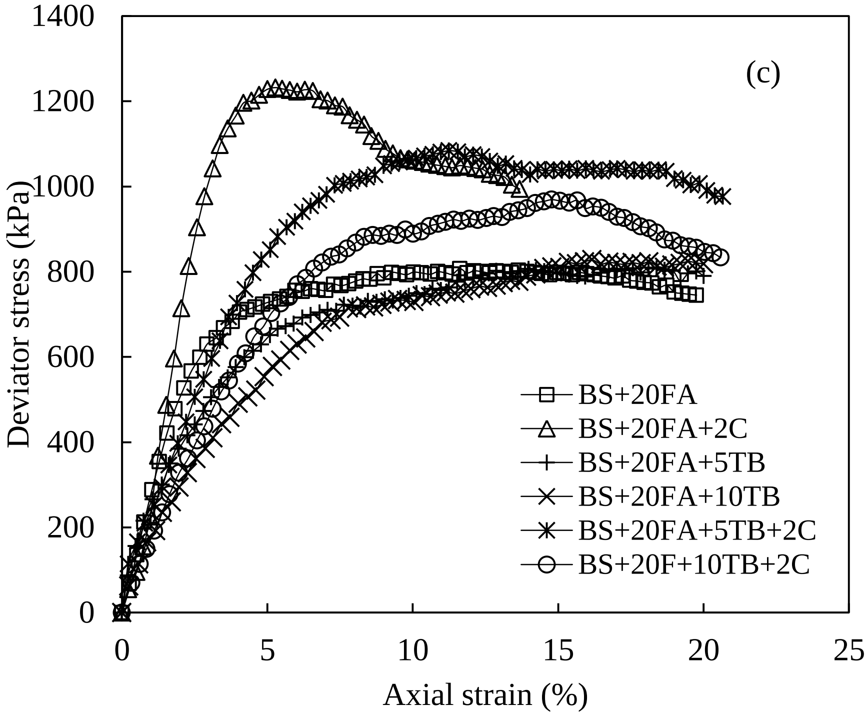
6.3.16.1 Stress-Strain Behaviour

From Figs. 6.73 to 6.75, it can be readily noted that addition of 2% cement to BS+FA+TB mixes has increased the peak deviator stress of mixes and it is more prominent for the specimens tested with 28 days curing period. However, BS+FA+TB+2C mixes have shown lower peak deviator stress values as compared to BS+FA+2C mixes, and this is due to inclusion of weaker tyre buffings. Table 6.26 shows the summary of peak deviator stress values of sand-fly ash-tyre buffing-cement mixes at different confining pressures and curing periods. Post-peak drop in the stress-strain plots of cemented sand mixes is seen for curing periods of 7 to 28 days. Moreover, this post-peak drop is found to be more distinct in cemented mixes containing 35% and 50% fly ash [Figs. 6.72(b), (c) and (d); and Figs. 6.73(b), (c) and (d)]. For BS+35FA+2C mix, the post-peak drop in strength is found to be 439 kPa at 28 days curing periods. But BS+35FA+5TB+2C and BS+35FA+10TB+2C mixes have shown values of post-peak drop in strength as 345 kPa and 171 kPa respectively. Generation of cementitious material within the mix has led to this post-peak drop in strength for the cemented mix.

Tsoi and Lee (2011) investigated the stress-strain-strength behaviour of lightly cemented scrap rubber tyre chips with fly ash and sand. Despite the high flexibility of the rubber chips and hence their higher ductility, the composite material behaviour was found to be generally similar to that of typical cemented soils. Initially the material behaved as a rigid skeleton as the cemented soils do.

Fig. 6.76 reveals that addition of 2% cement to sand-fly ash-tyre buffing mixes has decreased the failure strain of the mixes. In some cases, bulging failure is observed in TB added specimens and no peak deviator stress is observed till 20% axial strain as shown in Table 6.23. This is due to the ductile behaviour induced by the tyre buffing inclusions. Specimens with TB have failed at higher axial strain than samples without TB. Inclusion of tyre buffing has reduced the stiffness of soil mixes.


(a)
Deviator stress (kPa)
Axial strain (%)
BS
BS+20FA
BS+20FA+2C
BS+20FA+5TB
BS+20FA+10TB
BS+20FA+5TB+2C
BS+20F+10TB+2C
(b)
BS+20FA
BS+20FA+2C
BS+20FA+5TB
BS+20FA+10TB
BS+20FA+5TB+2C
BS+20FA+10TB+2C



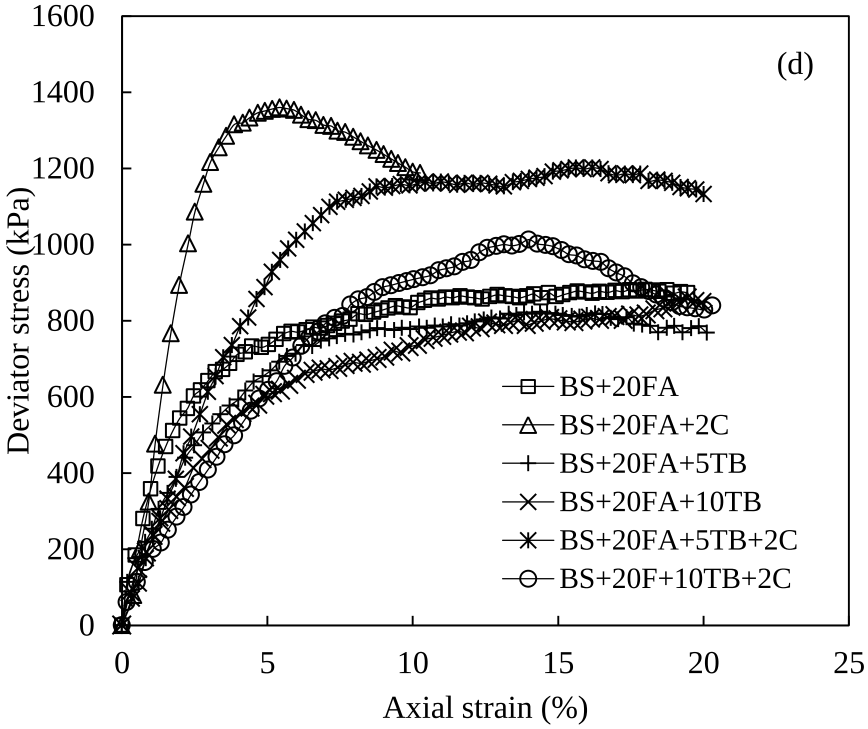
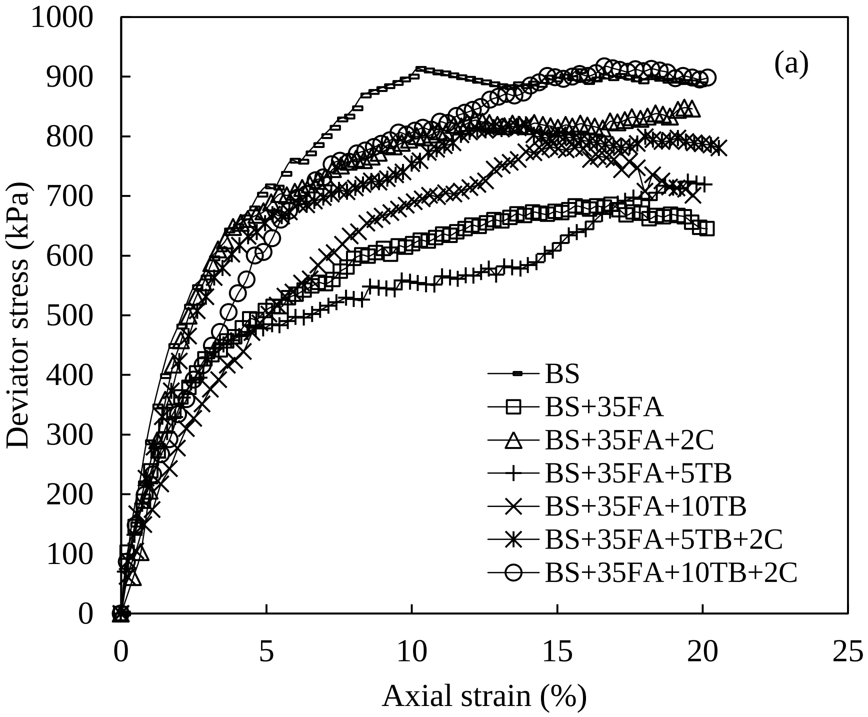
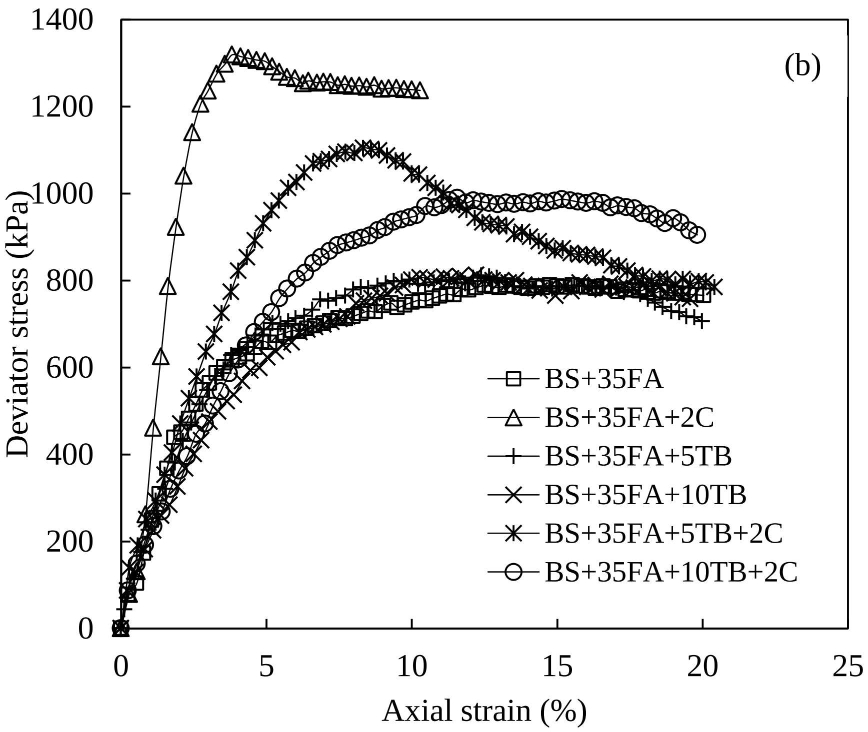
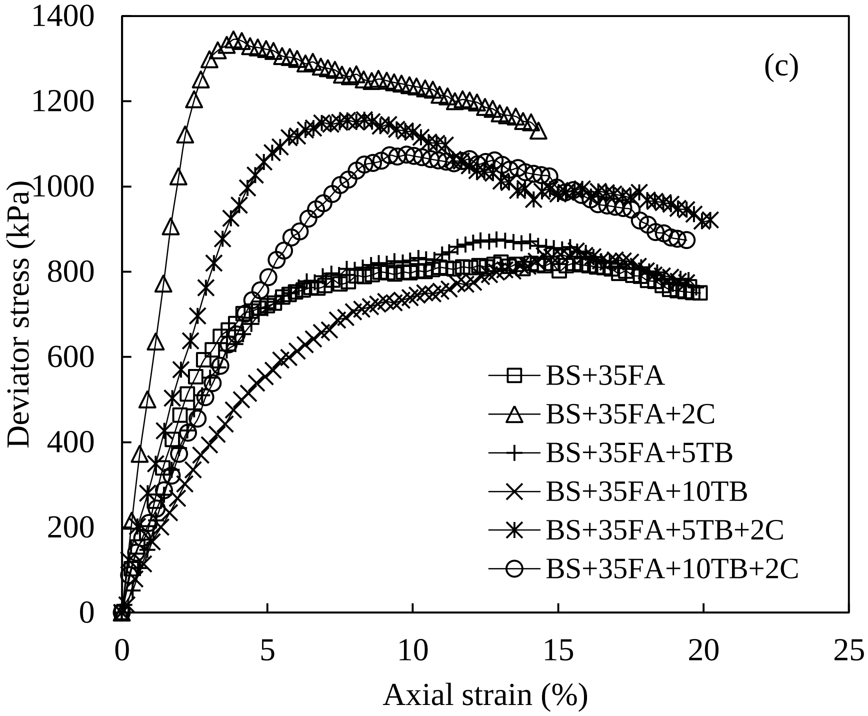


Fig. 6.73 Stress-strain plots of BS and various BS+20FA+TB+C mixes at 300 kPa for (a) 0, (b) 7, (c) 14 and (d) 28 days of curing


(a)
Deviator stress (kPa)
Axial strain (%)
BS
BS+35FA
BS+35FA+2C
BS+35FA+5TB
BS+35FA+10TB
BS+35FA+5TB+2C
BS+35FA+10TB+2C


(b)
Deviator stress (kPa)
Axial strain (%)
BS+35FA
BS+35FA+2C
BS+35FA+5TB
BS+35FA+10TB
BS+35FA+5TB+2C
BS+35FA+10TB+2C



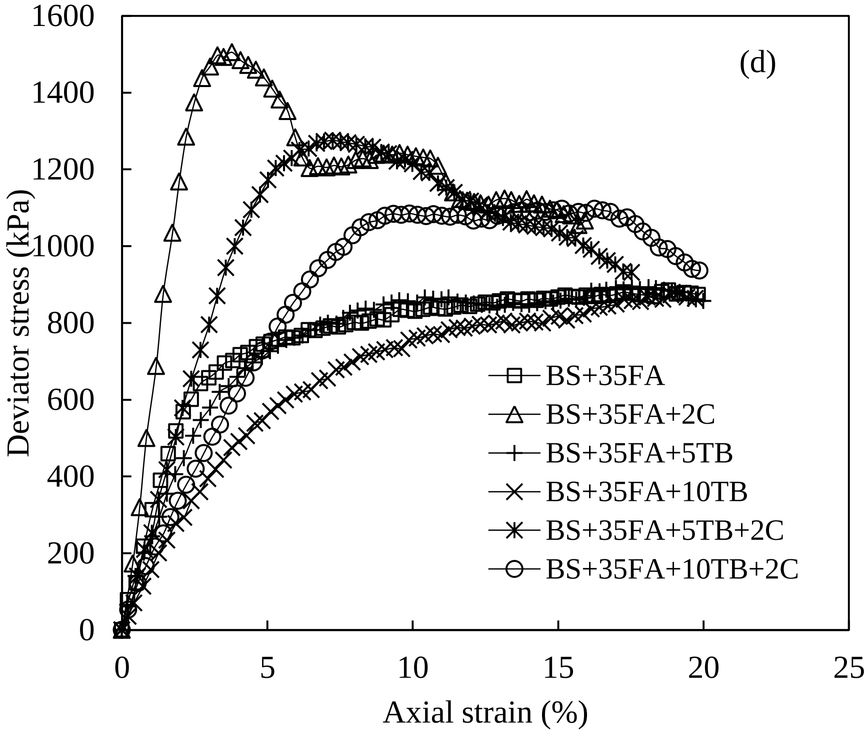
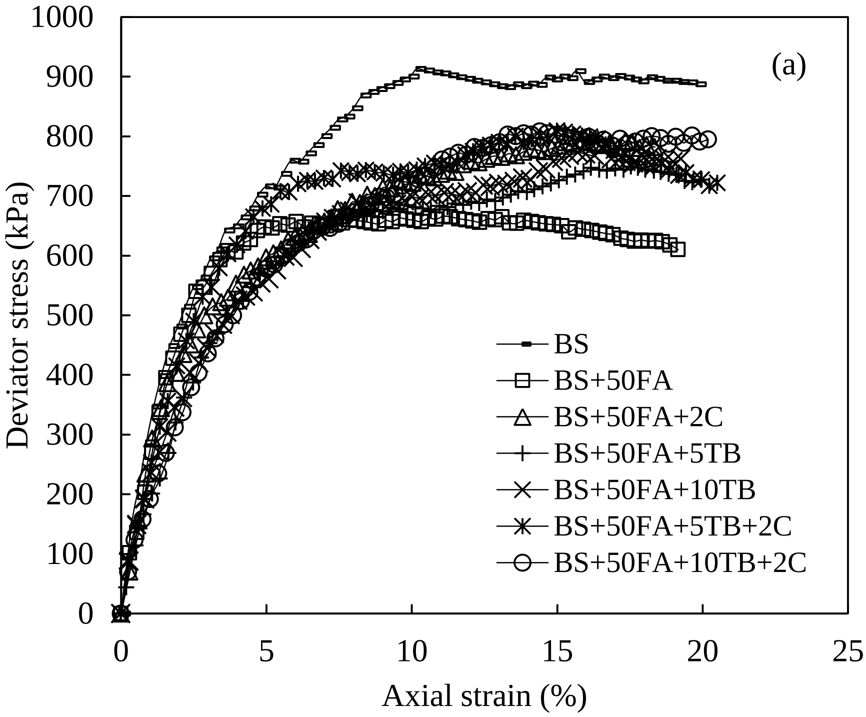
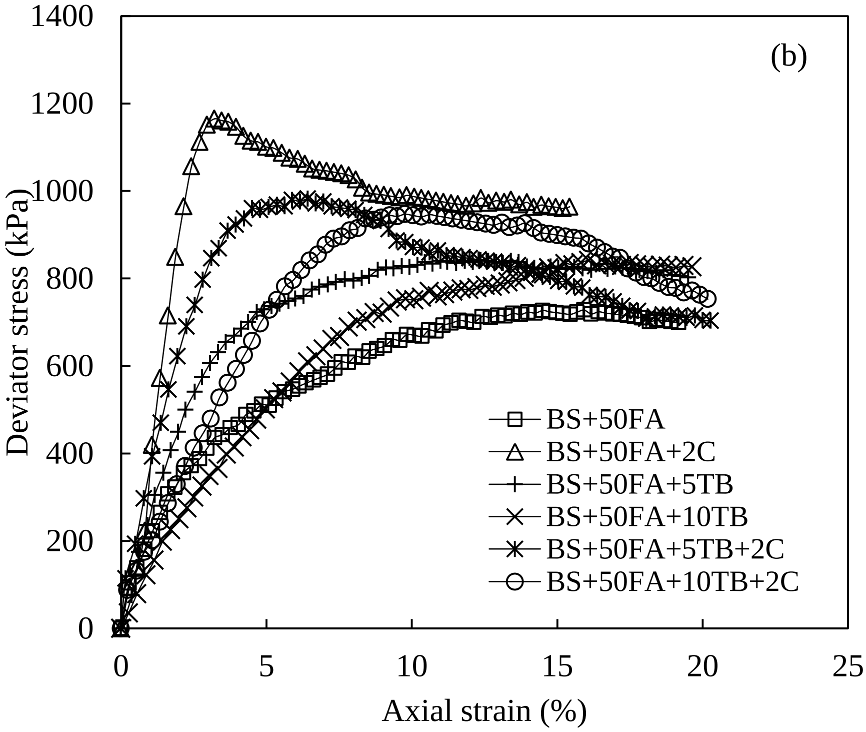


Fig. 6.74 Stress-strain plots of BS and various BS+35FA+TB+C mixes at 300 kPa for (a) 0, (b) 7, (c) 14 and (d) 28 days of curing


(a)
Deviator stress (kPa)
Axial strain (%)
BS
BS+50FA
BS+50FA+2C
BS+50FA+5TB
BS+50FA+10TB
BS+50FA+5TB+2C
BS+50FA+10TB+2C
0
100
200
300
400
500
600
700
800
900
1000
0
5
10
15
20
25


(b)
Deviator stress (kPa)
Axial strain (%)
BS+50FA
BS+50FA+2C
BS+50FA+5TB
BS+50FA+10TB
BS+50FA+5TB+2C
BS+50FA+10TB+2C
0
200
400
600
800
1000
1200
1400
0
5
10
15
20
25

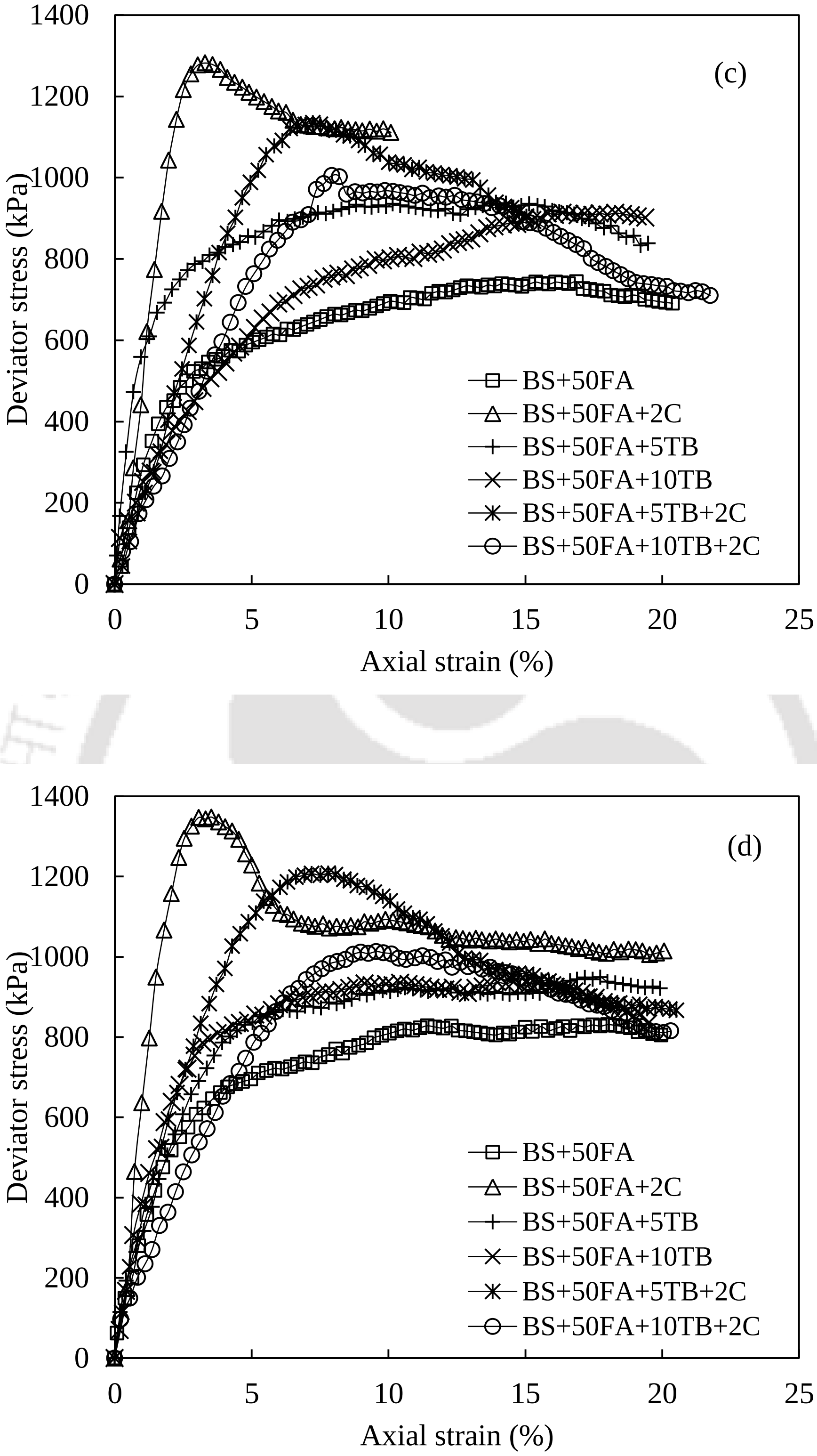


Fig. 6.75 Stress-strain plots of BS and various BS+50FA+TB+C mixes at 300 kPa and with 28 days of curing

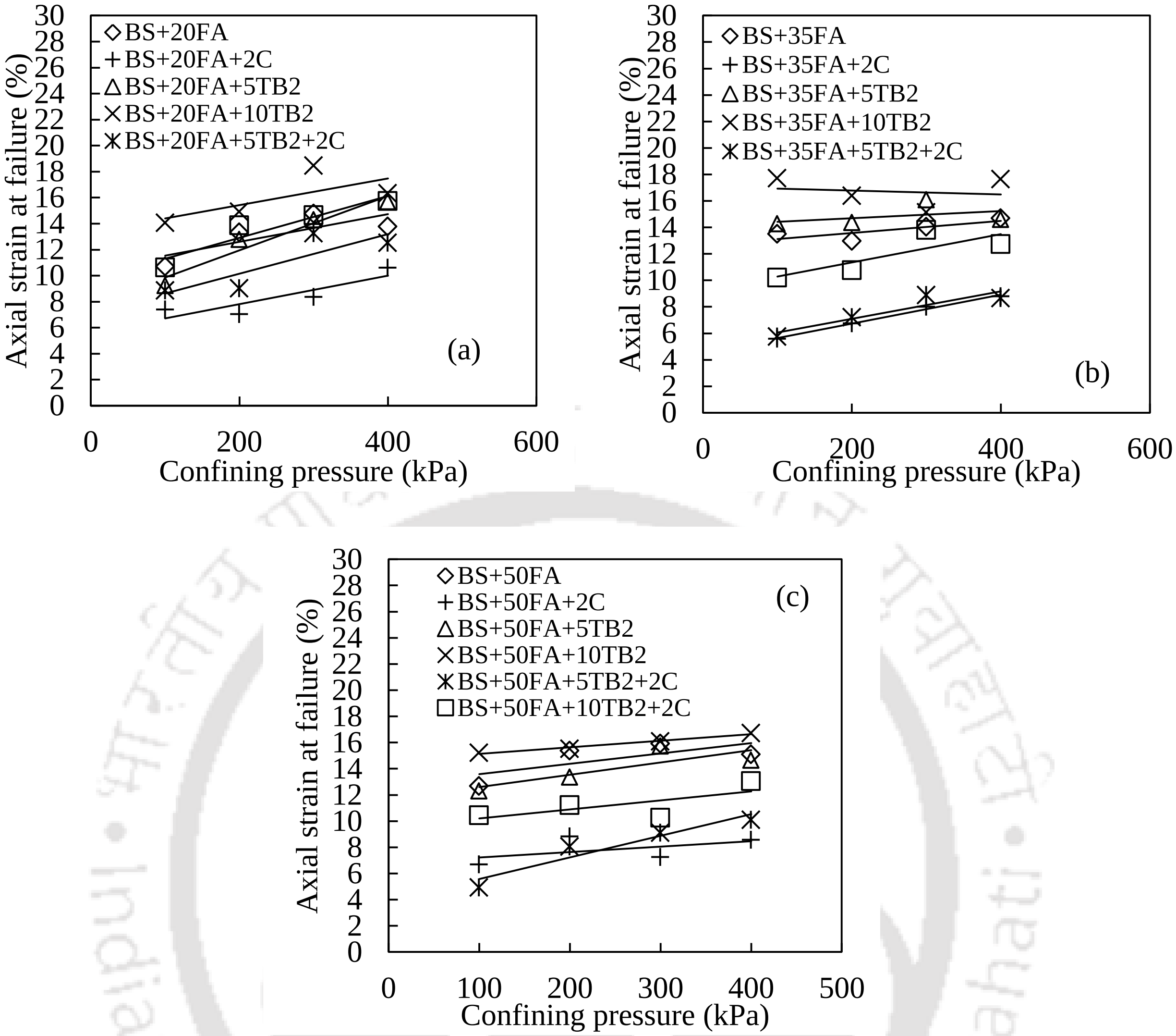


Fig. 6.76 Variation of failure axial strain of various BS+FA+TB+C mixes with confining pressure at (a) 20%, (b) 35% and (c) 50% FA content

Table 6.23: Failure patterns of BS+FA+TB+2C mixes tested at 300 kPa confining pressure

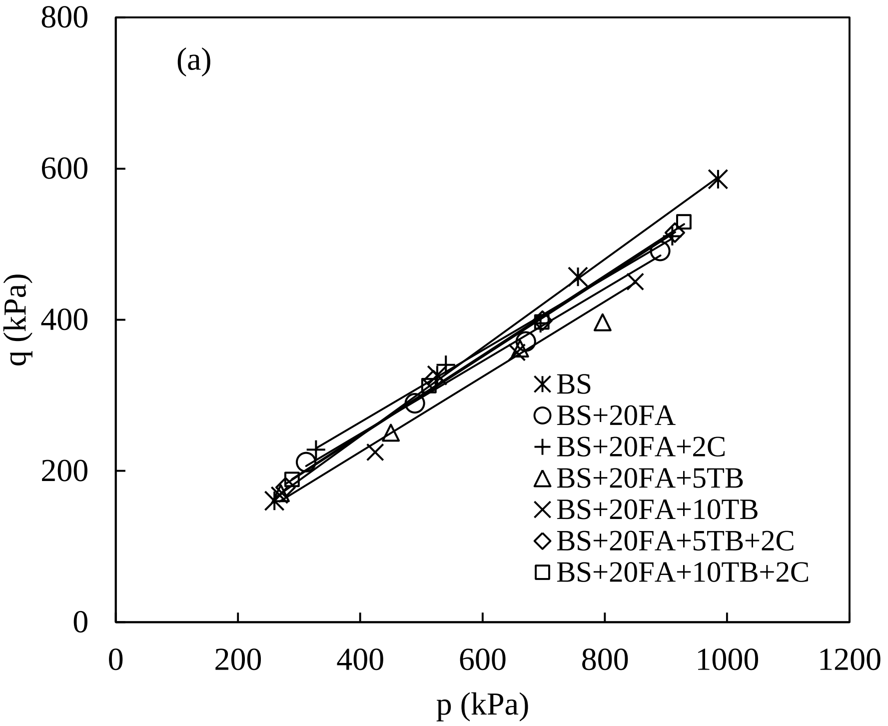
Curing	Mix			
	BS	BS+20FA+5TB+2C	BS+35FA+5TB+2C	BS+50FA+5TB+2C
0 Day				
7 Days				
14 Days				
28 Days				
	Mix			
	BS	BS+20FA+10TB+2C	BS+35FA+10TB+2C	BS+50FA+10TB +2C

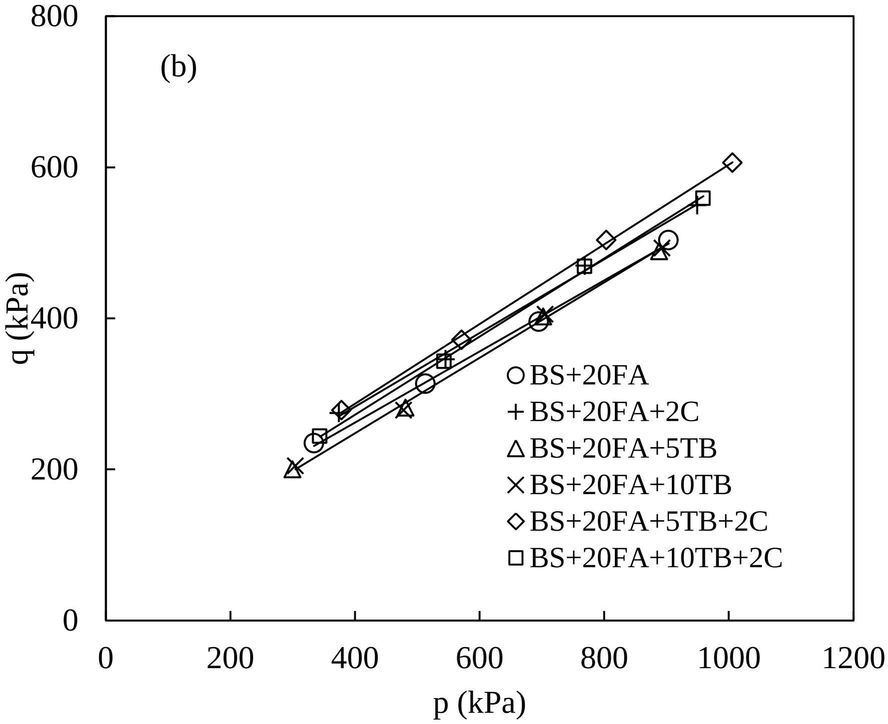
0 Day				
7 Days				
14 Days				
28 Days				

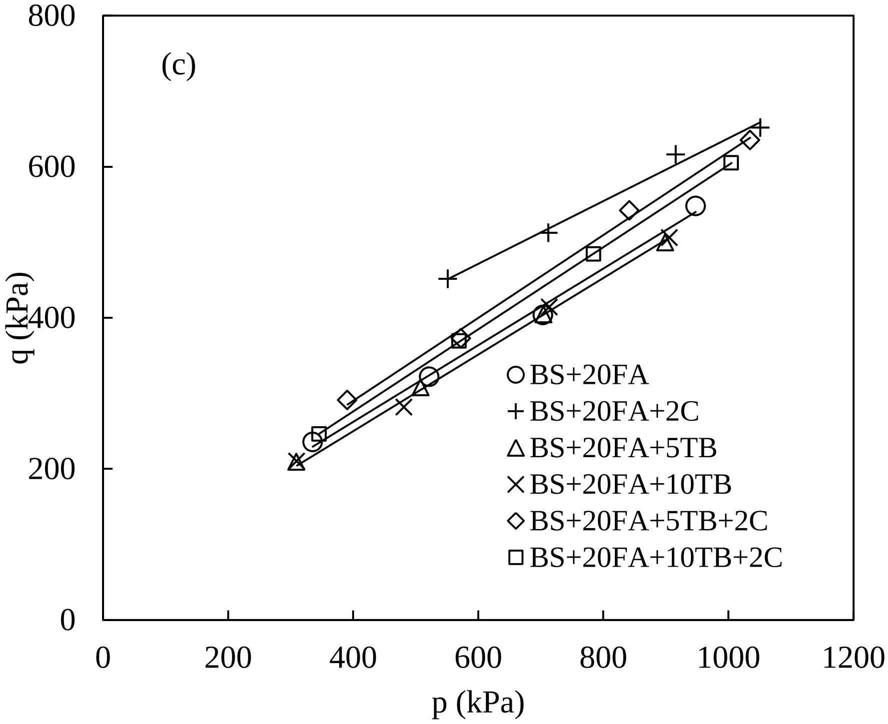
6.3.16.2 Shear strength characteristics

Figs. 6.77 to 6.79 show the p-q plots for different BS+FA mixes. For 0 day of curing, addition of 2% cement has not improved the strength of the mixes significantly. For 7, 14 and 28 days of curing, cemented samples have shown improvement in strength, but except for BS+20FA+TB+2C mix, strength of other BS+FA+TB+2C mixes is lower than the strength of mixes without tyre buffings.

Table 6.29 shows the shear strength parameters of different cemented sand mixes at different confining pressure and curing periods. It is seen that addition of 2% cement with BS+FA and BS+FA+TB mixes has increased the cohesion intercept of the mixes, and further improvement is observed with the increase in curing period. It is also seen that addition of cement to BS+FA and BS+FA+TB mixes has increased the internal friction angle.




(b)
q (kPa)
p (kPa)
0
200
400
600
800
1000
1200
BS+20FA
BS+20FA+2C
BS+20FA+5TB
BS+20FA+10TB
BS+20FA+5TB+2C
BS+20FA+10TB+2C


(c)
q (kPa)
p (kPa)
0
200
400
600
800
1000
1200
BS+20FA
BS+20FA+2C
BS+20FA+5TB
BS+20FA+10TB
BS+20FA+5TB+2C
BS+20FA+10TB+2C

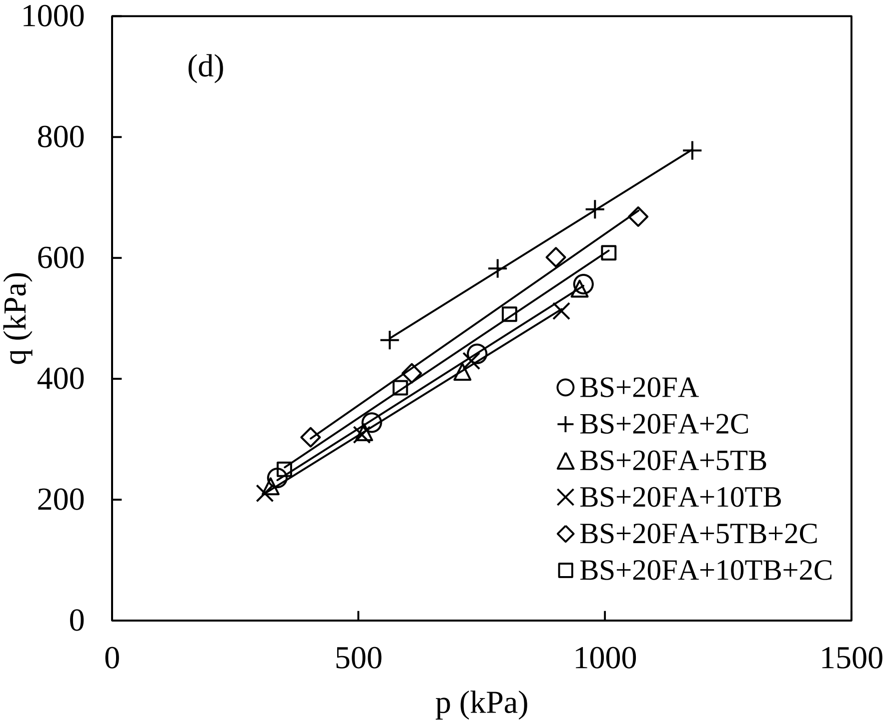
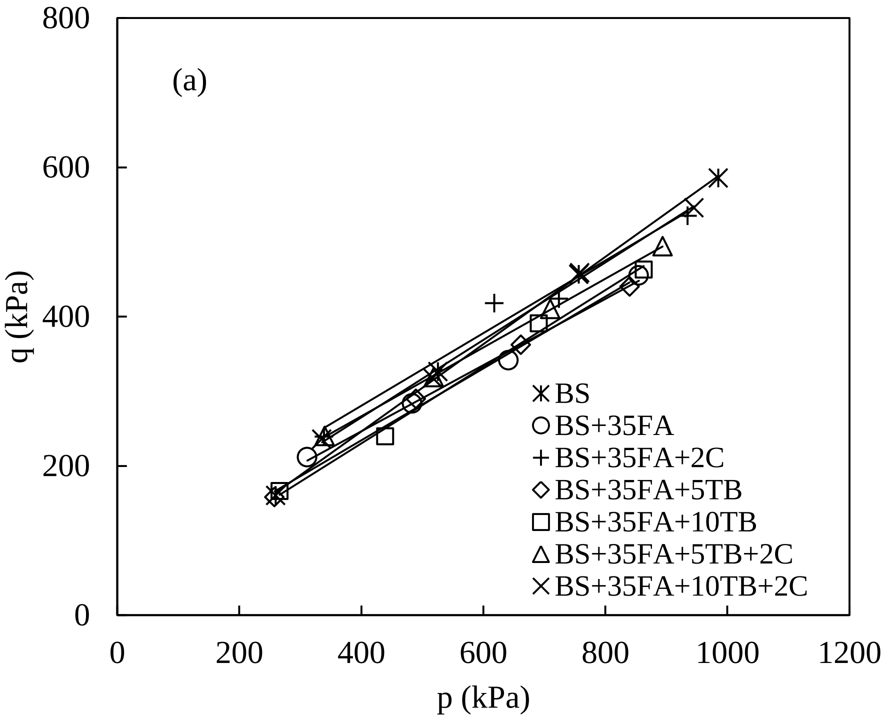
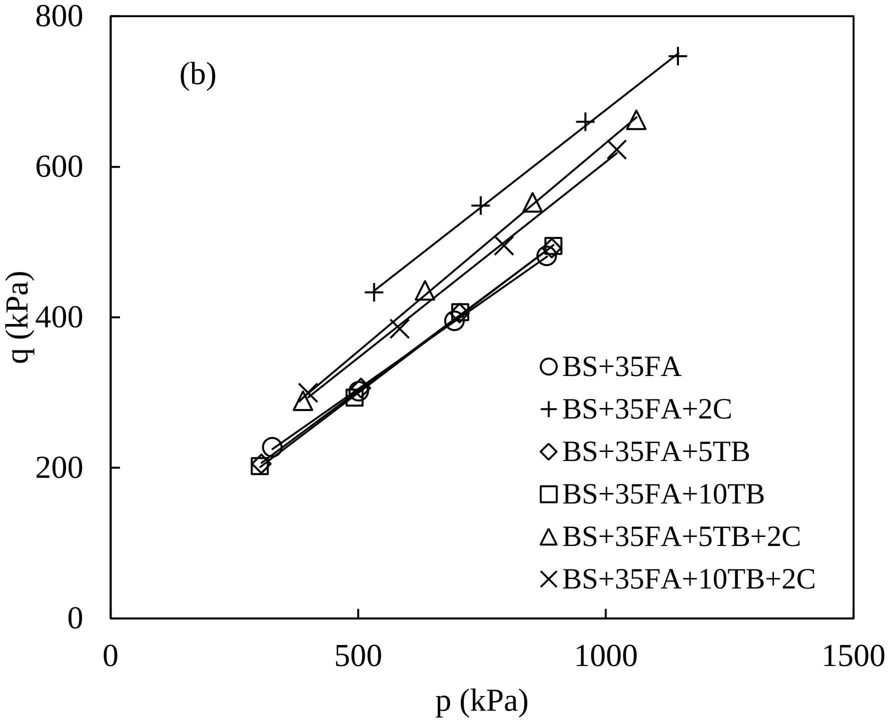
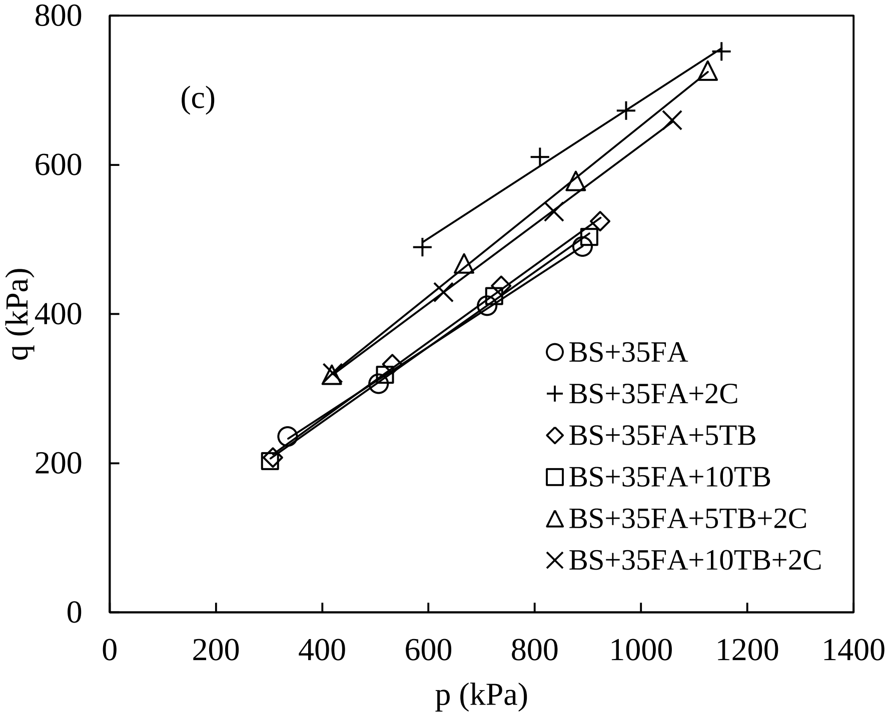


Fig. 6.77 p-q plots of BS and various BS+20FA+TB+C mixes with (a) 0, (b) 7, (c) 14 and (d) 28 days of curing




(b)
q (kPa)
p (kPa)
BS+35FA
BS+35FA+2C
BS+35FA+5TB
BS+35FA+10TB
BS+35FA+5TB+2C
BS+35FA+10TB+2C
0
200
400
600
800
0
500
1000
1500


(c)
q (kPa)
p (kPa)
BS+35FA
BS+35FA+2C
BS+35FA+5TB
BS+35FA+10TB
BS+35FA+5TB+2C
BS+35FA+10TB+2C
0
200
400
600
800
0
200
400
600
800
1000
1200
1400

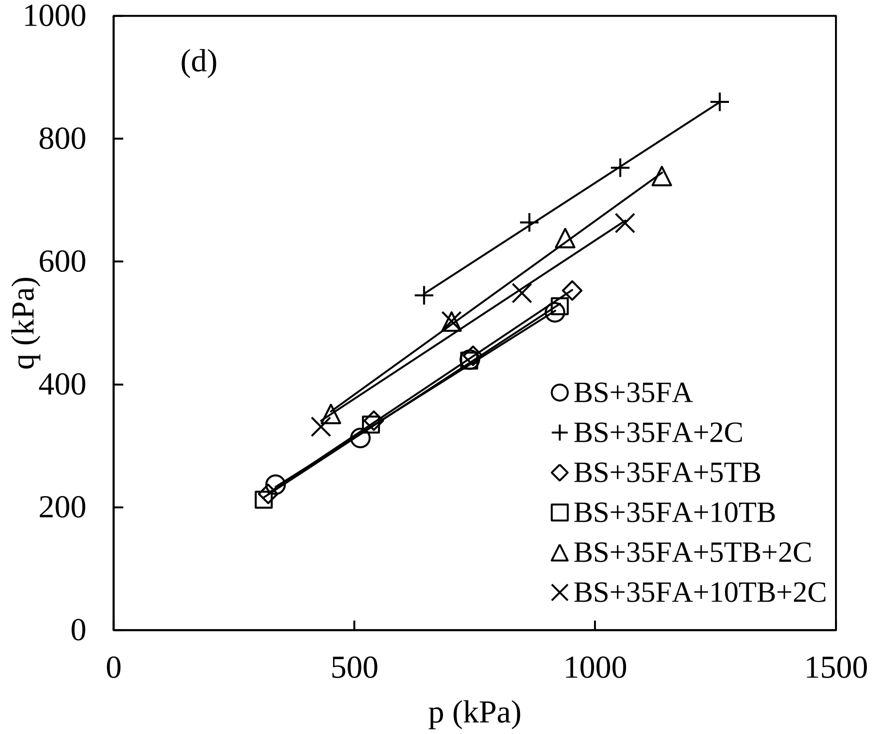
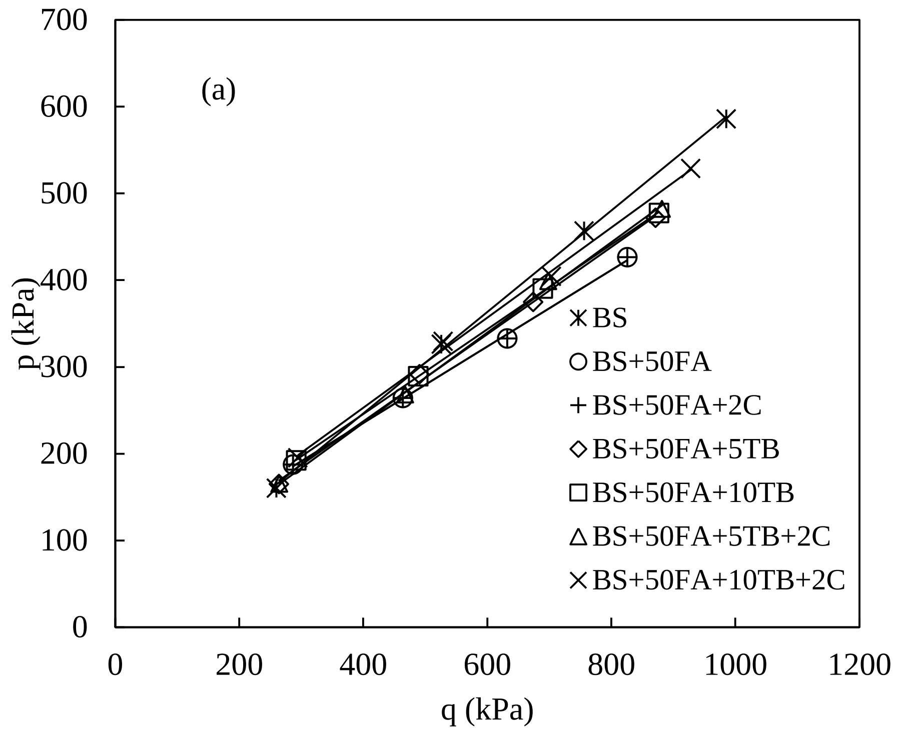
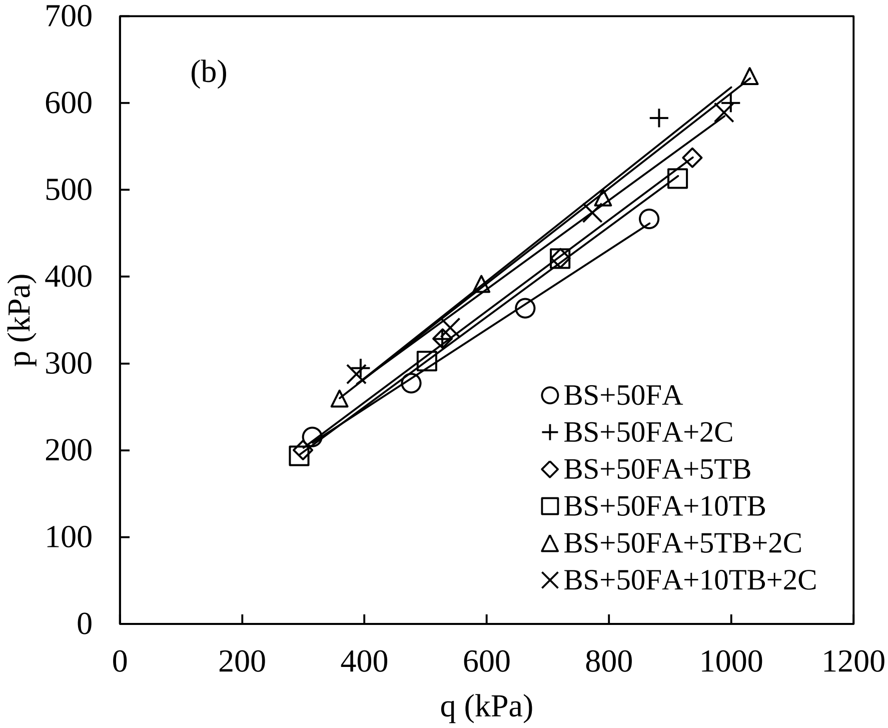
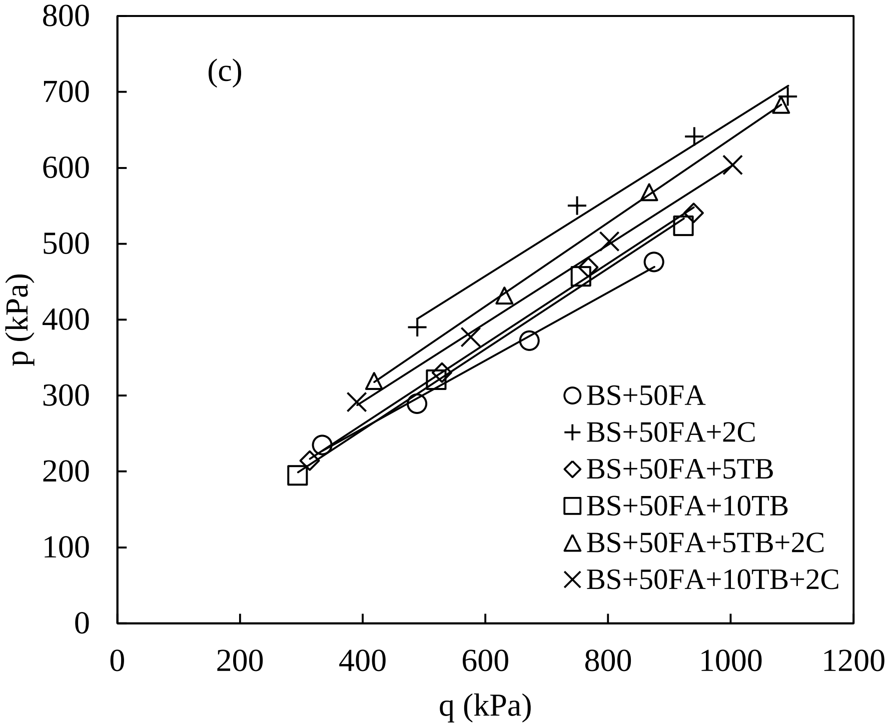


Fig. 6.78 p-q plots of BS and various BS+35FA+TB+C mixes with (a) 0, (b) 7, (c) 14 and (d) 28 days of curing




(b)
p (kPa)
q (kPa)
0
100
200
300
400
500
600
700
0
200
400
600
800
1000
1200
BS+50FA
BS+50FA+2C
BS+50FA+5TB
BS+50FA+10TB
BS+50FA+5TB+2C
BS+50FA+10TB+2C


(c)
p (kPa)
q (kPa)
0
100
200
300
400
500
600
700
800
0
200
400
600
800
1000
1200
BS+50FA
BS+50FA+2C
BS+50FA+5TB
BS+50FA+10TB
BS+50FA+5TB+2C
BS+50FA+10TB+2C

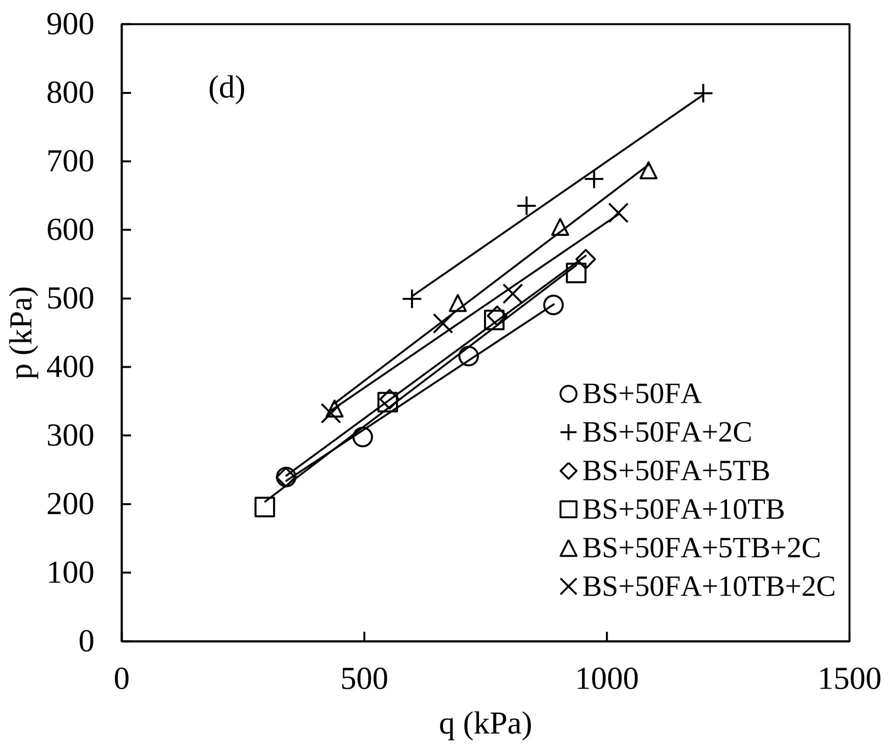


Fig. 6.79 p-q plots of BS and various BS+50FA+TB+C mixes with (a) 0, (b) 7, (c) 14 and (d) 28 days of curing

6.3.17 Stiffness of Sand Mixes

Secant elastic modulus (E_s) has been used to characterize stiffness of different sand mixes. The secant elastic modulus is the slope of a straight line drawn from the origin to a specified stress on the stress-strain curve. The value of E_s is expressed as:

$$E_s = q_{50}/\varepsilon_{50} \quad (6.3)$$

where,

q_{50} = half of the peak compressive strength, and

ε_{50} = the strain, which corresponds with q_{50}

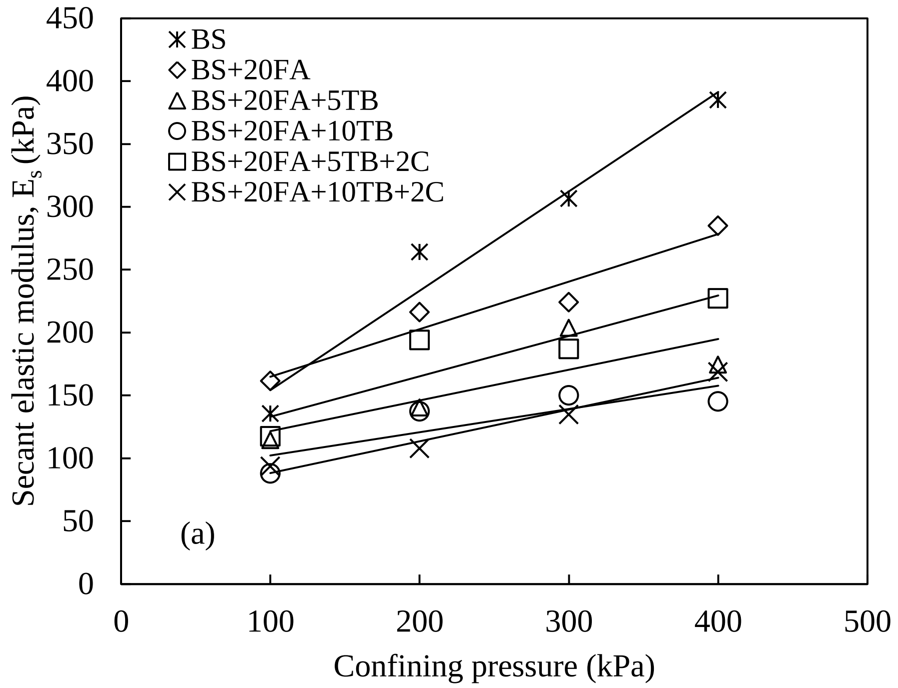
Figs. 6.80 to 6.82 depict the effect of fly ash, tyre buffings and cement on secant elastic modulus (E_s) value. It is seen that increase in fly ash content in sand-fly ash mixes has decreased the values of E_s. Again, inclusion of tyre buffing to sand-fly ash mixes has decreased the E_s value of BS+20FA mix but has increased modulus values of BS+35FA and BS+50FA mixes at 300 kPa and 400 kPa confining pressures. At 100 kPa and 200 kPa confining pressures, BS+FA+TB mixes have shown lower value of E_s than BS+FA mixes. Further addition of cement mixes increases the secant elastic modulus values of BS+FA+TB mixes. As in the case of BS mixes, curing is also found to be more effective in case of cemented sand mixes than uncemented sand mixes. In all cases it is seen that as confining pressure is increased, secant elastic modulus of soil mixes also has increased.

Consoli et al. (2001) presented values of secant deformation modulus for an axial strain of 0.1% and confining stresses ranging from 20 to100 kN/m^2. It was observed that the moduli of the compacted soil only and of the compacted soil-fly ash specimens were very similar. In some cases where the strain range was 0.1% or more, addition of fly ash to soil reduced the moduli. As expected, the addition of carbide lime to the soil and to the soil plus fly ash increased the moduli values.

The effect of fibres on strength characteristics was investigated by conducting unconsolidated undrained tests on fly ash-soil samples containing 1% fibre content (Kaniraj and Havanagi, 2001). The local soils used in fly- ash soil mixes were silt and fine sand. Class F type fly ash was used in the mixes. Secant modulus was calculated at one half of deviator stress of reinforced and unreinforced specimens. It was observed that the fiber inclusion decreased the secant modulus of fly ash-soil specimens, but this trend was not consistent at all confining stresses in pure fly ash.

Rao and Dutta (2006) carried out triaxial test to assess the strength behaviour of sand-tyre chip mixes. Tyre chip percentages of 5, 10, 15 and 20% were used in this study. It was concluded that the secant modulus increased linearly with confining pressure and decreased with an increase in chip content, the decrease being marginal at low confining pressure and significant at the highest confining pressure.

Consoli et al. (2009) investigated the effect of fiber content, cement content and confining pressure on secant modulus at 0.01% axial strain. It was reported that Inclusion fiber to cemented mixes reduced the secant moduli.



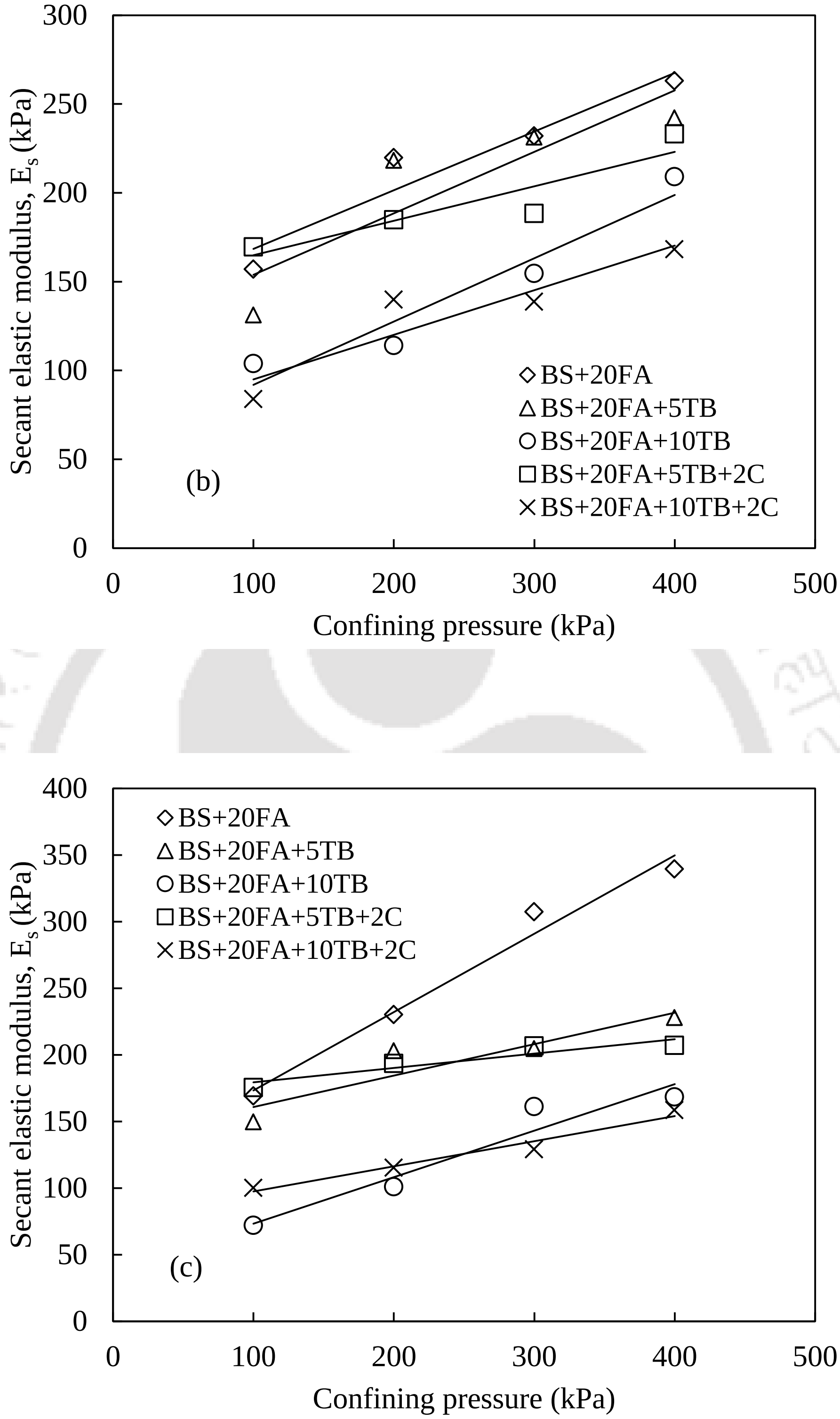
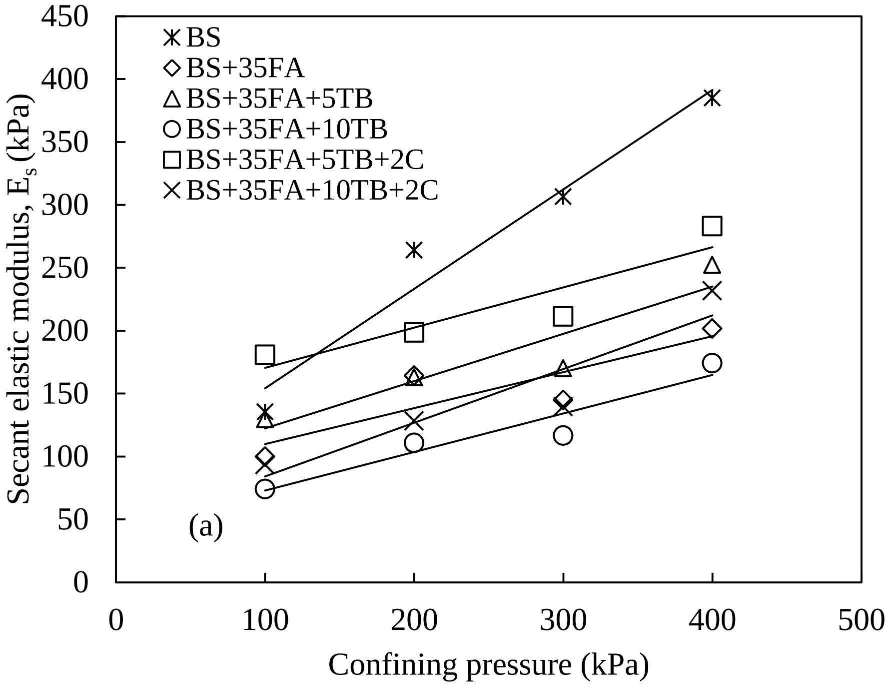
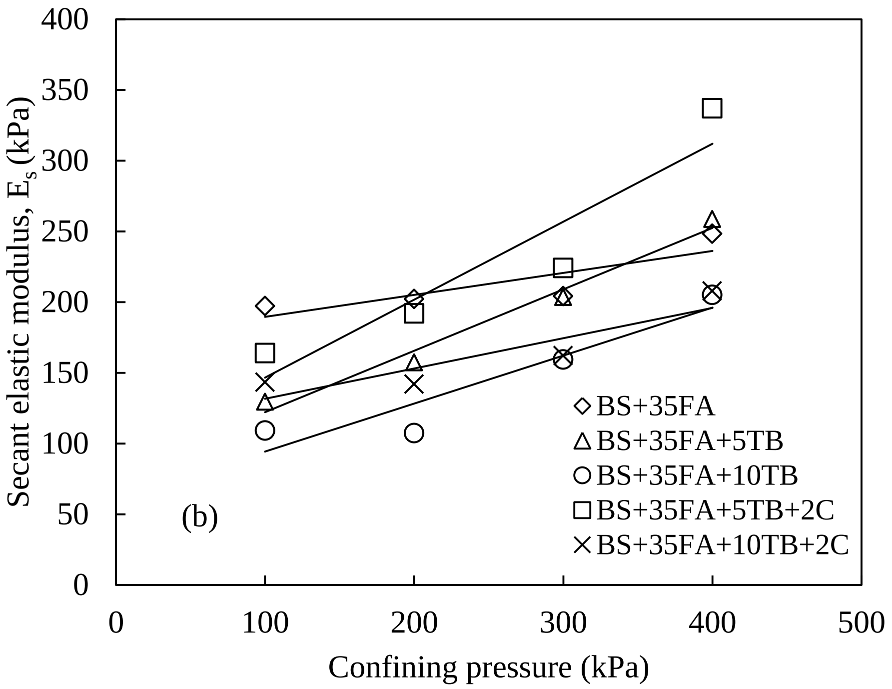


Fig. 6.80 Variation of E_s with confining pressure of BS alone and BS+20FA+TB+C mixes for (a) 0, (b) 7 and (c) 28 days curing period


BS
BS+35FA
BS+35FA+5TB
BS+35FA+10TB
BS+35FA+5TB+2C
BS+35FA+10TB+2C
(a)
Secant elastic modulus, E_s (kPa)
Confining pressure (kPa)
0
50
100
150
200
250
300
350
400
450
0
100
200
300
400
500


BS+35FA
BS+35FA+5TB
BS+35FA+10TB
BS+35FA+5TB+2C
BS+35FA+10TB+2C
(b)
Secant elastic modulus, E_s (kPa)
Confining pressure (kPa)
0
50
100
150
200
250
300
350
400
0
100
200
300
400
500

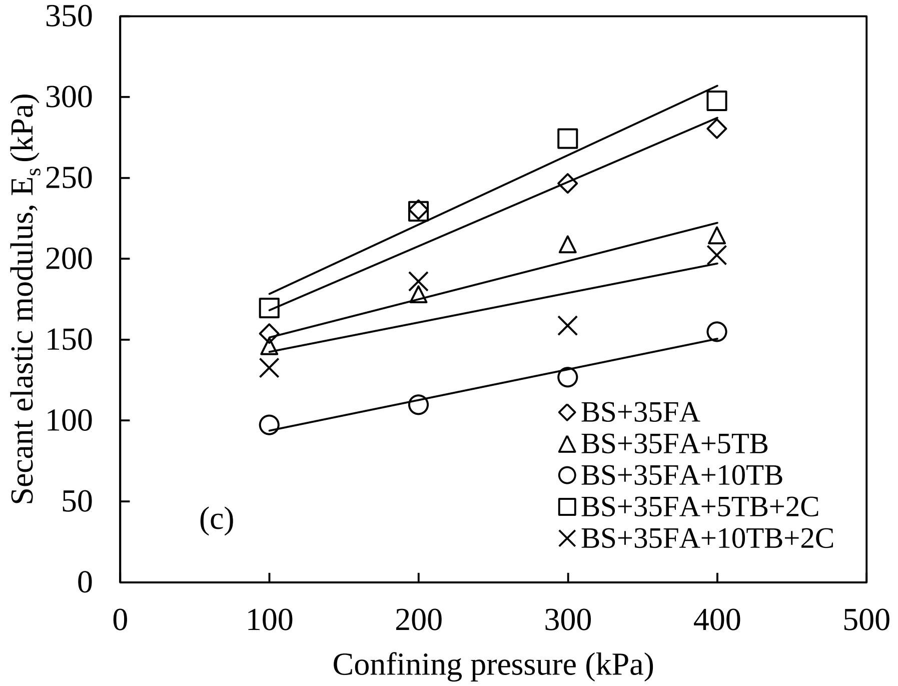
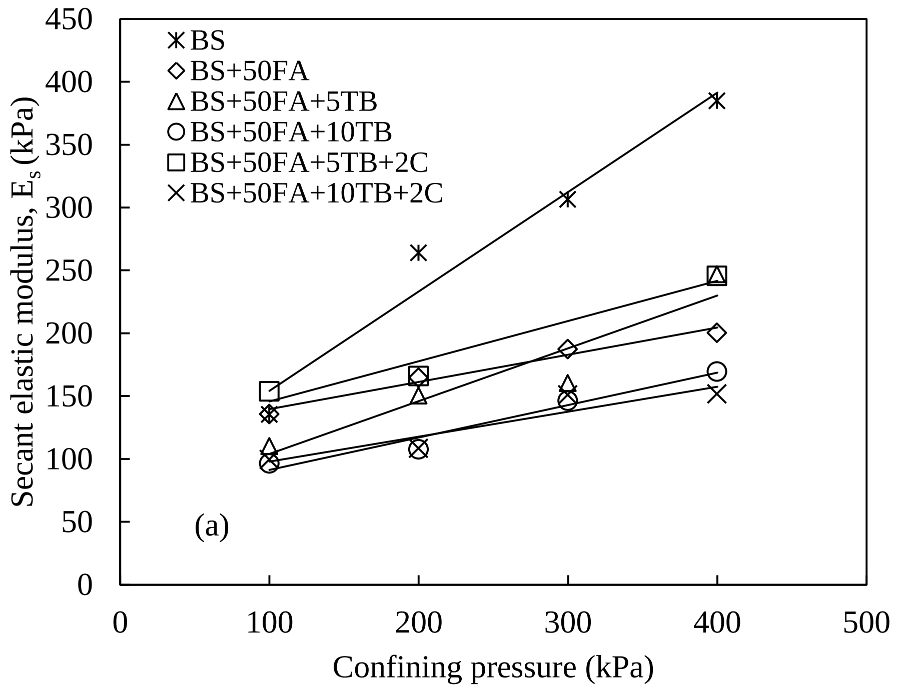


Fig. 6.81 Variation of E_s with confining pressure of BS alone and BS+35FA+TB+C mixes for (a) 0, (b) 7 and (c) 28 days curing period



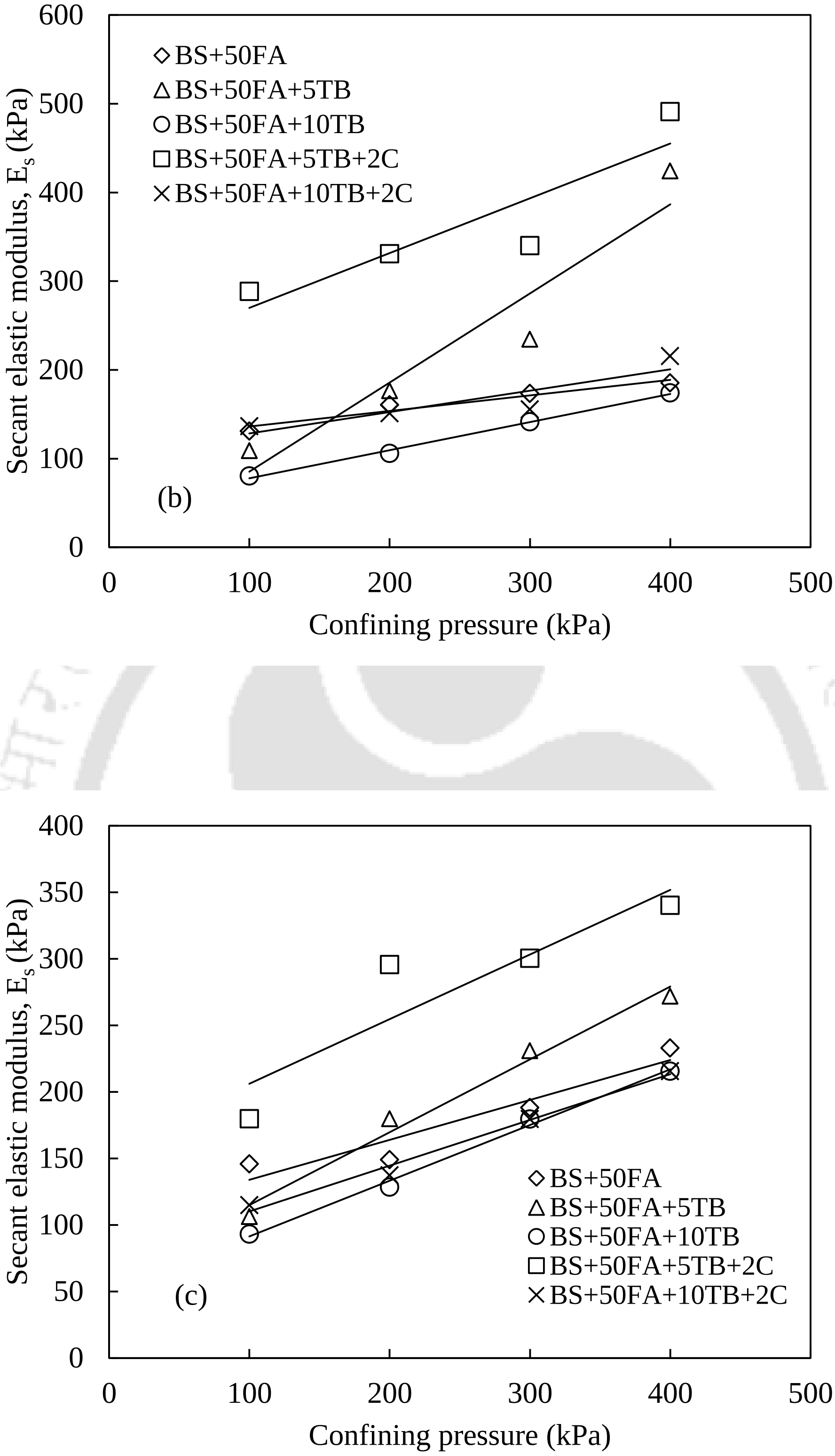


Fig. 6.82 Variation of E_s with confining pressure of BS alone and BS+50FA+TB+C mixes for (a) 0, (b) 7 and (c) 28 days curing period

6.3.18 Brittleness of Sand Mixes

The failure behaviour of different sand mixes was also examined in terms of brittleness index (I_B) in the similar way it is done in case of red soil mixes. From Fig. 6.83, it can be seen that addition of fly ash to sand increases the I_B value of the specimen. Increase in fly ash content to sand significantly increases the brittleness of the specimen up to 50% fly ash content; beyond 50% addition of fly ash has affected the brittleness of the specimen marginally. In most of the cases the lowest brittleness index values are found at 400 kPa.

From Fig. 6.84, inclusion of tyre buffings to fly ash admixed sand has reduced the I_B values of mixes. Similar behaviour has been observed when tyre buffings are added to cemented mixes as shown in Fig. 6.85. This is due to the elastic behaviour of tyre buffing which imparts ductility to the mixes. Addition of 10% tyre buffing to BS+50FA mix decreases the I_B value from 0.14 to 0.052 at 300 kPa confining pressure. BS+FA+2C mixes shows highest I_B values among all other mixes. Inclusion of tyre buffings to BS+50FA+2C decreases the I_B value from 0.29 to 0.19 reducing brittleness. Application of higher confining pressure (300 and 400 kPa) also has imparted ductility to some extent in TB added specimen.

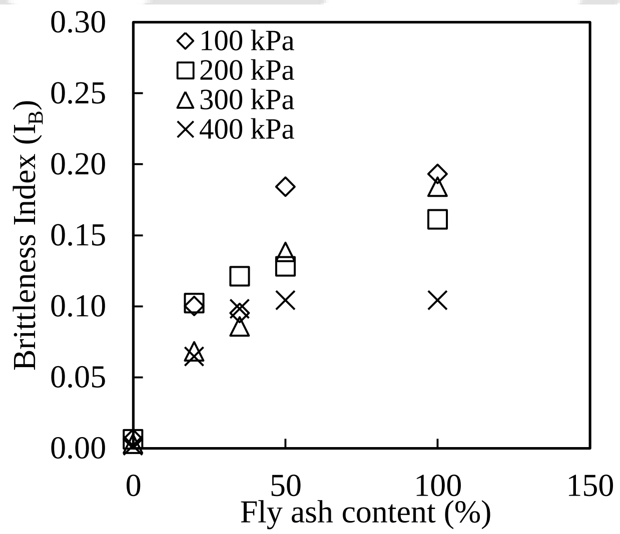


Fig. 6.83 Effect of fly ash content on brittleness of BS+FA mixes

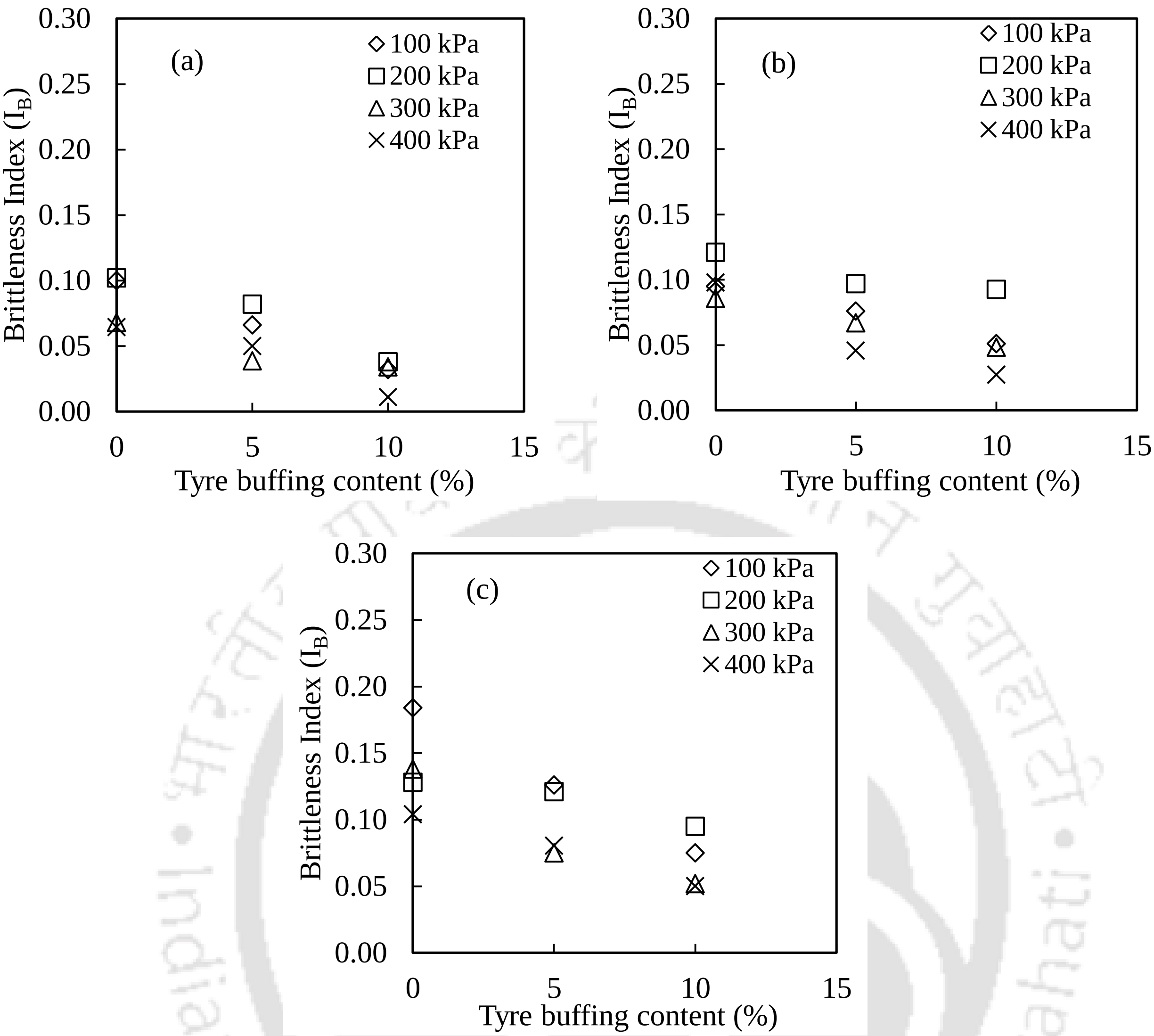


Fig. 6.84 Effect of fly ash content on brittleness of BS+FA+TB mixes at (a) 20%, (b) 35% and (c) 50% fly ash content

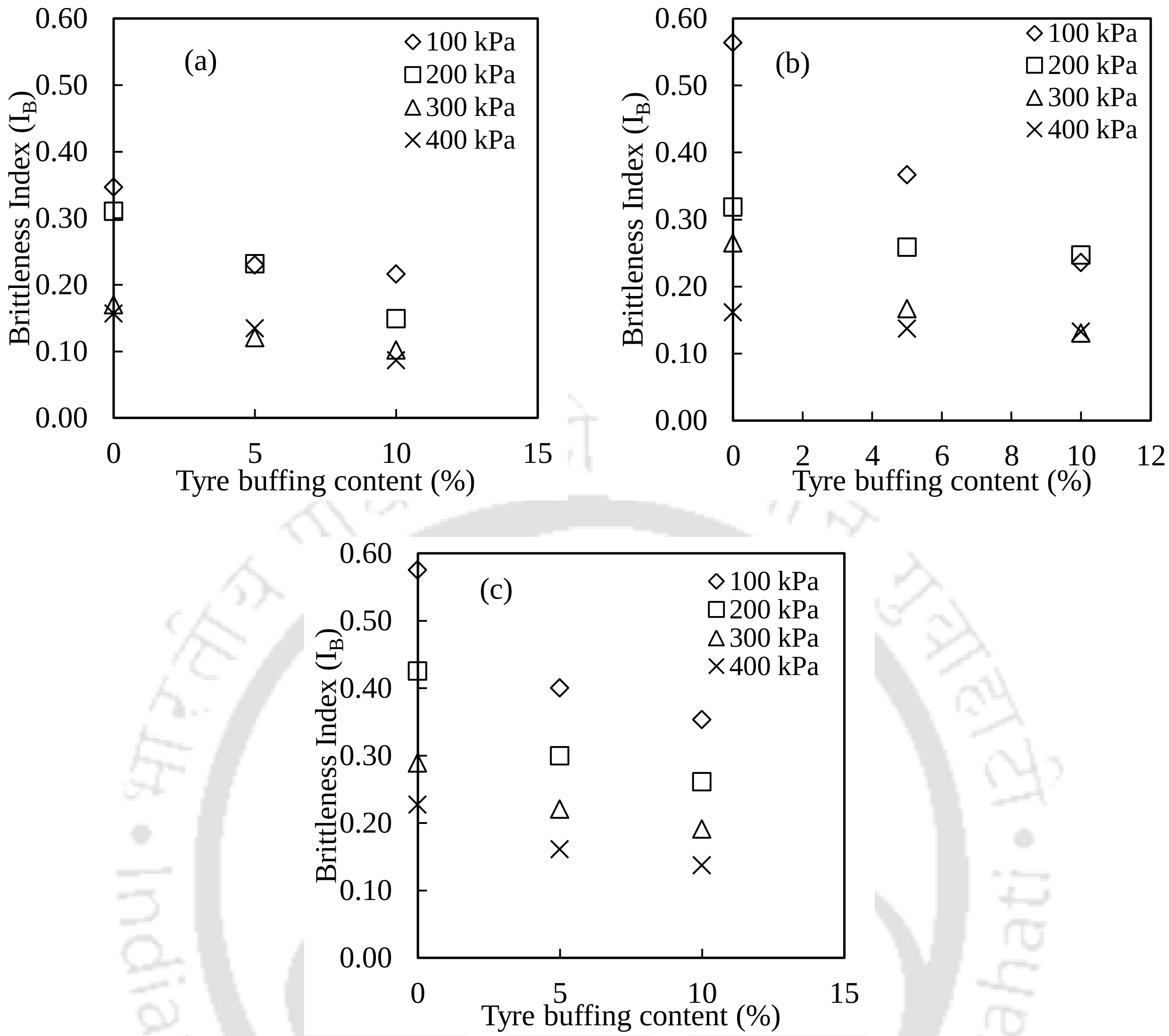


Fig. 6.85 Effect of fly ash content on brittleness of BS+FA+TB+2C mixes at (a) 20%, (b) 35% and (c) 50% fly ash content

6.3.19 Energy Absorption Capacity of Sand Mixes

Energy absorption capacity (EAC) is also used to study the post-peak behaviour of different sand mixes as in case of sand mixes. Although the triaxial compression tests were conducted up to 20% axial strain, effect of fly ash content, tyre buffing content and curing on EAC were studied considering a reference strain level up to 10%. EAC of each specimen has been calculated at 300 kPa confining pressure.

Addition of fly ash to sand decreases the EAC values of the specimens (Fig. 6.86) and as such BS+50FA mixes show lowest EAC values. Curing period is found to be an important factor as per as improvement of EAC of mixes is concerned. At 28 days curing period, EAC values of the specimens are found to be highest.

From Fig. 6.87, it is seen that further addition of tyre buffings to sand-fly ash mixes decreases the EAC of the BS+20FA and BS+35FA mixes. But a different behaviour has been observed when tyre buffings are added to BS+50FA mixes. BS+50FA+TB mixes show greater EAC value than BS+50FA mix. Generally, increase in curing period increases the EAC of the mixes.

Form Fig. 6.88, it is noted that inclusion of tyre buffings to cemented mixes has reduced the energy absorption capacity of the mixes. This is due to the presence of tyre buffings in the mixes which is ductile and less energy is required to induce deformation in tyre buffings. This kind of behaviour has also been observed in red soil mixes.

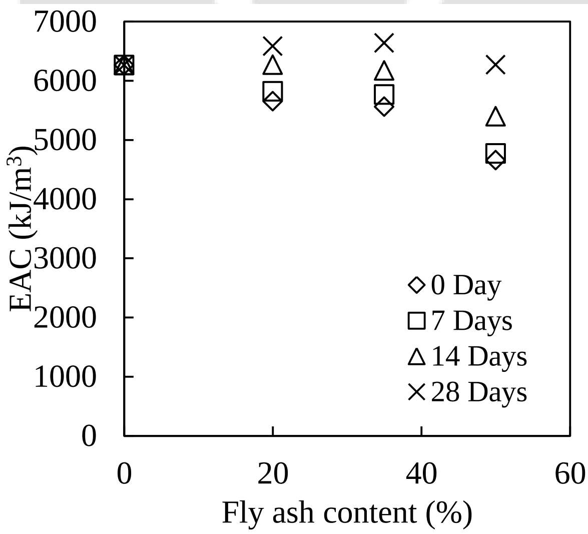


Fig. 6.86 Effect of fly ash content on EAC of BS+FA mixes

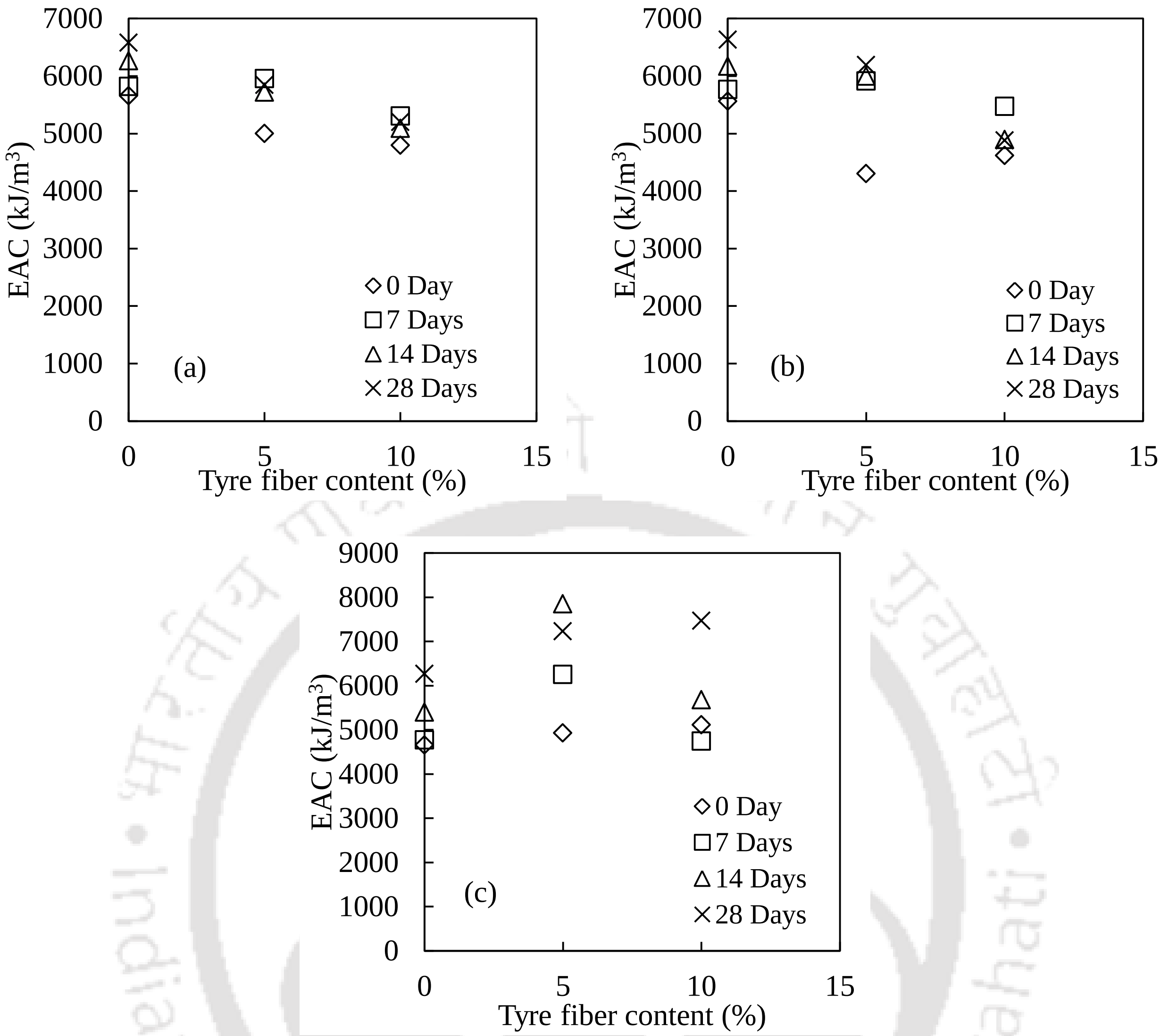


Fig. 6.87 Effect of tyre buffing content on EAC of BS+FA+TB mixes at (a) 20%, (b) 35% and (c) 50% FA content

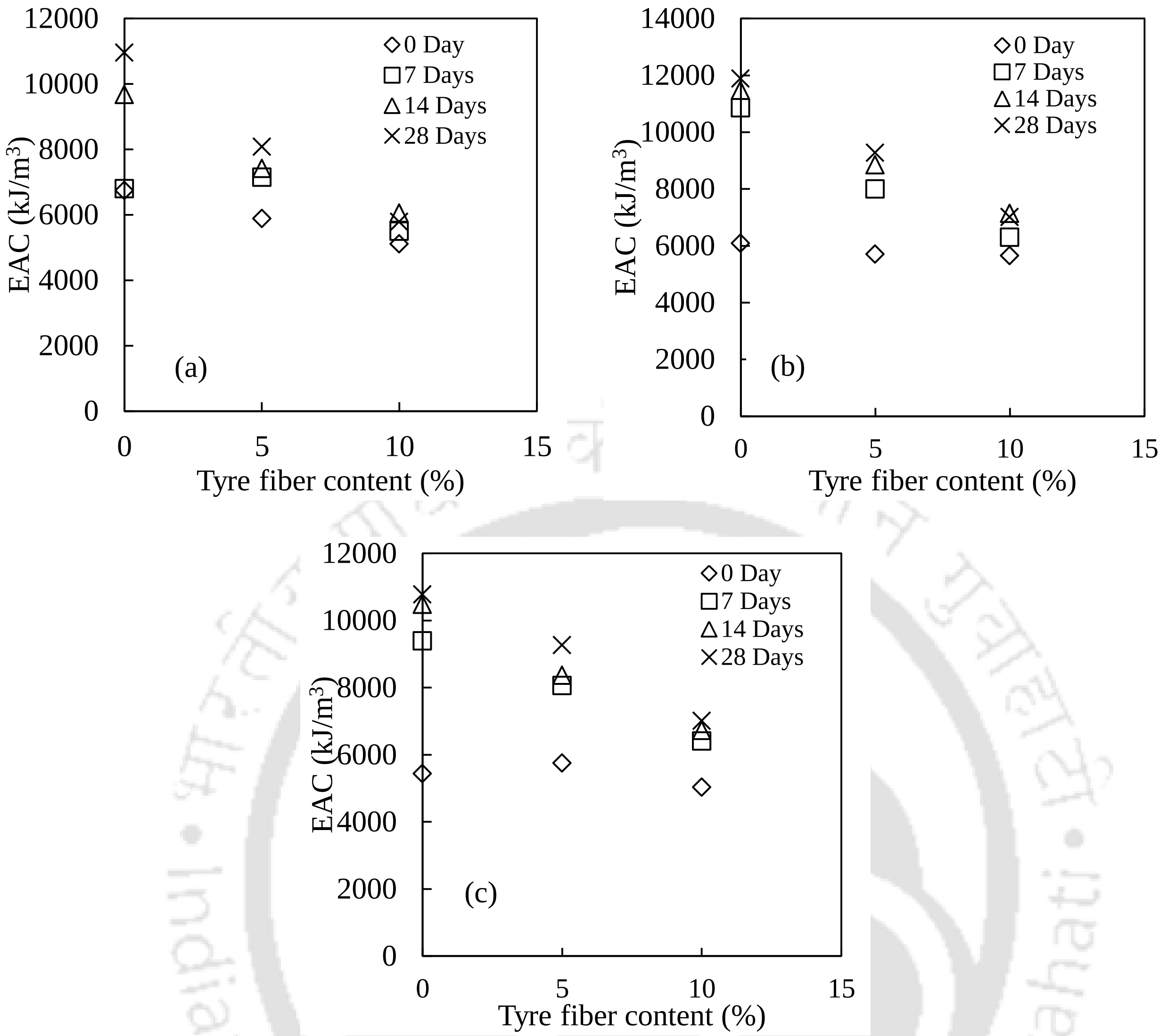


Fig. 6.88 Effect of tyre buffing content on EAC of BS+FA+TB+2C mixes at (a) 20%, (b) 35% and (c) 50% FA content

Table 6.24: Peak deviator stress (in kPa) of BS mixes using TB

Sl No.	Mix designation	Curing period																			
		0 Days				3 Days				7 Days				14 Days				28 Days			
		Confining Pressure (kPa)																			
		100	200	300	400	100	200	300	400	100	200	300	400	100	200	300	400	100	200	300	400
1	FA	227	356	456	665	256	377	643	770	279	398	646	809	294	504	672	922	335	583	888	1059
2	BS	320	652	913	1171	320	652	913	1171	320	652	913	1171	320	652	913	1171	320	652	913	1171
3	BS+5TB	358	571	895	1091	358	571	895	1091	358	571	895	1091	358	571	895	1091	358	571	895	1091
4	BS+10TB	372	509	841	962	372	509	841	962	372	509	841	962	372	509	841	962	372	509	841	962
5	BS+20FA	423	579	742	982	433	600	788	986	469	627	811	1007	471	644	828	1096	471	654	882	1113
6	BS+20FA+5TB	341	501	723	793	378	548	736	955	400	563	805	977	419	615	809	999	444	632	859	1098
7	BS+20FA+10TB	336	449	713	900	400	529	732	951	409	557	791	986	420	563	807	1012	421	614	823	1024
8	BS+35FA	423	567	683	910	430	603	776	947	430	603	790	963	471	613	822	981	473	624	880	1034
9	BS+35FA+5TB	316	579	724	880	356	586	749	971	410	612	811	983	415	665	875	1048	443	681	893	1105
10	BS+35FA+10TB	332	479	782	926	400	538	784	972	404	586	813	989	405	637	848	1006	424	669	877	1054
11	BS+50FA	384	528	665	852	446	552	688	924	454	554	727	933	469	578	744	951	479	595	831	981
12	BS+50FA+5TB	374	582	749	943	391	635	798	1060	400	657	842	1074	428	660	937	1080	478	705	949	1114
13	BS+50FA+10TB	329	578	780	954	385	588	792	980	387	605	841	1026	389	641	913	1047	391	697	937	1074

Table 6.25: Peak deviator stress of various BS, BS+C and BS+FA+C mixes

Sl. No.	Mix Designation	Peak deviator stress in different curing period (kPa)																			
		0 Days				3 Days				7 Days				14 Days				28 Days			
		Confining Pressure (kg/cm^2)																			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	BS	320	652	913	1171																
2	BS+1C	413	595	782	938	434	656	815	960	489	659	830	1018	502	677	886	1106	519	719	980	1172
3	BS+2C	454	608	789	1021	477	662	837	1119	512	726	861	1149	570	741	971	1208	601	752	997	1217
6	BS+20FA	423	579	742	982	433	600	788	986	469	627	791	1007	471	644	807	1096	471	654	882	1113
7	BS+20FA+1C	396	523	792	964	505	652	829	1001	516	662	851	1065	516	748	931	1098	558	823	948	1310
8	BS+20FA+2C	456	680	790	1021	525	674	842	1086	549	691	939	1099	689	1025	1232	1303	928	1165	1360	1555
11	BS+35FA	423	567	683	910	430	603	776	947	454	603	790	963	471	613	822	981	473	624	880	1034
12	BS+35FA+1C	423	696	775	1009	601	727	902	1085	616	866	944	1103	719	860	1074	1157	772	935	1176	1398
13	BS+35FA+2C	478	836	848	1070	622	864	914	1112	866	1096	1319	1493	979	1221	1345	1504	1090	1327	1505	1719
16	BS+50FA	374	528	665	852	446	552	688	924	430	554	727	933	469	578	744	951	479	595	831	981
17	BS+50FA+1C	458	542	766	1003	552	665	874	1056	566	722	939	1084	697	746	978	1110	779	901	1015	1369
18	BS+50FA+2C	497	549	792	1029	557	652	839	1094	689	857	1165	1200	779	1100	1282	1387	998	1270	1348	1598

Table 6.26: Peak deviator stress (in kPa) of BS+FA+TB+2C mixes

Sl No.	Mix designation	Curing period																			
		0 Days				3 Days				7 Days				14 Days				28 Days			
		Confining Pressure (kPa)																			
		100	200	300	400	100	200	300	400	100	200	300	400	100	200	300	400	100	200	300	400
1	BS+20FA+5TB+2C	356	640	797	1030	413	743	900	1117	557	743	1007	1212	582	745	1084	1270	606	817	1202	1336
2	BS+20FA+10TB+2C	377	625	794	1059	465	666	880	1077	488	686	938	1118	492	739	969	1210	500	770	1013	1216
3	BS+35FA+5TB+2C	480	638	820	988	578	774	1065	1308	637	871	1105	1324	678	935	1156	1452	703	1004	1276	1478
4	BS+35FA+10TB+2C	471	635	917	1091	512	765	948	1172	599	769	990	1245	641	858	1074	1319	662	1005	1097	1325
5	BS+50FA+5TB+2C	330	536	797	964	413	743	809	1120	519	783	982	1262	638	863	1135	1365	678	986	1208	1373
6	BS+50FA+10TB+2C	390	658	808	1057	530	659	943	1114	575	682	947	1178	582	753	1005	1207	664	926	1013	1249

Table 6.27: Shear strength parameters of fly ash and sand mixes at different curing periods using TB

Sl. No.	Mixes	Cohesion, C (kPa) and Angle of friction, φ (Degree)									
		0 Days		3 Days		7 Days		14 Days		28 Days	
		C	ϕ	C	ϕ	C	ϕ	C	ϕ	C	ϕ
1	BS	15.05	35.81								
2	FA	20.86	24.84	16.11	28.54	6.53	31.18	11.39	31.21	19.31	34.11
3	BS+5TB	25.20	33.90								
4	BS+10TB	38.18	31.13								
5	BS+20FA	64.82	28.72	71.01	28.70	83.25	28.12	68.52	30.48	69.24	31.14
6	BS+20FA+5TB	58.57	26.41	50.81	29.35	55.50	29.82	66.26	29.45	58.56	31.31
7	BS+20FA+10TB	30.57	29.80	54.97	28.87	55.57	29.95	55.06	30.44	61.37	30.48
8	BS+35FA	76.94	26.31	78.16	27.57	74.87	28.15	86.34	27.76	77.23	29.58
9	BS+35FA+5TB	47.54	28.78	48.61	30.10	65.60	29.32	62.79	3094	64.51	31.58
10	BS+35FA+10TB	29.04	30.88	52.34	29.77	58.44	19.87	62.92	30.17	65.30	30.84
11	BS+50FA	65.86	26.13	78.76	26.34	80.38	26.64	86.16	26.63	85.19	27.87
12	BS+50FA+5TB	42.21	30.14	49.49	31.42	53.15	31.67	59.29	31.96	76.46	31.27
13	BS+50FA+10TB	57.36	29.27	54.63	29.91	49.51	31.25	49.90	32.10	53.24	32.50

Table 6.28: Shear strength parameter of various mixes of sand and cemented sand

Sr. No.	Mixes	Cohesion, c (kPa) and Angle of internal friction, ϕ (Degree)									
		0 Days		3 Days		7 Days		14 Days		28 Days	
		c	ϕ	c	ϕ	c	ϕ	c	ϕ	c	ϕ
1	**BS**	15.05	35.81								
2	**BS+1C**	72.55	27.94	84.45	27.77	88.81	28.24	82.48	30.19	81.16	31.77
3	**BS+2C**										
6	**BS+20FA**	64.82	28.72	71.01	28.70	83.25	28.12	68.52	30.48	69.24	31.14
7	**BS+20FA+1C**	45.52	29.91	101.11	27.03	92.83	28.65	99.12	29.45	82.06	33.22
8	**BS+20FA+2C**	83.93	28.45	93.32	28.84	100.41	29.22	149.17	31.09	208.54	30.60
11	**BS+35FA**	76.94	26.31	78.16	27.57	74.87	28.15	86.34	27.76	77.23	29.58
12	**BS+35FA+1C**	76.61	28.90	129.68	26.70	154.95	25.82	148.58	29.22	152.40	31.01
13	**BS+35FA+2C**	98.31	29.10	136.06	26.37	189.01	30.88	252.69	27.52	254.99	30.53
16	**BS+50FA**	65.86	26.13	78.76	26.34	80.38	26.64	86.16	26.63	85.19	27.87
17	**BS+50FA+1C**	64.33	29.10	107.16	27.60	115.17	28.05	160.12	25.42	151.97	29.74
18	**BS+50FA+2C**	71.52	29.10	97.32	28.56	146.78	29.23	177.27	30.53	241.74	29.27

Table 6.29: Shear strength parameters of BS+FA+TB+2C mixes at different curing periods

Sr. No.	Mixes	Cohesion, C (kPa) and Angle of internal friction, φ (Degree)									
		0 Days		3 Days		7 Days		14 Days		28 Days	
		C	φ	C	φ	C	φ	C	φ	C	φ
1	BS	15.05	35.81								
2	BS+20FA+5TB+2C	44.15	31.53	60.33	32.31	89.33	31.84	84.58	33.25	88.03	34.56
3	BS+20FA+10TB+2C	44.04	31.76	74.27	30.41	76.37	31.17	69.70	32.94	74.81	33.03
4	BS+35FA+5TB+2C	92.66	27.41	82.79	33.67	113.05	32.30	111.08	34.07	121.53	34.49
5	BS+35FA+10TB+2C	67.53	31.24	86.40	31.33	100.80	31.34	113.75	31.97	138.06	31.08
6	BS+50FA+5TB+2C	32.07	31.36	57.36	31.94	75.08	33.28	103.98	33.44	131.10	32.56
7	BS+50FA+10TB+2C	52.73	31.31	85.09	30.46	90.85	30.82	99.91	31.06	146.18	28.88

6.3.20 Comparison between Strength of Both Soil-Fly Ash Mixes

From Fig. 6.89, it is seen that inclusion of fly ash to soil mixes is effective only in case of red soil mixes. RS+FA mixes show highest strength at 35% fly ash content. Addition of fly ash to sand has reduced the strength of mixes.

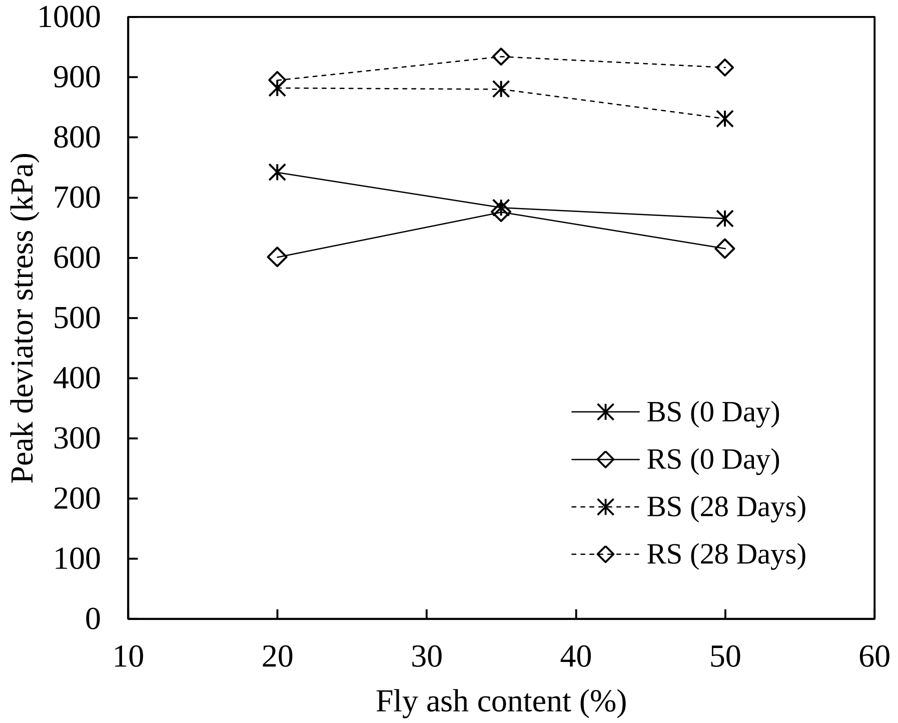


Fig. 6.89 Effect of fly ash content on peak deviator stress of BS and RS mixes for 0 day and 28 days curing periods

Fig. 6.90 depicts that inclusion of fly ash to soil mixes has affected the shear strength parameters of soil mixes. Addition of fly ash to red soil has reduced the cohesion of mixes, whereas BS+FA mix shows improvement in cohesion as compared to BS mix [Fig. 90(a)]. RS+FA mixes show lower values of cohesion as compared to BS+FA mixes. As shown in Fig. 90(b), addition of fly ash has increased the internal friction angle of RS mix but has reduced these values of BS mix.

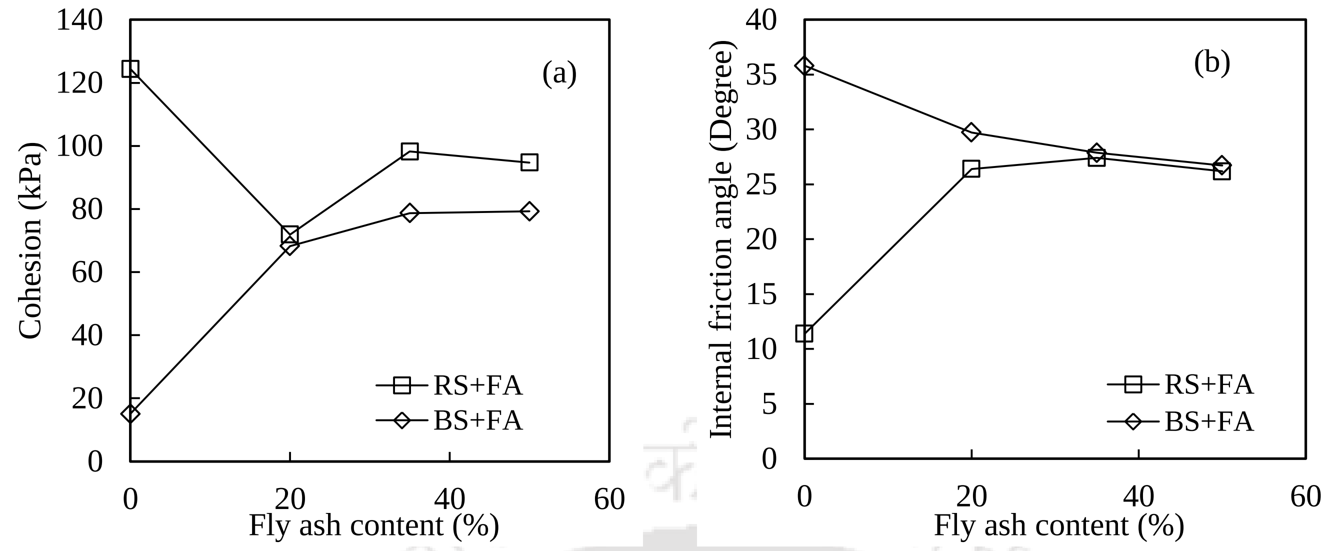
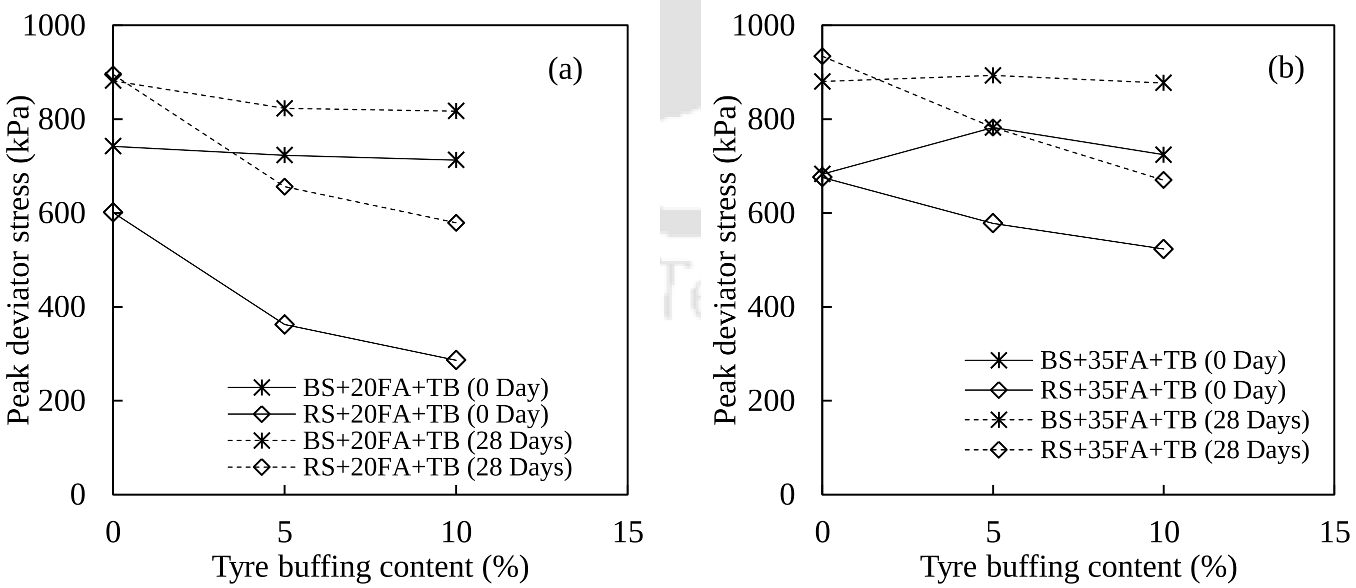


Fig. 6.90 Effect of fly ash content on cohesion and internal friction angle of BS and RS mixes

6.3.21 Comparison between Strength of Both Soil-Fly Ash-Tyre Buffing Mixes

From Fig. 6.91, it is seen that inclusion of tyre buffing to red soil-fly ash mixes has exhibited lower strength. But the improvement in strength is observed due to addition of tyre buffing to sand- fly ash mixes having fly ash content more than 35%. The frictional component of the mixes has played important role in this case.



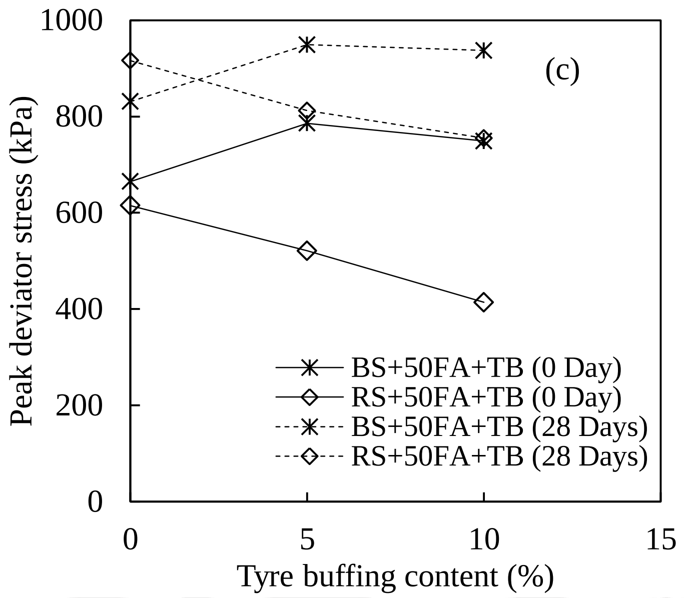


Fig. 6.91 Effect of tyre buffing content on peak deviator stress of both soil-FA-tyre buffing mixes for 0 day and 28 days curing periods at (a) 20% FA, (b) 35% FA and (d) 50% FA content

Shear strength parameters of soil-fly ash mixes are influenced by inclusion of tyre buffings to these mixes. Addition of tyre buffings to soil-fly ash mixes reduces the cohesion of mixes as shown in Figs. 92(a), 93(a) and 94(a). RS+FA+TB mixes show greater cohesion than BS+FA+TB mixes. Presence of tyre buffings in red soil-fly ash-tyre buffing mixes reduces the frictional resistance of mixes, whereas BS+FA+TB mix shows improvement in internal fiction angle at fly ash contents of 35% and 50% [Figs. 93(b) and 94(b)].

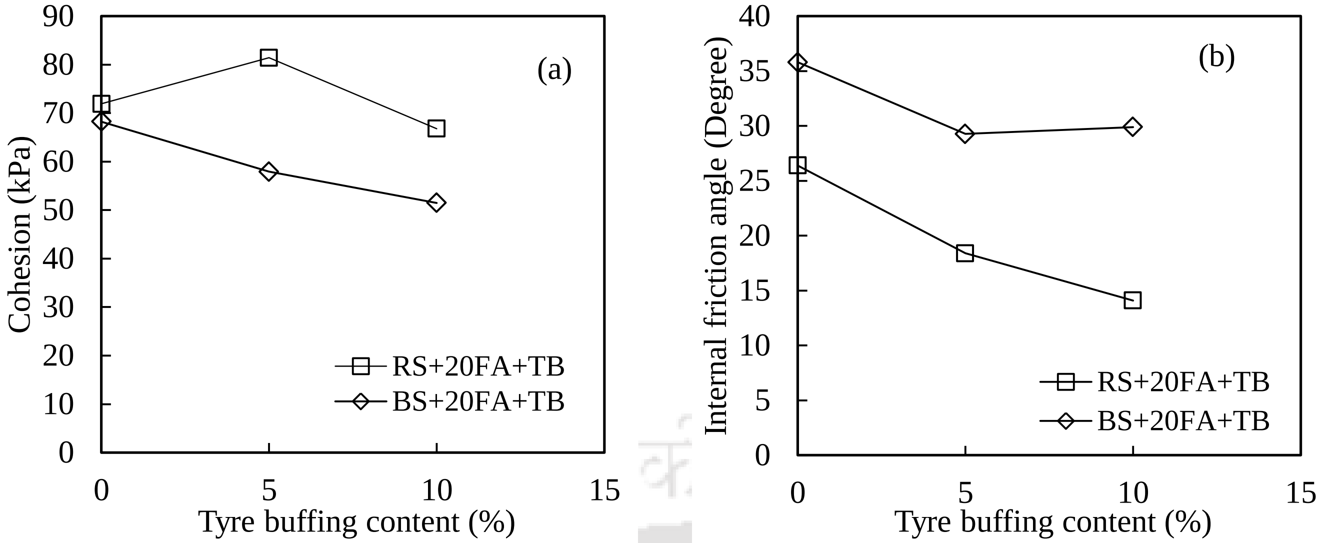


Fig. 6.92 Effect of tyre buffing content on cohesion and internal friction angle of both soil-20FA-tyre buffing mixes

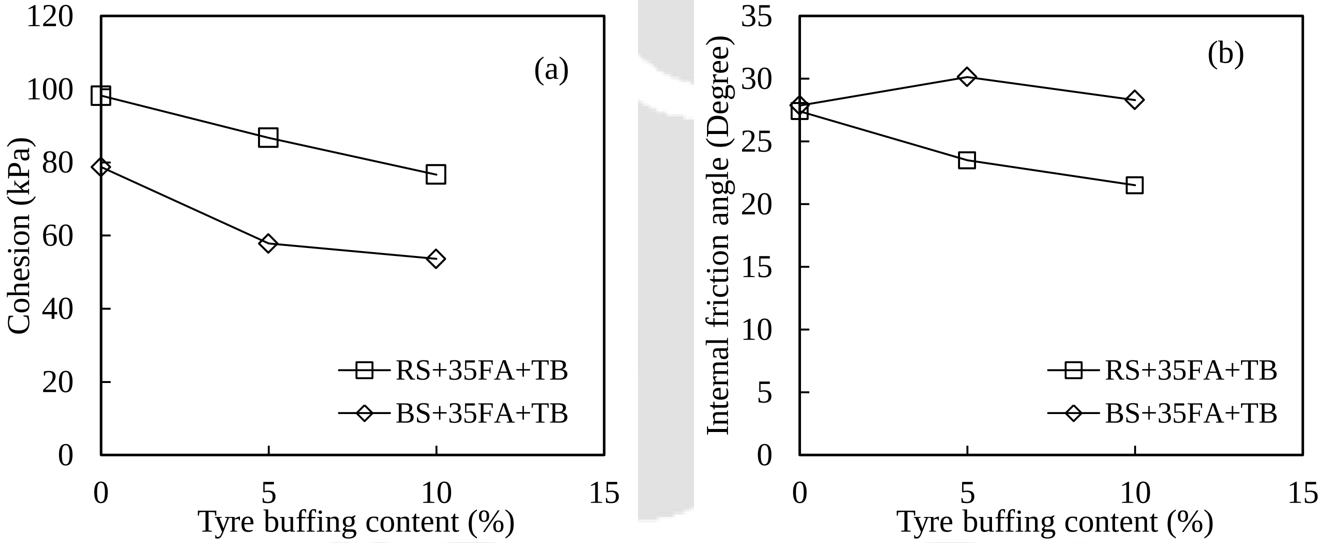


Fig. 6.93 Effect of tyre buffing content on cohesion and internal friction angle of both soil-35FA-tyre buffing mixes

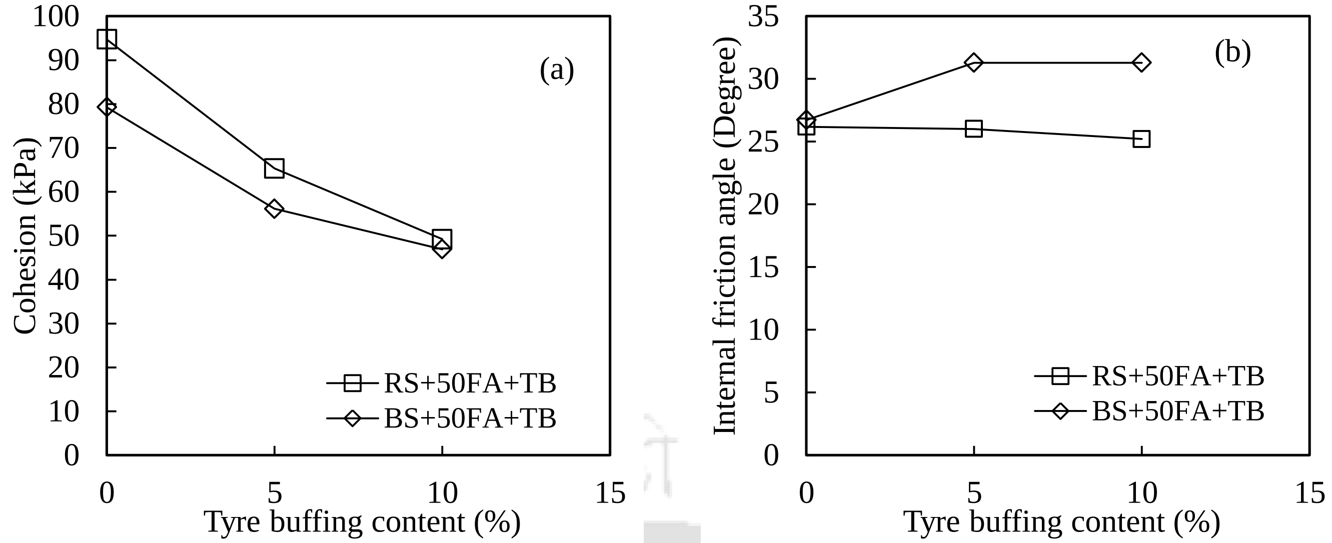
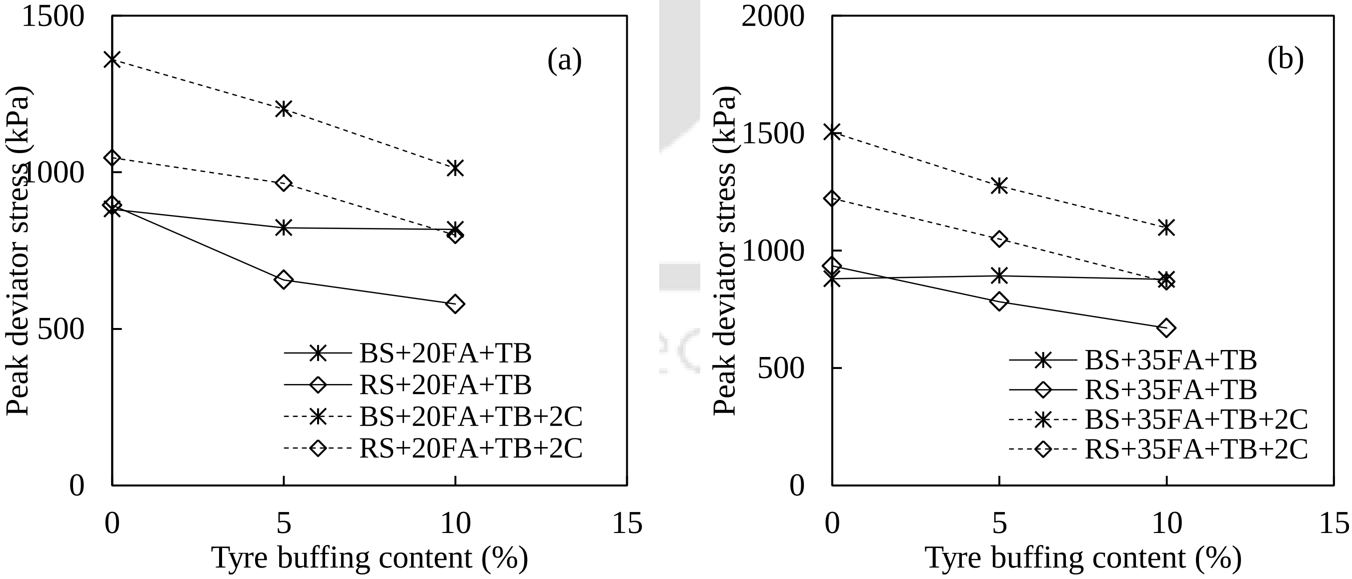


Fig. 6.94 Effect of tyre buffing content on cohesion and internal friction angle of both soil-50FA-tyre buffing mixes

6.3.22 Comparison between Strength of Both Soil-Fly Ash-Tyre Buffing-Cement Mixes

From Fig. 6.93, it is seen that inclusion of cement to soil-fly ash-tyre buffing mixes leads to higher strength compared to uncemented mixes. But the reduction in strength with the increase in tyre buffing content is observed in all cemented mixes.



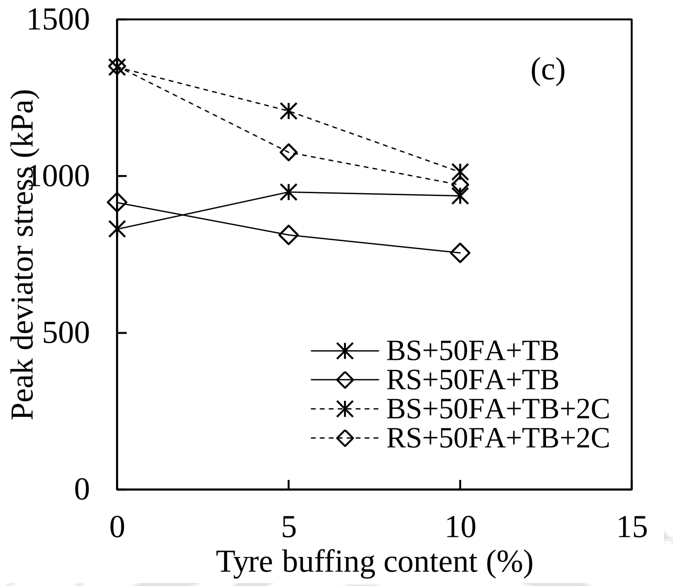


Fig. 6.95 Effect of tyre buffing content and cement content on peak deviator stress of both soil-FA-tyre buffing mixes for 28 days curing periods at at (a) 20% FA, (b) 35% FA and (d) 50% FA content

Figs. 6.96 to 6.98 show the influence of tyre buffing inclusion on shear strength parameters of cemented soil-fly ash mixes. Presence of tyre buffings in soil-fly ash-cement mixes reduces the cohesion component of mixes as compared to cemented mixes without tyre buffing mixes. RS+FA+TB+2C mixes show greater cohesion than BS+FA+TB+2C mixes. On the other hand, as TB content in BS+FA+TB+2C mixes increases internal friction angle of these mixes is also increased. Unlike BS+FA+TB+2C mix, RS+FA+TB+2C shows reduction in frictional resistance with increase in tyre buffing content in mixes.

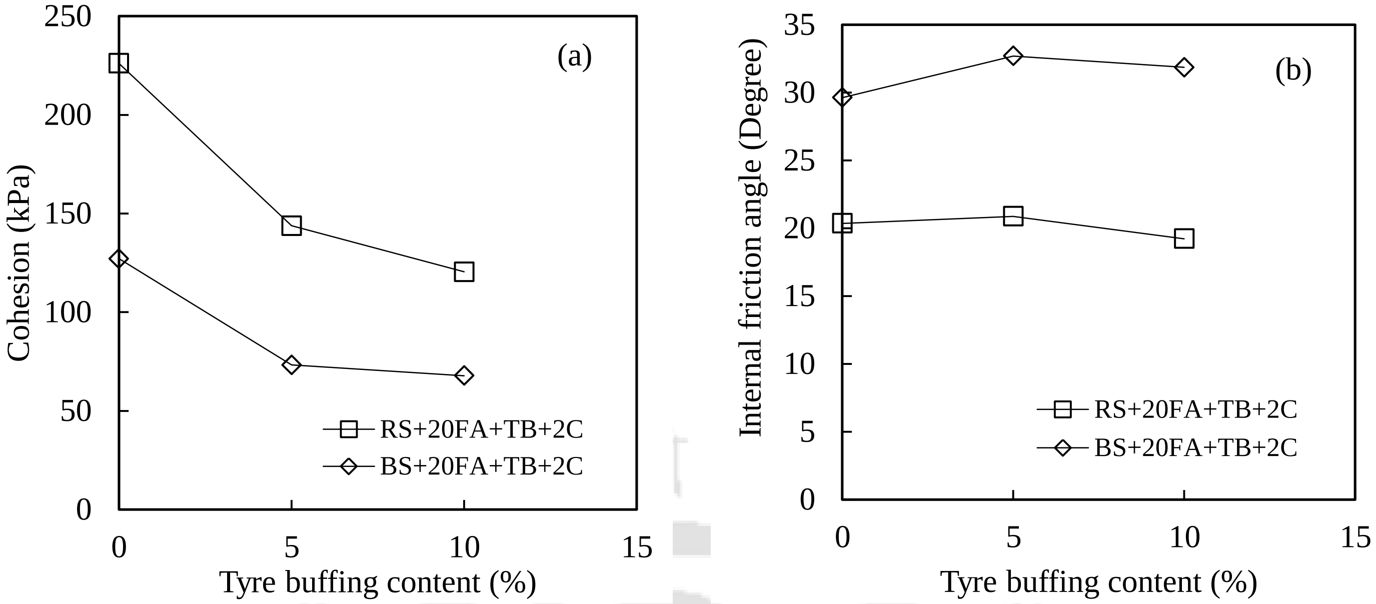


Fig. 6.96 Effect of tyre buffing content on cohesion and internal friction angle of both soil-20FA-tyre buffing-cement mixes

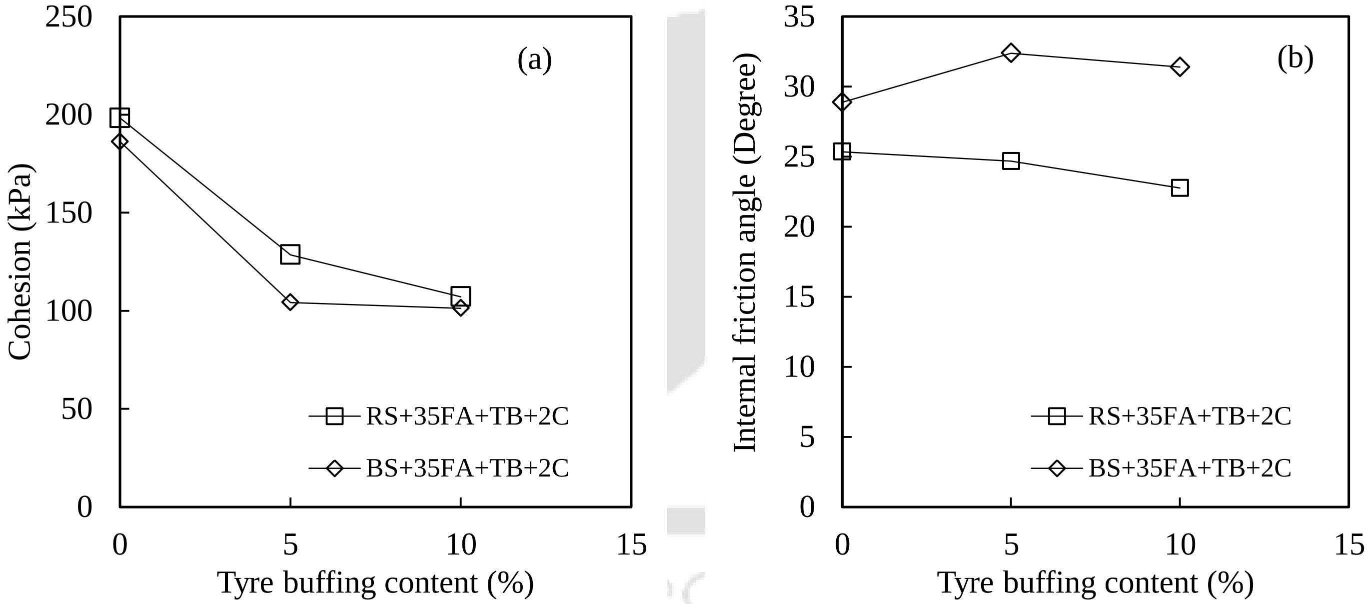


Fig. 6.97 Effect of tyre buffing content on cohesion and internal friction angle of both soil-35FA-tyre buffing-cement mixes

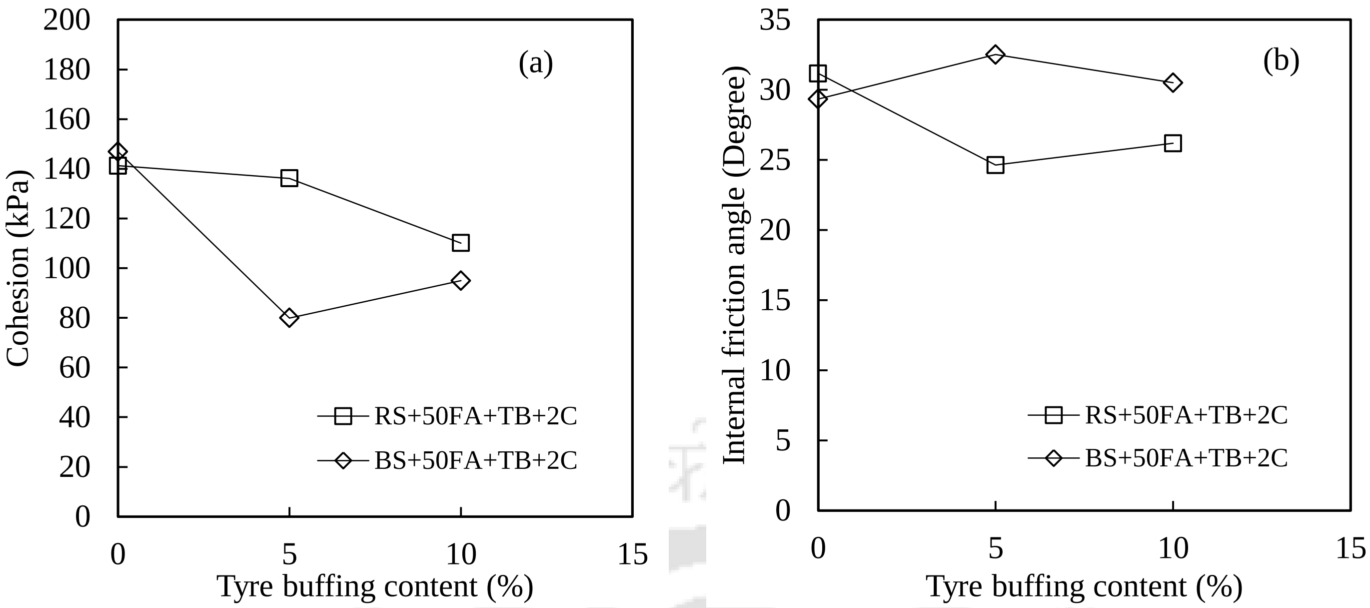


Fig. 6.98 Effect of tyre buffing content on cohesion and internal friction angle of both soil-50FA-tyre buffing-cement mixes

6.4 REGRESSION ANALYSIS

Based on triaxial compression test results some researchers developed regression models for predicting the strength characteristics of fibre-reinforced soil (Ranjan et al., 1996; Babu and Vasudevan, 2008; Patel and Sing, 2017). In this study, to investigate the effect of various factors on deviator stress at failure of the specimens, multiple-regression statistical analysis was conducted based on the experimental results. In multiple regression analysis, the relationship between dependent and independent variables can be presented as follows:

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_k x_{ik} \quad (6.4)$$

where,

$i = 1, 2, 3\ldots, n$ is the number of observations;

y_i = dependent variable;

$x_{i1}, x_{i2}, \ldots x_{ik}$ = independent variables and

$\beta_0, \beta_1, \beta_2, \ldots, \beta_k$ = regression coefficients.

The different influencing parameters identified as independent variables in the model are fly ash content (FA), tyre buffing content (TB), curing period and confining pressure (σ_3). The effects of these parameters on deviator stress at failure of tyre buffing added RS specimens have been evaluated by the following regression model,

$$\sigma_d = 48.64+13.77(FA)-41.27(TB)+13.23(\text{curing period})+1.1(\sigma_3)-0.14(FA)^2+1.87(TB)^2-0.23(\text{curing period})^2 \quad \ldots\ldots\ldots\ldots\ldots \quad (6.5)$$

The model developed to investigate the effects of different parameters as mentioned above on deviator stress at failure of tyre buffing added BS specimens is as follows:

$$\text{Log}_{10}(\sigma_d) = 1.15+0.07\log_{10}(FA)-0.04\log_{10}(TB)+0.06\log_{10}(\text{curing period})+0.66\log_{10}(\sigma_3) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6.6a)$$

Or, $$\sigma_d = 14.125 \times (FA)^{0.07} \times (TB)^{-0.04} \times (\text{curing period})^{0.06} \times (\sigma_3)^{0.66} \quad \ldots\ldots\ldots\ldots\ldots \quad (6.6b)$$

The respective values of R^2 for equations 6.5 and 6.6b are 0.88 and 0.98 respectively. It is observed that the equations 6.5a and 6.6b obtained by regression analysis indicate the goodness of fit to the data. Hence it can be stated that the relationship between the deviator stress at failure and other influencing parameters can be well explained by those regression equations and prediction of deviator stress can also be made.

6.5 CONCLUDING REMARKS

Triaxial compression test was carried out to study the effect of fly ash, tyre derived materials and cement addition on geotechnical behaviour of compacted soil specimens. The effect of addition of those blending materials and curing period on stress-strain-strength behaviour, deformation mode, stiffness, and EAC behaviour of soil specimens under varying confining pressure was studied. The following conclusions have been drawn from the test results:

1. Increase in strength due to addition of fly ash to soil is more significant in red soil than in sandy soil. Increase in fly ash content in RS+FA mixes improves the strength, stiffness and energy absorption capacity of mixes, but it also imparts brittleness. Addition of fly ash to red soil mixes decreases the cohesion component but increases the internal friction angle. For 28 days curing, the red soil only mix shows the reduction in cohesion value from 156.17 kPa to 87.55 kPa on addition of 20% fly ash content. Similarly the internal friction angle of red soil only sample increases from 14.15^o to 29.0^o for the same curing period and fly ash content.

   Increase in fly ash content in sand reduces the strength, energy absorption capacity and stiffness of specimens. But sand-fly ash mixes are more brittle than sand alone mixes. Generally, addition of fly ash to sand increases the cohesion component but reduces the internal friction angle of sand-fly ash mixes. Curing has also influence on strength of soil-fly ash mixes.

2. Further addition of cement to soil-fly ash mixes exhibits significant change in stress-strain response of the mixes. Cemented mixes show improvement in strength and stiffness as well. Curing alters the overall stress-strain characteristics of the mixes by increasing peak strength and brittleness. Effect of curing on strength improvement is more significant in sand-fly ash-cement mixes than cemented red soil-fly ash mixes. Addition of cement to both the soil-fly ash mixes increases the cohesion parameter which reflects the increase in cementation.

3. Tyre buffing inclusion to both the soil type reduces the strength of the mixes and affects the stiffness and brittleness of the material. It has been found that addition of tyre buffing causes significant loss in strength of red soil-fly ash mixes. However, RS+FA+TB mix with 5% TB content shows improvement in shear strength as compared to RS alone mixes.

Moreover, sand-fly ash-tyre buffing mixes show some improvement in strength and stiffness as compared to sand-fly ash mixes especially in higher confining pressure (300 kPa and 400 kPa) and higher fly ash content (35% and 50%). The tyre buffings added soil mixes also show reduction in failure strain and secant modulus. EAC values of BS+FA+TB mixes are lower than BS+FA mixes at 20% and 35% FA content, but these mixes show greater EAC values than BS+FA mixes at 50% fly ash content.

4. Strength of soil-fly ash-tyre buffing mixes can be increased by adding cementitious material. Influence of cement addition on strength improvement is more effective in case of samples tested under curing. In general, cemented soil-fly ash-tyre buffing mixes show greater strength and stiffness than soil-fly ash mixes with or without tyre buffings. Presence of tyre buffings in soil-fly ash-tye buffing-cement mixes makes the specimen more ductile as compared to soil-fly ash-cement specimen. However, EAC of BS+FA+TB+2C mixes are lower than BS+FA+TB mixes. Therefore, it is beneficial to use tyre buffing with soil-fly ash mixes in presence of a cementitious material.
5. Inclusion of tyre crumb to cemented red soil-fly ash mixes shows significant improvement in strength compared to other tyre fiber added mixes. The strength of tyre crumb added mixes is even greater than cemented red soil-fly ash mixes. In most of the cases, tyre crumb inclusion increases both the shear strength parameters. Moreover, curing plays an important role in progressive increase in shear strength.

CHAPTER-7
SUMMARY AND CONCLUSIONS

7.1 SUMMARY

In this research work an investigation has been carried out to study the strength characteristics of two soils, a fine-grained residual lateritic soil (red soil) and granular riverbank sand (Brahmaputra sand) blended with a low-calcium fly ash and scrap tyre materials with or without ordinary Portland cement. This has been emphasized and examined in detail through a systematic series of compaction tests, unconfined compression tests and triaxial consolidated drained tests.

7.2 CONCLUSIONS

Based on the laboratory test results and the analyses carried out, the following conclusions have been drawn:

Compaction Characteristics

1. The cohesive red soil has a relatively higher unit weight than the cohesionless sand under a given compactive effort. The red soil particles cannot be packed as compactly as the sand particles by virtue of either double layer repulsion or flocculent nature of the soil fabric. With the result, their water holding capacity is also relatively more. Hence, red soil mixes exhibit a lower maximum dry unit weight and a higher OMC.
2. It is evident that the maximum dry unit weight decreases with increase in fly ash content in the soil-fly ash mixes. The maximum dry unit weight values of red soil-fly ash mixes are lower than the corresponding maximum dry unit weight values of sand-fly ash mixes. But the OMC values of red soil-fly ash mixes are higher than that of sand-fly ash mixes at the same fly ash content. The lower specific gravity and

poorly graded particles of the fly ash along with the presence of cenospheres are dominating factors controlling the compaction behaviour of the soil mixes.

3. Addition of tyre buffing to soil alone or soil-fly ash mixes decreases the maximum dry unit weight of the mixes. As the fly ash content of RS+FA+TB increases the maximum dry unit weight of the mixes decreases, whereas maximum dry unit weight of BS+FA+TB mixes decreases only after addition of 20% fly ash, and increase in maximum dry unit weight of BS+FA+TB is observed up to 20% fly ash addition. The lower specific gravity of tyre buffings is responsible for reduction in maximum dry unit weight of soil-fly ash-tyre buffing mixes.

Unconfined Strength Characteristics

1. Addition of fly ash to soil immediately reduces the compressive strength of the mixes and it is due to the increased content of non-cohesive fraction in soil-fly ash mixes. UCS values are observed to be the highest for soil-fly ash mixes with 20% fly ash content. Further addition of fly ash reduces the compressive strength of the soil-fly ash mixes. Curing does not significantly alter the overall stress-strain characteristics of the mixes.
2. Compressive strength of sand is increased on the addition of fly ash to it due to the denser structure occurring within the specimen by the increased fly ash content in sand-fly ash mixtures. Therefore, sand-fly ash mixtures with 50% fly ash content show the highest UCS value among all sand-fly ash mixtures. Sand-fly ash mixes also shows progressive increase in compressive strength with fly ash content and also with curing duration.
3. Tyre buffing inclusion to soil-fly ash mixes affects the stress-strain behaviour by causing change in compressive strength and stiffness of the mixes. For all tyre buffings added red soil mixes strength ratio values (SR_{RS}) are smaller than 1.0. It

indicates reduction in compressive strength of mixes due to the inclusion of fly ash and tyre buffings to red soil. On the other hand, the strength ratio values for sand mixes (SR_{BS}) are greater than 1.0 indicating improvement of UCS on addition of fly ash and tyre buffings. Increase in fly ash content in BS+FA+TB mixes is more effective and as such BS+50FA+5TB mix bears the highest compressive strength.

4. Although inclusion of tyre buffing to soil-fly ash mixes reduces the compressive strength, the reduction in compressive strength is less in case of sand-fly ash mixes than red soil-fly ash mixes irrespective of curing period.
5. Inclusion of tyre buffings to soil-fly ash mixes improves ductility of the specimens which is evident from the increase in ductility ratio of mixes. Addition of tyre buffings to soil-fly ash mixes reduces the secant modulus values of mixes. However, these values are affected by the fly ash content in mixes.
6. Addition of fly ash and tyre buffings in soil also affects energy absorption capacity of soil mixes. Increase in FA content in RS+FA and RS+FA+TB mixes reduces EAC values of mixes. In contrary to that, increase in FA content in BS+FA and BS+FA+TB mixes increases the EAC values of mixes. Further addition of TB in soil-fly ash mixes decreases the EAC values of RS+FA mixes but improves absorption energy of BS+FA mixes. At 28 days curing period, EAC values of BS+50FA and BS+50FA+10TB are 76.83 kJ/m^3 and 115.84 kJ/m^3 respectively, whereas RS+50FA and RS+50FA+10TB mixes have EAC values of 571 kJ/m^3 and 450 kJ/m^3 respectively.

Shear Strength Characteristics

1. Increase in strength due to addition of fly ash to soil is more significant in the red soil than in the sandy soil. Addition of fly ash in red soil improves the strength, stiffness and energy absorption capacity of mixes, but it also imparts brittleness. Curing has

also influence on strength of soil-fly ash mixes. Addition of fly ash to red soil mixes decreases the cohesion component but increases the internal friction angle. However, a non-linear behaviour is observed in case of sand-fly ash mixes in the variation of shear strength parameters with fly ash content. Increase in fly ash content in sand reduces the strength, energy absorption capacity and stiffness of specimens, and also introduces brittle behaviour of sand mixes.

2. Further addition of cement to soil-fly ash mixes exhibits significant change in stress-strain response of the mixes. Cemented mixes show improvement in strength and stiffness as well. Effect of curing on strength improvement is more significant in cemented sand-fly ash-cement mixes than in cemented red soil-fly ash mixes. Addition of cement to both the soil-fly ash mixes increases the cohesion parameter which reflects the increase in cementation. At 300 kPa confining pressure addition of 2% cement to BS+20FA mix shows 790 kPa and 1360 kPa peak deviator stress values at 0 and 28 days curing period respectively.
3. Tyre buffing inclusion to red soil reduces the strength of the mixes and affects the stiffness and brittleness of the material. Further reduction in strength of mixes is observed as the tyre buffing content in red soil-tyre buffing mixes increases. At 300kPa confining pressure and no curing period, addition of 10% TB to RS alone mix reduces the peak strength of mixes from 261 kPa to146 kPa. Addition of tyre buffings to sand improves the strength up to 372 kPa at lower confining pressure of 100 kPa. At confining pressure ranging from 200 kPa and 400 kPa, sand-tyre buffing mixes show lower strength than sand alone mixes.
4. Red soil-fly ash-tyre buffing mixes also show decrease in strength, energy absorption capacity and stiffness as compared to soil-fly ash mixes. Inclusion of tyre buffing which is a weaker material may lead to the reduction in strength of mixes. Still

improvement in strength has been observed for red soil-fly ash-tyre buffing mixes containing 5% tyre buffing and fly ash content higher than 20% as compared to red soil alone mixes. RS alone, RS+50FA and RS+50FA+10TB mixes showed the peak strength values as 599, 916 kPa and 755 kPa respectively at 300kPa confining pressure and 28 days curing period. The cohesion and internal friction angle values of red soil-fly ash mixes are reduced with the addition of tyre buffing to the mixes.

5. Tyre buffing inclusion to sand-fly ash mixes reduces the shear strength of the mixes at a fly ash content of 20%. Confining pressure and fly ash content influence the strength of the sand-fly ash-tyre buffing mixes. At lower confining pressure, sand-fly ash-tyre buffing mixes show lower strength than sand-fly ash mixes. Still improvement in strength has been observed for sand-fly ash-tyre buffing mixes containing fly ash content higher than 20% as compared to sand alone mixes when the confining pressure is more than 100 kPa. Inclusion of tyre buffings to sand-fly ash mixes also affects the stiffness of the composite material. The cohesion values of sand-fly ash mixes is reduced with the addition of tyre buffing to the mixes. Usually internal friction angle increases with addition of tyre buffings to sand-fly ash mixes. EAC values of BS+FA+TB mixes are lower than BS+FA mixes at 20% and 35% FA contents, but these mixes show greater EAC values than BS+FA mixes at 50% fly ash content.
6. Strength and stiffness of soil-fly ash-TB mixes can be increased by adding cementitious material. Presence of tyre buffings in soil-fly ash-tyre buffing-cement mixes makes the specimen more ductile as compared to soil-fly ash-cement specimen. Influence of cement addition on strength improvement is more effective in case of samples tested under curing. In general, cemented soil-fly ash-tyre buffing mixes show greater strength than soil-fly ash mixes. However, EAC of soil-fly ash-

tyre buffing-cement mixes are lower than soil-fly ash-cement mixes. It is beneficial to use tyre buffing with soil-fly ash mixes in presence of a cementitious material.

7. Inclusion of tyre crumb to cemented red soil-fly ash mixes shows significant improvement in strength compared to other tyre fiber added mixes. In most of the cases, tyre crumb inclusion increases both the shear strength parameters. Moreover curing plays an important role in progressive increase in shear strength.

7.3 Contribution of Present Investigation to the Existing Knowhow in Literature

Contributions from this research work to the current scenario may be as stated below:

1. Understanding of the compaction characteristics of soil mixed with fly ash and tyre-fiber in different proportions.
2. Investigating the strength behaviour of a soil mixed with fly ash and tyre-fiber in different proportions or in combination with cement by means of laboratory tests.
3. Evaluating the mechanism controlling the shearing behaviour of soil-fly ash and soil-fly ash-tyre buffing mixes.
4. Proposing the way out of utilization of fly ash and tyre-fiber with soil in many geotechnical applications.

7.4 Scope for Further Research

For more understanding of size effect on strength of the mixes, tyre crumb (TC) may also be used in with different cemented and uncemented sand mixes. Moreover, CBR test can also be conducted on soil mixed with different proportions of fly ash and scrap tyre materials with or without cement which may give a proper understanding of utilization of these waste materials in many geotechnical applications.

7.5 Limitation of Present Work

In this study, specimen size of 38mm×76mm is used in triaxial compression tests considering the size effect of individual particle present in the specimen. Specimen size of 50mm×100mm can be used in triaxial compression tests accommodating tyre fiber of larger size which will help to understand the size effect of tyre fiber on strength characteristics of soil.

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