PROPERTIES OF CONCRETE
WITH
CRUSHED BRICK COARSE AGGREGATES

BY

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ABSTRACT

Three types of bricks were selected for testing properties of brick aggregates and brick aggregate concrete. W/C ratios from 0.63 to 0.24 were investigated. The mix design method given in 'Design of Normal Concrete Mixes' specified by the Department of Environment, U K. was followed initially. Permeability testing for concrete with brick aggregates was carried out by the help of ISAT, capillary rise test and Voltage driven chloride diffusion test. Tests for evaluation of frost resistance of concrete with brick aggregates were carried out along with sulphate resistance tests on concrete with brick aggregates. Investigations on high strength concrete with brick aggregates were also made along with tests on mixes with Thames Valley gravel replaced partially by brick aggregates.

Mixes with brick aggregates were generally observed to be less workable as compared to mixes with gravel. Performance of concrete with brick aggregates depends basically on the crushing strength and absorption of bricks from which the aggregates are obtained. Brick aggregate concrete developed satisfactory cube compressive strength. Cylinder strength was observed to be about 10% lower, as compared to concrete with gravel. Split cylinder tensile strength varied from 18% lower to 20% higher whereas flexural strength was observed to vary from 13% lower to 22% higher than concrete with gravel. Strains were observed to be 10 to 83% higher at failure, for brick aggregate concrete. Static modulus of elasticity was found to be 28 to 59% lower whereas dynamic modulus was also observed to be lower by 13 to 26% as compared to concrete with gravel. Densities of concrete with brick aggregates were lower by 5 to 13% than concrete with gravel. Coefficient of thermal expansion varied from 35% lower to 5% higher than the values of normal concrete.

Concrete with brick aggregate was found to have the values of surface absorption ranging from about the same to twice than for concrete with gravel aggregate. Chloride ion diffusion rates also varied from two to three times the amount for concrete with gravel.

Concrete with normal construction brick aggregates was observed to be highly frost susceptible whereas concrete with sandlime brick aggregate performed better and concrete with engineering brick aggregate performed in a similar manner to concrete with gravel aggregate.

In the sulphate resistance test, the reduction in dynamic modulus for concrete with gravel was rapid as compared to a gradual reduction for concrete with brick aggregates. High strength concretes with engineering brick aggregate developed satisfactory strengths up to $80N/mm^2$. Concrete with brick aggregates mixed with gravel showed reduced frost resistance, 37% reduction in static modulus and 23% reduction in dynamic modulus of elasticity as compared to concrete with gravel aggregate.

OBJECTIVES

The main objective of this research was to carry out a systematic and detailed study of the characteristics of coarse brick aggregates and performance of concrete with crushed brick coarse aggregates, including the following:

a. Investigate the crushing strength and absorption of different types of bricks used for crushing and obtaining coarse brick aggregates and to establish a relationship between crushing strength of bricks and compressive strength of concrete with crushed brick aggregates.

b. Investigate the relevant properties of coarse crushed brick aggregates obtained by crushing different types of bricks, including shape and texture, absorption, densities, strength, toughness, grading and presence of sulphates and chlorides in brick aggregates.

c. Investigate the design of mixes for concrete with crushed brick coarse aggregates and develop a design procedure.

d. Investigate the mechanical properties of brick aggregate concrete such as cube and cylinder compressive strengths, flexural and tensile strength, stress/strain behaviour, static and dynamic moduli of elasticity, coefficient of thermal expansion and ultrasonic pulse velocity and hence recommend the suitability of different types of crushed brick aggregates for use in concrete with different compressive strength ranges.

e. Investigate the time-dependent properties such as shrinkage and creep for concrete with crushed brick coarse aggregates and study the affects of different types of crushed brick aggregates in concrete as compared to gravel aggregates.

f. Investigate the permeability of concrete with different types of crushed brick coarse aggregates using surface absorption, capillary rise and chloride ion diffusion tests to study the affect of different types of brick aggregates in concrete on permeability and to compare it with permeability of concrete with gravel aggregate.

g. Investigate the frost resistance of concrete with different types of crushed brick coarse aggregates and its affects such as length change, weight change and change in modulus of elasticity thereby studying the varying affects of frost resistance in concretes with gravel aggregate and with different types of crushed brick coarse aggregates hence differentiating frost prone types of brick aggregates from frost resistant types.

h. Investigate the sulphate resistance of concrete with different types of crushed brick coarse aggregates and observe the affects of sulphate attack such as length change, weight change and change in modulus of elasticity thereby studying the variation in performance of concrete with different types of crushed brick coarse aggregates as compared to concrete with gravel aggregate when subjected to sulphate attack and identifying brick aggregates susceptible to sulphate attack.

j. Investigate the design of high strength concrete with brick aggregates and to study mechanical properties of brick aggregate high strength concrete such as cube and cylinder compressive strengths, flexural and tensile strength, stress/strain behaviour, static and dynamic moduli of elasticity, surface absorption and ultrasonic pulse velocity measurements hence recommend use of brick aggregates for high strength concrete, suggest a design method for high strength brick aggregate concrete and compare mechanical properties of high strength concrete with crushed brick coarse aggregates and with gravel aggregate.

k. Investigate the performance of concrete with brick aggregates partly mixed with natural aggregates. This investigation includes mechanical properties of concrete like cube and cylinder compressive strengths, flexural strength, stress/strain behaviour, static and dynamic moduli of elasticity and ultrasonic pulse velocity measurements. The frost resistance of such concrete will also be evaluated.

PART 1

REVIEW OF PREVIOUS WORK

This part presents a review of previous work on the properties of brick aggregates and concrete with brick aggregates where bricks were deliberately crushed for use in concrete. Very limited research has been carried out on a very small scale in this field in the recent past and exists in the form of five papers.
Past research has been restricted to aggregates from highly porous, low quality bricks with relative density of about 1.9. No attempts were made to investigate the use of crushed brick aggregates from a wider selection of bricks with higher strengths and lower absorption for use in concrete. Very few properties of brick aggregates and brick aggregate concrete have been investigated. Brick aggregates have been investigated for relative and bulk densities, absorption and strength whereas concrete with brick aggregate has been investigated for compressive, flexural and tensile strengths only. The static modulus of elasticity was investigated in two cases only.

CHAPTER 1

COARSE BRICK AGGREGATES AND COARSE BRICK AGGREGATE CONCRETE - REVIEW OF PREVIOUS WORK

1.1. GENERAL

Broken brick aggregate has been extensively used in India, Pakistan and Bangladesh for production of concrete and the performance of such concrete has been quite satisfactory. Almost 80% of concrete work in Bangladesh has broken brick as aggregate[3]. Broken brick aggregate concrete has been extensively used in foundation concrete for light buildings, walkways, lightweight reinforced concrete floors and reinforced concrete roof slabs of domestic buildings. In spite of being used extensively, there has been no systematic study of the physical and mechanical behaviour of brick aggregate concrete. In India, broken brick aggregate is obtained by crushing wasted/damaged bricks, in spite of the abundance of natural aggregates, since it brings overall economy[2] . In Pakistan, natural aggregates are available in abundance but still broken brick aggregate is used for concrete as the cost is about 30% lower than using natural aggregates. In Bangladesh, natural angular aggregates are scarce since over 70% of total land is made up of alluvial plains, however, smooth, rounded gravel is available, which does not give the bond strength required for structural concrete[3]. Good quality bricks are available in abundance in all these areas due to cheap labour and the presence of huge amounts of the raw materials required for the manufacture of bricks. Hence good bricks are available at very cheap rates. Breaking bricks manually is also very cheap due to low labour costs, hence the broken brick aggregate is obtained at a significantly lower price than natural aggregates. First class and overburnt bricks are normally used for breaking into aggregate. Table 1.1 gives properties of different classes of bricks found in Bangladesh.

BRICK TYPE	SOUNDNESS	COLOUR	COMPRESSIVE STRENGTH N/mm ^{2}	ABSORPTION %	DENSITY kg/m ^{3}
Picked Jhama	Good metallic sound when hit by hammer	Mauve to dark	27.6 to 41.4	3 to 10	1796 to 2287
First Class	Good metallic sound	Bright red	20.7 to 34.5	5 to 12	1633 to 2041
Second Class	Feeble metallic sound	Dull red	13.8 to 20.7	5 to 12	1470 to 1960
Third Class	Faint metallic sound	Dull red or yellow	6.9 to 13.8	5 to 12	1470 to 1960
Dry Pressed (Machine made bricks)	strong metallic sound	Bright red	31.05 to 62.1	5 to 10	2042 to 2205

Table 1.1: Properties of different classes of bricks in Bangladesh.

Broken bricks, overburnt bricks and damaged bricks are waste products obtained at brickworks and construction sites. Broken brick aggregates are also obtained by deliberately crushing bricks.

After the Second World War, some work was done on recycled waste brick aggregates concrete by Newman[9] in Great Britain where waste brick aggregates were obtained from demolished, unplastered shelters. Recently some work on recycled waste brick aggregate concrete has been done by Schulz[7] in West Germany and Hendriks[8] in Netherlands but the work mainly comprised of brick aggregates obtained from demolished masonry structures only. No work was done by them on crushed brick aggregate concrete where bricks were deliberately crushed for use as aggregates.

1.2. EXPERIMENTAL DETAILS

Akhtaruzzaman and Hasnat[2] studied the physical and mechanical properties of concrete such as compressive strength, tensile strength and elastic modulus. Six 150*300mm cylinders, three 150mm cubes and two 150*150*600mm beams were cast and cured for 28 days before testing. Well burnt clay bricks were broken into graded coarse aggregate of maximum 19mm size.

Similar tests were carried out by Khan and Choudhry[3].

1.3. DISCUSSION OF RESULTS

1.3.1. Properties of aggregates

Tables 1.2, 1.3 and 1.4 give the properties of brick aggregate observed by different researchers. Brick aggregates used by Akhtaruzzaman and Hasnat[2] for their investigations had average absorption of 10.7% and average crushing strength of bricks from which these aggregates were obtained was 36.7N/mm^2. Brick aggregates used by Khan and Choudhry[3] for their investigations had average absorption of 11.5%. Kumar, Roy and Sai[4] also carried out testing of brick aggregate concrete by testing a number of cubes, cylinders and beams. The brick aggregates used by

ENGINEERING PROPERTY	BRICK AGGREGATE PICKED JHAMA	BRICK AGGREGATE FIRST CLASS	CRUSHED STONE	ROUNDED GRAVEL
Relative density	1.8-2.2	1.4-1.8	2.6-2.9	2.6-2.7
Compacted density (kg/m^3)	1143 to 1388	1143 to 1388	1388 to 1796	1388 to 1796
Absorption(%)	10-15	10-20	0.5-2	1-3
Density-concrete (kg/m^3)	1796 to 2287	1715 to 2205	2368 to 2532	2287 to 2450

Table 1.2: Properties of aggregates reported by Khan and Choudhry in 1978 from Bangladesh.

ENGINEERING PROPERTY	BRICK AGGREGATE	CRUSHED STONE	ROUNDED GRAVEL
Relative density	1.4-1.8	2.6-2.9	2.6-2.7
Compacted density(kg/m^3)	1121 to 1362	1362 to 1762	1362 to 1762
Absorption(%)	10-20	0.5-2	1-3
Density-concrete(kg/m^3)	1683 to 2163	2324 to 2484	2243 to 2400

Table 1.3: Properties of aggregates reported by Swamy.

ENGINEERING PROPERTY	BRICK AGGREGATE
Relative density	1.93
Compacted density(kg/m^3)	1038
Loose density(kg/m^3)	972
Absorption(%)	11.2

Table 1.4: Properties of aggregates reported by Akhtaruzzaman in 1983 from Saudi Arabia.

Kumar, Roy and Sai[4] had average absorption of 12.77% and average compressive strength of bricks from which these aggregates were obtained was $17.7 N/mm^2$.

The values given in the Tables 1.2 to 1.4 suggest similarities in relative and bulk densities, absorption and densities of concrete made from these aggregates. The bricks used by all the above researchers were similar clay bricks with high absorption and low relative density. No attempts were made at testing brick aggregates from a variety of different types of bricks used in construction, with higher crushing strengths and low absorptions.

1.3.1.1. Shape and Texture

Brick aggregate is angular in shape, with well defined edges and honeycombed in surface texture. Angular aggregates have high ratio of surface area to volume (specific surface) and hence have reduced workability. Angular shaped, rough surfaced aggregates do not pack easily. Rougher surface and greater surface area result in better bonding and interlocking of the aggregate hence higher compressive strengths may be obtained from brick aggregate concrete as compared to concrete with gravel aggregate(3).

1.3.1.2. Porosity and Absorption

Brick aggregate is highly porous and has high absorption. If the aggregate in a mix is not fully saturated it absorbs water from the mix, thereby reducing the workability considerably in the first ten to fifteen minutes(3). Khan and Choudhry(3) reported 11.5% absorption by the brick aggregate, whilst 11.2% absorption was observed by Akhtaruzzaman(2) as compared to 1 to 3% for round gravel.

1.3.1.3. Density

Unit weight of coarse brick aggregate, in dry loose state, was observed to be 953kg/m^3 and in dry compacted state, it was 1017kg/m^3 [2]. Khan and Choudhry[3] observed that density of coarse brick aggregate, in compacted form, varied from 1120 to 1360kg/m^3 as compared to 2287 to 2450kg/m^3 for concrete with gravel aggregate.

1.3.1.4. Specific gravity

Khan and Choudhry[3] observed that the specific gravity of brick aggregate varied from 1.4 to 2, according to the quality of bricks used. The bulk specific gravity (SSD) was reported to be 1.93 by Akhtaruzzaman[2] as compared to 2.6 to 2.7 for round gravel.

1.3.1.5. Strength and hardness

Khan[3] reported 28 to 50% Los Angeles abrasion value for brick aggregate, depending upon the quality of bricks used. Good quality brick aggregate gave abrasion values from 28 to 40% and aggregate from slightly inferior quality bricks gave values from 30 to 50% as compared to 25 to 30% for gravel.

1.3.2. Concrete with brick aggregates

Design of concrete mixes by the method given by Road note 4[1] of the Department of Environment, Great Britain considers properties and surface characteristics of aggregates and has been used for design of mixes by Khan and Choudhry[3], and Akhtaruzzaman[2]. Kumar and Roy[4] however adopted Indian Standards for their research.

1.3.2.1. Properties of fresh concrete

Workability for brick aggregate concrete is considerably lower in comparison with normal concrete, due to the angular shape and honeycombed, rough texture of the brick aggregates(4). However, workability can be improved by the use of plasticisers and other workability aids. Very low workabilities have been reported for concrete with brick aggregates. On compaction, brick aggregate is likely to be partially crushed thereby requiring more water to wet the surfaces, hence lower workability(4).

Fully compacted wet density of concrete with brick aggregates has been reported to vary from 1820 to 1920kg/m^3 by Akhtaruzzaman(2) and 2075 to 2120kg/m^3 reported by Khan and Choudhry(3). Tables 1.5 and 1.6 give the mix proportions used by different researchers.

TEST SERIES	CHARACTERISTIC STRENGTH N/mm^2	W/C RATIO	*AGG/C RATIO	PER CUBIC METRE CONCRETE CEMENT kg	SAND kg	AGGREGATE kg
A	34.5	0.54	4.17	335	522	874
B	27.6	0.61	4.89	289	528	885
C	20.7	0.70	5.60	257	539	902
D	13.8	0.88	7.06	203	535	898

* AGG/C is aggregate/cement ratio

Properties of aggregates used.	
Maximum aggregate size	19mm
Average strength of bricks	36.7N/mm^2
Average absorption - bricks	10.7%

Table 1.5: Mix proportions reported by Akhtaruzzaman in 1983 from Saudi Arabia.

Slightly lower w/c ratio were used by Akhtaruzzaman(2) due to relatively higher crushing strength of brick aggregates used whereas an average of about 38% higher aggregate/cement ratio and 17% higher quantity of cement

CHARACTERISTIC STRENGTH N/mm^2	W/C RATIO	AGGREGATE/ CEMENT RATIO	PER CUBIC METRE CONCRETE CEMENT kg	SAND kg	AGGREGATE kg	WATER kg
20.7	0.796	7.90	215	597	1105	171
27.6	0.670	6.70	250	586	1092	167
34.5	0.575	5.75	288	578	1073	165
41.4	0.480	4.60	348	562	1041	167

Maximum aggregate size	20mm	Properties of aggregates used.
Grading of aggregate	Curve 2	
Absorption-brick aggregate	11.5%	

Table 1.6: Mix proportions reported by Khan and Choudhry in 1978 from Bangladesh.

was used as compared to mixes by Khan and Choudhry(3). Akhtaruzzaman(2) used 37% of fines as compared to 35% by Khan and Choudhry(3). Grading of coarse brick aggregates used by Akhtaruzzaman(2) shows that 90% of brick aggregates were between the size of 10mm and 19mm and 10% between 10mm and 5mm whereas Khan and Choudhry(3) mixed different size of aggregates according to a grading curve specified in the old version of Road Note 4 method of mix design.

1.3.3. Properties of hardened concrete

Tables 1.7 and 1.8 give the properties observed for concrete with brick aggregates.

CHARAC-TERISTIC STR N/mm^2	CYLINDER STR fc	CUBE STR fb	RATIO fc/fb	TENSILE STR fct	RATIO fct/fc	FLEXURAL STR fr	RATIO fr/fc
34.5	38.00	42.30	90.1	4.02	10.6	4.36	11.5
27.6	30.26	35.10	86.2	3.47	11.5		
20.7	25.00	31.47	79.5	3.14	12.6	3.33	13.3
13.8	16.42	22.12	74.3	2.29	14.0	2.79	17.1

str - strength

Table 1.7: Properties of concrete with brick aggregates reported by Akhtaruzzaman in 1983 from Saudi Arabia.

Brick aggregate concrete can be classified as medium weight concrete since its properties lie between normal weight and lightweight concrete[2]. Unit weight of brick aggregate concrete is about 17% lower than normal weight concrete[4].

CHARACTERISTIC STR N/mm^2	SLUMP USED	SLUMP OBSERVED	CUBE STR N/mm^2	TENSILE STR N/mm^2	FLEXURAL STR N/mm^2	MODULUS OF ELASTICITY N/mm^2
20.7	low	very low (1/2 of design slump)	27.3	2.28	4.33	11109
27.6	low	very low (1/4 of design value)	31.3	2.44	4.02	13800
34.5	low	very low (no slump)	40.3	2.57	5.00	not tested
41.4	low	very low (no slump)	43.2	3.28	4.69	16422

Table 1.8: Properties of concrete with brick aggregates reported by Khan and Choudhry in 1978 from Bangladesh.

Akhtaruzzaman[2] reported densities of brick aggregate concrete to be between 2000 to 2080kg/m^3. The lower density of the brick aggregate concrete is due to lower density and relatively high porosity of the brick aggregate. High porosity of brick aggregates makes brick aggregate concrete less resistant to penetration by moisture.

1.3.3.1. Compressive strength

Tables 1.7 and 1.8 give the compressive strengths of brick aggregate concrete observed in different tests. Akhtaruzzaman[2,6] observed that compressive strength of brick aggregate concrete varied with water/cement ratio just as compressive strength varies with w/c ratio for normal aggregate concrete. For mixes similar to normal concretes, about 10% higher compressive strengths were observed for brick aggregate concrete. A similar increase in strength has been reported by Khan and Choudhry[3] where specimen of brick aggregate concrete were designed from design strength curves of Road Note 4.

For higher concrete strengths a higher ratio of cylinder to cube strength were observed. Akhtaruzzaman[2] reported that the average cylinder strength varied from 71 to 93% of average cube strength whereas in other cases the ratio of cylinder to cube strength was reported to vary from 55 to 60%.

Akhtaruzzaman[2] suggested following equation to determine the ratio of cylinder and cube strengths of brick aggregate concrete:

$$f_{cy}/f_b = 0.44 \log_{10} (f_{cy}/50)$$

where,

f_{cy} is cylinder strength,

f_b is cube strength.

1.3.3.2. Tensile strength

The split cylinder tensile strength was observed to be about 12% greater than that of normal weight concrete[2,6]. The split cylinder tensile strength reported by Khan and Choudhry[3] for brick aggregate concrete is similar to that for normal concrete.

1.3.3.3. Flexural strength

Flexural strength of brick aggregate concrete is reported to be almost 20% greater than normal concrete[3]. In another case, the flexural strength of brick aggregate concrete was observed to be about 10% greater than for normal concrete[2]. Kumar[4] reported about 5% higher flexural strength for brick aggregate concrete.

1.3.3.4. Modulus of Elasticity

Akhtaruzzaman[2,6] reported that the modulus of elasticity of brick aggregate concrete is about 30% lower than for normal concrete. Khan and Choudhry[3] reported a reduction of almost 50% in the elastic modulus of brick aggregate concrete compared to normal concrete.

1.4. CONCLUSIONS

Brick aggregate is angular in shape and honeycombed in texture. Brick aggregates are highly porous with an average water absorption of about 12%. Prewetting of aggregates is neccessary to avoid loss of workability soon after mixing[3]. Density of brick aggregates is lower compared to natural aggregates and varies from 1000 to 1300kg/m^3. Relative density of brick aggregate varies between 1.4 to 2. Aggregate Crushing Value is also high and varies between 28 to 50%, depending on the quality of bricks used.

Brick aggregate concrete has appreciably lower workability compared to normal concrete due to high porosity and angular shape of the brick aggregates. The density of brick aggregate concrete lies between the density of normal weight and lightweight concrete.

Compressive strength of brick aggregate concrete is similar and in few cases better than normal concrete, where coarse brick aggregates and similar workability and mix proportions were used. The split cylinder tensile and flexural strengths were observed to be about 10% greater than those of normal weight concrete.

On the basis of limited testing, modulus of elasticity of brick aggregate concrete is reported to be about 30 to 50% lower compared to normal concrete whereas tensile and flexural strengths are 10% higher compared with normal concrete.

The limited research work done on concrete with brick aggregate is restricted to limiting tests on crushed clay brick aggregates with high absorption and low strength. In all cases of previous research, almost similar qualities of low strength and high absorption clay bricks have been crushed and used in similar range of low compressive strengths of concrete. Investigations have been restricted to compressive, flexural and tensile strengths of concrete with brick aggregates. Static modulus of elasticity has only been investigated by two researchers.

Apart from the small amount of work carried out in investigating a limited range of properties of concrete with brick aggregates, no attempts have been made to investigate different types of bricks with a variety of crushing strengths and absorptions available for use in concrete. The investigations have been carried out in a low range of compressive strengths and no attempts were made to investigate a wider range of compressive strengths of concrete with brick aggregates. No guidelines have been recommended on design of concrete with brick aggregates and no information on the durability of such concrete exists. The properties like moduli of elasticity, shrinkage, creep, frost resistance, sulphate resistance, surface water penetration, permeability and concentration of salts in brick aggregate concrete have scarcely been investigated and extensive further testing is needed before a conclusion can be made on the performance of brick aggregate concrete.

1.5. SUMMARY

1.5.1. Brick aggregates

Brick aggregates are angular in shape and honeycombed in texture. They have very high porosity and absorption as compared to normal aggregates. Brick aggregates are lighter in weight and have lower relative densities than normal aggregates. Brick aggregates have lower crushing strength and abrasion values as compared to normal aggregates.

1.5.2. Fresh brick aggregate concrete

Brick aggregate concrete has significantly lower workability due to the shape and texture of brick aggregates.

1.5.3. Hardened brick aggregate concrete

Brick aggregate concrete is about 17 to 20% lighter than normal aggregate concrete and develops about 10% higher compressive strength than normal concrete where only coarse brick aggregates are used and comparison is made on the basis of similar w/c ratios.

The ratio of cylinder strength to cube strength for brick aggregate concrete is slightly lower as compared to normal concrete. Brick aggregate concrete has about 10% higher split cylinder tensile strength and flexural strength than normal concrete. Modulus of elasticity for brick aggregate concrete is about 33 to 50% lower than normal concrete. Properties like Dynamic modulus of elasticity, stress/strain behaviour and ultrasonic pulse velocity measurements have not yet been investigated. Lot of work has yet to be done to assess these properties of brick aggregate concrete.

1.5.4. Time dependent properties of brick aggregate concrete

There has been no investigation at all on shrinkage and creep properties of brick aggregate concrete. A comprehensive investigation is required to investigate shrinkage and creep properties of concrete with crushed brick aggregates obtained from a variety of different types of bricks available as well as for different crushing strengths available in each type of brick.

1.5.5. Durability of brick aggregate concrete

No detailed study on durability of brick aggregate concrete has been carried out yet. Properties like permeability, frost resistance and sulphate resistance have yet to be investigated. The durability of concrete with crushed brick aggregates needs extensive investigations before a decision could be made on the performance of concrete with brick aggregates.

PART 2

EXPERIMENTAL WORK

MECHANICAL PROPERTIES OF CRUSHED BRICK COARSE AGGREGATES AND CONCRETE WITH CRUSHED BRICK COARSE AGGREGATES.

This part comprises of the work carried out in investigating the mechanical and time dependent properties of crushed brick aggregates and crushed brick aggregate concrete. The investigations are divided in four chapters.
Chapter 2 gives details of investigations carried out to assess different types of crushed brick coarse aggregates for use in concrete. Similar investigations were carried out for gravel and the values obtained for crushed brick aggregates were compared with the values obtained for gravel. The investigations on crushed brick aggregates comprise all the relevant tests necessary for evaluating aggregates for use in concrete. Later, different types of crushed brick aggregates are evaluated for their suitability for use in concrete.
Chapter 3 gives the mix design of concrete with gravel aggregate and concrete with different types of crushed brick aggregates with different workabilities for the selected w/c ratios. The performance of different mixes was evaluated and a mix design procedure for concrete with crushed brick aggregates is suggested.
Chapter 4 gives details of investigations made on concrete with different types of crushed brick aggregates along with control specimens made from concrete with gravel aggregates. The mechanical properties of concrete with different types of crushed brick aggregates were assessed and a comparison was made with the performance of similar specimens of control mix.
Chapter 5 covers investigations on the time dependent properties of concrete with different types of crushed brick aggregates. Shrinkage and creep properties of concrete with different types of brick aggregates have been investigated and values compared with similar concrete with gravel aggregate. Reasons for variations in behaviour of different concretes have also been considered.
Three specimens from three different batches were tested to assess each property hence the values given for each property represent an average of a total of nine specimens.

CHAPTER 2

CRUSHED BRICK COARSE AGGREGATES

This chapter gives the details of investigations carried out on selected bricks and brick aggregates obtained from them. The selected bricks, which were later crushed to obtain brick aggregates, were tested for crushing strength, absorption and density. After crushing the bricks manually and removing fines and oversized particles, relevant aggregate tests were carried out such as absorption, relative and bulk densities, strength tests based on 10% fines value, toughness tests based on impact value, grading and amount of sulphate and chlorides present. The values obtained from experimental investigations were compared with similar values for natural aggregates and also with values specified in British Standards.

2.1. GENERAL

Three types of bricks most commonly available were selected for testing properties of brick aggregate concrete. They were the weakest normal construction brick(LBC), sandlime brick and engineering 'B' bricks. Sandlime bricks used are the weakest out of all three types selected with lowest crushing strength. The bricks were crushed manually by the help of a mason's hammer to a maximum size of 37.5mm.

Tests on selected bricks were carried out in the laboratory to assess the absorption, density and crushing strength of these bricks using the standard procedures given in BS 3921: 1985 and BS 187: 1978. Table 2.1 gives the properties of bricks evaluated in the laboratory tests.

S/NO.	TYPE OF BRICK	CRUSHING STR	ABSORPTION	DENSITY
1.	London brick	19.54N/mm ^{2}	23.245%	1292.8kg/m ^{3}
2.	Sandlime brick	15.39N/mm ^{2}	14.808%	1721.5kg/m ^{3}
3.	Engineering brick	40.25N/mm ^{2}	6.395%	1872.2kg/m ^{3}

Table 2.1: Properties of bricks.

Sandlime bricks were observed to have an average crushing strength of 15N/mm^2. Average absorption of sandlime bricks was observed to be 15% and the density about 1700kg/m^3. Normal construction bricks (LBC) have an average crushing strength of 19.5N/mm^2 with absorption of about 23% and density around 1300kg/m^3. Engineering 'B' bricks used have an average crushing strength of 40N/mm^2, average absorption of about 6% and density around 1875kg/m^3.

The bricks used in India, Pakistan and Bangladesh for crushing and making brick aggregate concrete are overburnt and well burnt first class bricks with average crushing strength between 20.7 and 41.4N/mm^2, average absorption of about 10% and density between 1800 to 2300kg/m^3. Hence the crushing strength of these bricks lies between the crushing strength of normal construction bricks and engineering 'B' bricks whereas the absorption is about 4% higher and density is almost similar to slightly higher as compared with engineering 'B' bricks.

2.2. PROPERTIES OF CRUSHED BRICK COARSE AGGREGATES

Table 2.2 gives the properties of the brick aggregates used. Procedures given in BS 812: 1975 have been followed in evaluating the properties of brick aggregates.

On comparing the absorption values of crushed brick aggregates from Table 2.2 with absorption values of bricks given in Table 2.1 it is observed that absorption reduces by about 3.6% for normal construction brick aggregates, 5.3% for sandlime brick aggregates and 3.6% for engineering

TYPE	RELATIVE DENSITY SSD	BULK DENSITY kg/m³ uncompacted	compacted	IMPACT VALUE	10% FINES VALUE kN	ABSORPTION %
London brick	1.8592	839.720	900.710	46.065	59.85	19.6
Sandlime brick	2.3325	1011.35	1093.62	45.695	40.76	9.55
Engineering brick	2.3164	1126.24	1263.12	31.610	144.3	2.76
Gravel	2.4900	1560.99	1738.30	22.960	391.0	1.05

Table 2.2: Properties of brick aggregates.

brick aggregates as compared to absorption of bricks. This reduction in absorption is due to opening up of a number of pores in the crushing process thereby reducing absorption.

2.2.1. Shape and texture

Brick aggregates have angular shape with well defined edges and honeycombed texture. Brick aggregates have high surface area to volume ratio (specific surface). Due to their angular shape and honeycombed texture, brick aggregates require more compaction effort to pack but thereafter better bonding and interlocking results. Higher compressive strengths are hence possible, depending upon the crushing strength of the bricks from which the aggregates have been obtained. The angular shape and rough texture of brick aggregates results in less workable mixes.

2.2.2. Porosity and absorption

Brick aggregates have higher porosity and absorption as compared to normal aggregates. Aggregates obtained by crushing normal construction bricks(LBC) have the highest absorption of around 20%. Aggregates obtained by crushing sandlime bricks have an absorption of around 9.5% and aggregates obtained from engineering bricks have absorption of about 3%. Thames Valley gravel used for control mix has absorption of 1%.

Where brick aggregates are not used in saturated surface dry condition in a concrete mix, they rapidly absorb water in first ten to fifteen minutes from the mix, thereby reducing the water/cement ratio and the workability.

2.2.3. Density

Uncompacted bulk density of brick aggregate varies from 800 to 1125kg/m^3 and compacted bulk density varies from 900 to 1250kg/m^3 depending upon the type of bricks from which the aggregate is obtained. Lowest bulk density has been observed to be of aggregates obtained by crushing normal construction bricks(LBC) and highest being of aggregates obtained from engineering bricks. Bulk density of Thames Valley gravel used for control mix has been observed to be 1560 and 1738kg/m^3 on uncompacted and compacted basis respectively.

Relative density on SSD basis of brick aggregates varies from 1.85 to 2.3, lowest being for normal construction brick aggregates and highest for engineering brick aggregates. Relative density of Thames Valley gravel on SSD basis has been observed to be 2.49.

2.2.4. Strength

10% fines value for sandlime brick aggregate is 41kN, 60kN for normal construction brick(LBC) aggregate and 144kN for engineering brick aggregates as compared to 391kN for Thames Valley gravel. BS 882: 1983 specifies a minimum value of 50kN for aggregates for normal concrete, 100kN for aggregates for concrete pavement wearing services and 150kN for aggregates for heavy duty floor finishes hence sandlime brick aggregate with a value of 41kN does not satisfy the lowest requirements of BS 882 for normal concrete, normal construction brick(LBC) aggregate with 10% fines value of 60kN satisfies the BS requirement for normal concrete only whereas engineering brick aggregate with 10% fines value of 144kN satisfies the BS requirement for normal concrete as well as concrete for pavement wearing services. 10% fines value for Thames Valley gravel of 391kN satisfies the requirements of BS 882 for all grades of concrete.

2.2.5. Toughness

Aggregate impact test on brick aggregates yielded values of 45% for sandlime brick aggregates, 46% for normal construction brick(LBC) aggregates and 31% for engineering brick aggregates as compared to 23% for Thames Valley gravel.

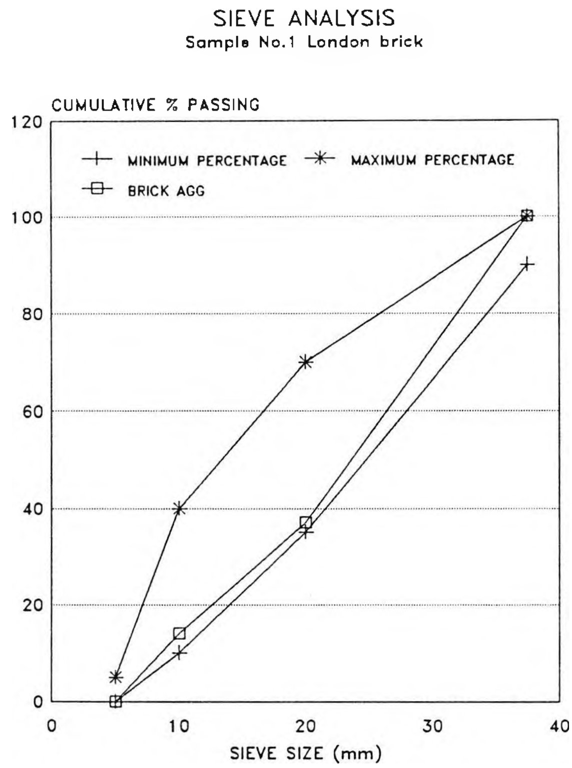
BS 882: 1983 limits the maximum impact values to 25% for aggregates for heavy duty floor finishes, 30% for aggregates for concrete pavement wearing surfaces and 45% for aggregates for other concretes. Hence aggregates obtained from sandlime brick and normal construction brick(LBC) just satisfy marginally the requirements of BS 882 for normal concrete whereas aggregates obtained by crushing engineering bricks satisfy the requirements of BS 882 for normal concrete and just marginally satisfy the requirement for aggregates for concrete pavement wearing surfaces. Thames Valley gravel with impact value of 23% satisfies all the requirements of BS 882: 1983.

2.2.6. Grading

After crushing the bricks manually, the aggregates were sieved so as to remove the aggregate sizes over 37.5mm and less than 5mm. Aggregates over 37.5mm size were recrushed to reduce them to lower sizes and resieved. Fines less than 5mm size were removed. Manual crushing of normal construction bricks(LBC) generated about 13% fines(<5mm). About 25% fines were generated by manual crushing of sandlime bricks and about 8% fines from crushing of engineering bricks. Hence after crushing and sieving, 87%, 75% and 92% of the crushed material from normal construction bricks, sandlime brick and engineering brick aggregates, respectively, is the useful part which is available for concreting. Crushing of bricks in mechanical crushers is likely to generate a larger amount of fines thereby decreasing the useful percentage of aggregates after crushing, although the crushing process could be accelerated. Generating larger amount of fines in mechanical crushing is due to the fact that whilst crushing bricks manually the strokes can be given on bricks in selected planes which generate less fines and better shaped aggregates whereas it is not possible in mechanical crushing. It was observed whilst crushing manually that crushing bricks in a horizontal position generated lesser fines as compared to crushing them in vertical position which generates more flakier particles with larger amount of fines.

Selecting larger maximum size of the aggregates, for aggregate sizes less than 40mm, is advantageous since the larger the size of particle the smaller is the surface area to be wetted per unit mass by free water, hence lowering the free water requirement of the mix for specified workability. Selection of largest size of aggregate of 37.5mm achieves this benefit.

Samples for sieve analysis were sieved into sizes between 37.5mm to 20mm, 20mm to 10mm, 10mm to 5mm. Figures 2.1 and 2.2 show the grading curves of the aggregate samples to be used for brick aggregate concrete. Figure 2.3 gives the grading of sand used. All the samples remained within the limits laid by BS 882: 1983. Due to the lower relative densities and larger volumes of the brick aggregates, the limits on weights which can be loaded on different sieves (vide BS 1881: Part 103.1) are not practical. In the case of normal construction brick(LBC) aggregate, 5 to 6kg only could be loaded, for efficient sieving, on 37.5mm size 300mm diameter sieve against a minimum of 15kg specified in the BS. An average of 63% of aggregates were observed to be between 37.5mm to 20mm and hence about 4kg of aggregates were retained on 20mm sieve 300mm diameter size whereas BS



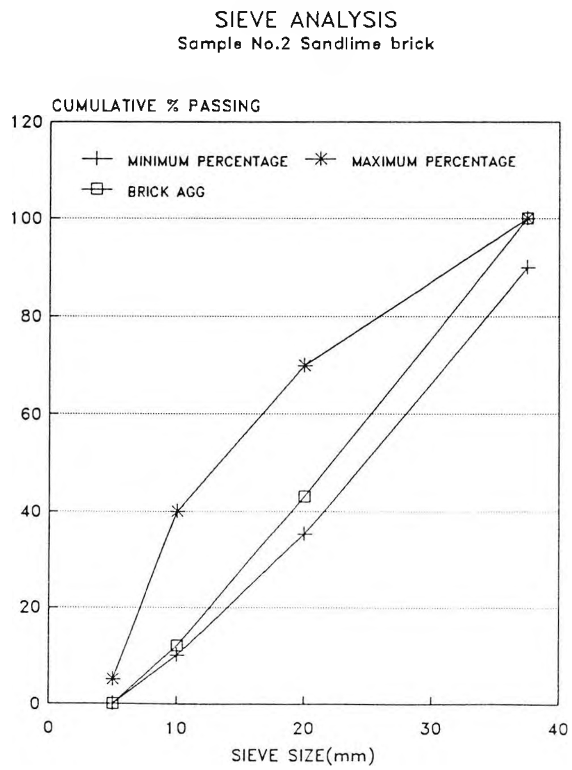
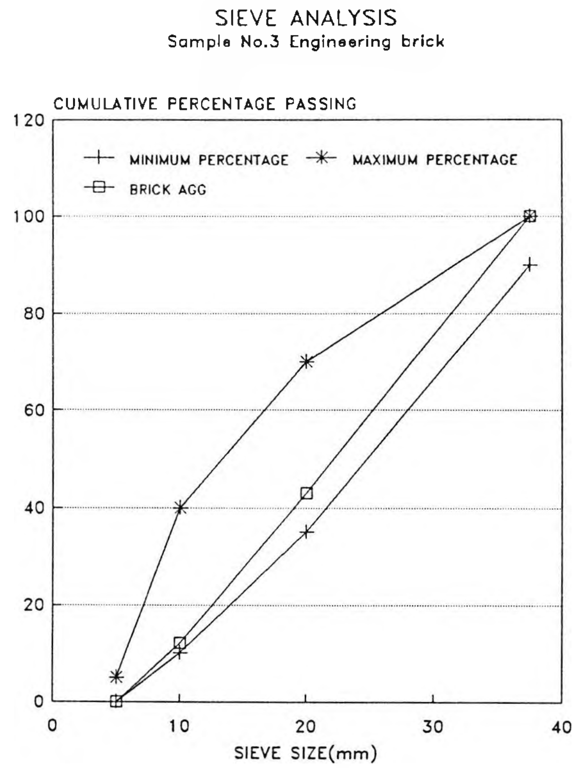


Figure 2.1: Sieve analysis - Sample No.1 London brick
Sieve analysis - Sample No.2 Sandlime brick



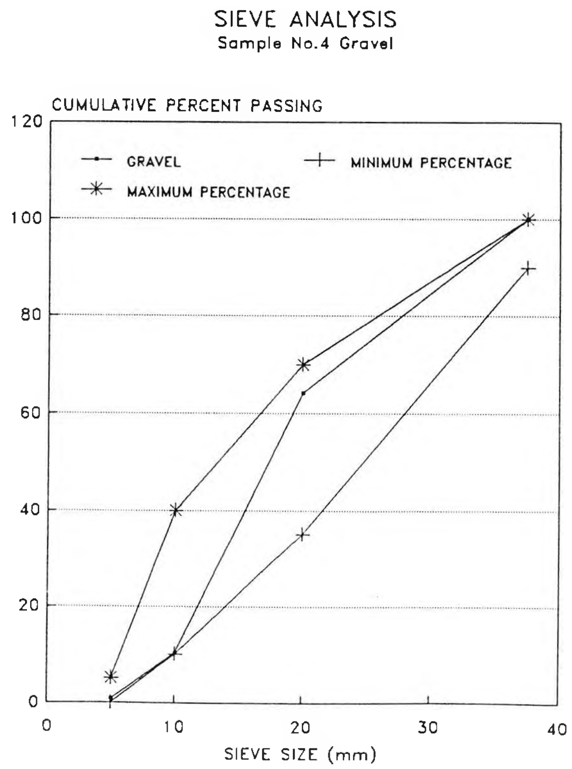


Figure 2.2: Sieve analysis - Sample No.3 Engineering brick
Sieve analysis - Sample No.4 Gravel

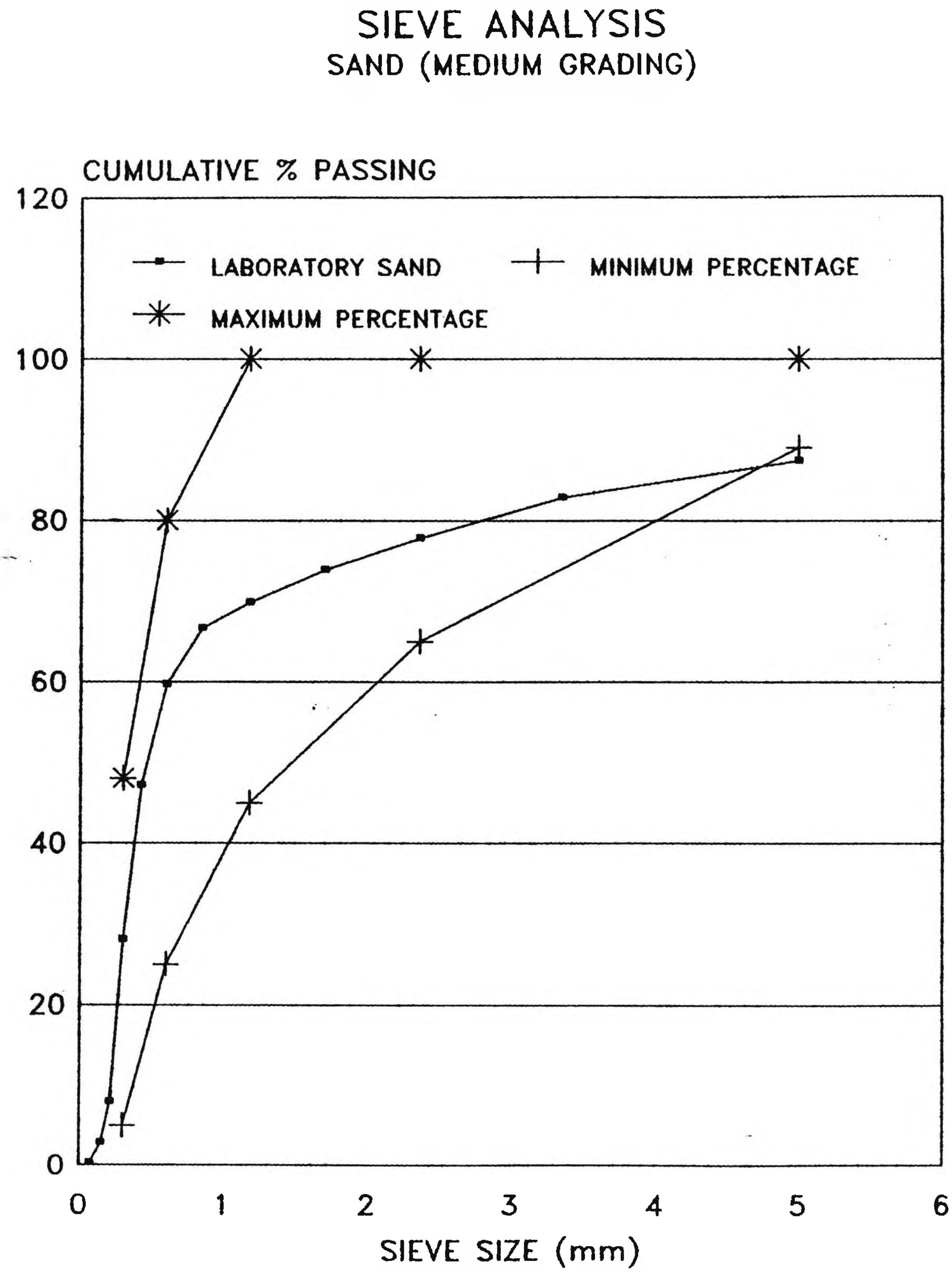


Figure 2.3: Sieve analysis - Sand (Medium grading)

permits a maximum weight of 2.5kg to be retained on 20mm sieve. Hence only about 3.5kg of normal construction brick aggregate can be loaded on the top 37.5mm 300mm diameter sieve according to BS. Similarly about 65% of aggregates from sandlime brick are in the range of 37.5mm to 20mm and are retained on 20mm sieve resulting into the overloading of the sieve. Hence to avoid any overloading of the sieves, smaller amounts are to be loaded on the sieves resulting in longer sieving time and greater effort.

2.2.7. Sulphate and chloride content.

Since bricks are manufactured from natural materials like clays, they are likely to contain some quantities of sulphates and chlorides. The brick aggregates used were analysed for sulphates and chlorides. The solutions of 1:1 concentration were prepared and analysed by the method of Ion chromatograhy to obtain accurate results. Table 2.3 gives the amounts of sulphates and chlorides present in bricks.

SAMPLE	CHLORIDES %	SULPHATES %
London brick	0.2375	0.2755
Sandlime brick	0.0218	0.0096
Engineering B brick	0.0193	0.0825

Table 2.3. Sulphate and chloride contents of brick.

Maximum chloride content specified in BS 882: 1983 is 0.06% for reinforced concrete with cements conforming to BS 12, 0.04% for concrete with sulphate resisting and supersulphated cements and 0.02% for prestressed concrete and steam-cured structural concrete. Hence aggregates from normal construction brick exceed limits laid down by BS 882 whereas aggregates from sandlime brick and engineering brick are well within limits.

BS 882: 1983 does not specify the sulphate content of aggregates. BS 8110: Part 1: 1985 specifies a maximum amount of sulphates in concrete of 4% SO_3 by mass of cement in the mix. This percentage does not apply to mixes with supersulphated cement. German standard DIN 1048 specifies a maximum of 1% of sulphates in aggregates.

2.3. CONCLUSIONS

Brick aggregates have angular shape and honeycombed texture. Although brick aggregates require more compaction effort to pack due to their shape and texture, they result in better bonding and interlocking and hence higher compressive strengths are possible. They are highly porous with absorption up to a maximum of 20% hence they should be used in saturated surface dry state preferably. The density of brick aggregates varies from 839 to 1125kg/m^3 as compared to 1550kg/m^3 for gravel. Strength of brick aggregates based on 10% fines value, varies from 41 to 144kN as compared to 391kN for gravel. According to BS 882: 1983, aggregates from sandlime bricks have a 10% fines value of 41kN which is less than 50kN hence do not qualify for use in normal concretes. Aggregates from normal construction bricks(LBC) with 10% fines value of 59.85kN qualify for use in normal concrete only being higher than 50kN, whereas aggregates from engineering bricks with 10% fines value of 144.3kN qualifies for normal concrete and concrete for pavement wearing surfaces being greater than 100kN but does not qualify for concrete for heavy duty floors for which a minimum 10% fines value of 150kN is required. However, in practice, it has been observed in this experimental investigation that aggregates obtained from sandlime bricks and normal construction bricks (LBC) can be satisfactorily used for concrete up to $35N/mm^2$ compressive strength despite the fact that sandlime brick aggregates do not satisfy the requirements of BS 882: 1983. Flexural strength, tensile splitting strength and static modulus of elasticity were also observed to be similar for concrete with normal construction brick aggregate and sandlime brick aggregate. Hence it suggests that the strength of bricks from which the aggregates are obtained after crushing could be specified as an alternate to 10% fines value in case of concrete with crushed brick aggregates.

As regards toughness, brick aggregates from normal construction bricks(LBC) and sandlime bricks qualify for normal concrete with impact values of 45% and 46%, respectively, since BS 882: 1983 specifies a maximum impact value of 45% for normal concrete. Aggregates from engineering bricks lie at the margin to qualify for concrete for pavement wearing surfaces in addition to normal concrete with impact value of 31% whereas BS 882: 1983 specifies a maximum limit of 30%. None of the brick aggregates qualify for aggregates for heavy duty floor finishes with a maximum impact value of 25%. After crushing and sieving, 87, 75 and 92% of the crushed material from normal construction bricks(LBC), sandlime bricks and engineering bricks, respectively, can ultimately be used as aggregate for concrete.

CHAPTER 3

MIX DESIGN

This chapter deals with design of economic mixes for concrete with gravel aggregate and also concrete with different types of crushed brick aggregates for different workabilities and for selected w/c ratios. The w/c ratios were selected to remain constant for different mixes of selected compressive strengths so as to keep the paste characteristics constant thereby facilitating the study on performance of concrete in which gravel aggregates were merely replaced with different types of crushed brick aggregates. Characteristics of fresh concrete like fresh density, slump, bleeding and segregation were observed and compared with normal concrete along with investigating the possible reasons for variation in behaviour of mixes with different types of crushed brick aggregates. Later, a mix design method for concrete with crushed brick aggregates is suggested.

3.1. GENERAL

Five strengths of concrete were selected for experimental investigation and mixes of three different workabilities were designed for each strength. The five characteristic strengths selected were 20.7, 27.6, 35, 50 and 65N/mm^2 to cover a wide range of usual compressive strengths in practice. The three workabilities considered were low with a slump of 10 to 30mm, medium, with slump of 30 to 60mm and high with slump of 60 to 180mm. Mixes with slump value from 10 to 30mm were observed to be mostly unworkable whereas mixes with slump values from 60 to 180mm tend to become uneconomical, hence medium workability mixes with slump values from 30 to 60mm were used in the experimental investigations. The mix design was based on the method given in Design of Normal Concrete Mixes specified by the Department of Environment, United Kingdom. After designing concrete with gravel aggregate for five selected compressive strengths for three different workabilities, mixes for concrete with three types of selected crushed brick coarse aggregates were designed with similar w/c ratios. The w/c ratio was kept constant so that there was no variation in the paste characteristics and merely aggregates were changed from gravel to different types of crushed brick coarse aggregates. Maintaining a constant w/c ratio facilitated comparative study, especially on durability of different concretes due to change of aggregates only whilst all other aspects were mostly kept constant. After designing the mixes for concrete with gravel for selected compressive strengths, the mixes were designated thereafter by the type of aggregate and the w/c ratio. For example, concrete mix with gravel aggregate for compressive strength of 20.7N/mm^2 and w/c ratio of 0.63 was designated as GC/63 where GC represents gravel concrete and 63 represents w/c ratio of 0.63. Similarly LBC represents crushed London brick coarse aggregate concrete, SBC represents crushed sandlime brick coarse aggregate concrete and EBC represents crushed engineering brick coarse aggregate concrete. Table 3.2 gives the quantities required for different strengths/workabilities as designed.

To compare the quantities of cement, water, sand and aggregate, mixes were designed with maximum aggregate size of 20mm and 37.5mm. Table 3.1 gives the quantities required for maximum aggregate size of 20mm and Table 3.2 gives the quantities required for maximum aggregate size of 37.5mm. The quantities of cement and water are lower in Table 3.2 as compared to those in Table 3.1 since the larger the size of particle the smaller is the surface area to be wetted per unit mass, hence lowering the water requirement of the mix for specified workability. Hence use of larger size of aggregate i.e. 37.5mm is economical in terms of quantities of cement.

MIX	W/C RATIO	CEMENT kg	WATER kg	SAND kg	AGGREGATE kg	SLUMP
Sample 1:	**London brick**					
LBC/63	0.63	335	210	510	995	30-60mm
LBC/56	0.56	375	210	485	980	30-60mm
LBC/50	0.50	420	210	450	970	30-60mm
LBC/385	0.385	545	210	335	785	30-60mm
LBC/296	0.296	760	225	345	720	60-180mm
Sample 2:	**Sandlime brick**					
SBC/63	0.63	335	210	570	1110	30-60mm
SBC/56	0.56	375	210	540	1100	30-60mm
SBC/50	0.50	420	210	500	1095	30-60mm
SBC/385	0.385	545	210	435	1035	30-60mm
SBC/296	0.296	760	225	400	840	60-180mm
Sample 3:	**Engineering brick**					
EBC/63	0.63	335	210	560	1095	30-60mm
EBC/56	0.56	375	210	535	1080	30-60mm
EBC/50	0.50	420	210	495	1075	30-60mm
EBC/385	0.385	545	210	425	1020	30-60mm
EBC/296	0.296	760	225	395	820	60-180mm
Sample 4:	**Gravel**					
GC/63	0.63	285	180	630	1230	30-60mm
GC/56	0.56	320	180	600	1225	30-60mm
GC/50	0.50	360	180	560	1225	30-60mm
GC/385	0.385	470	180	495	1180	30-60mm
GC/296	0.296	610	195	495	1025	60-180mm

Table 3.1: Mix design for maximum aggregate size 20mm.

3.2. WORKABILITY

It can be observed from Table 3.2 that an increase in the

MIX	W/C RATIO	CEMENT kg	WATER kg	SAND kg	AGGREGATE kg	SLUMP
Sample 1:	**London brick**					
LBC/63	0.63	280	175	485	1110	10-30mm
	0.63	305	190	530	1030	30-60mm
	0.63	325	205	600	920	60-180mm
LBC/56	0.56	315	175	460	1100	10-30mm
	0.56	340	190	500	1020	30-60mm
	0.56	365	205	555	925	60-180mm
LBC/50	0.5	350	175	425	1100	10-30mm
	0.5	380	190	475	1005	30-60mm
	0.5	410	205	525	910	60-180mm
LBC/385	0.385	455	175	370	1050	10-30mm
	0.385	495	190	410	955	30-60mm
	0.385	530	205	445	870	60-180mm
LBC/296	0.296	590	175	315	970	10-30mm
	0.296	640	190	350	870	30-60mm
	0.296	695	205	380	770	60-180mm
Sample 2:	**Sandlime brick**					
SBC/63	0.63	280	175	540	1230	10-30mm
	0.63	305	190	590	1145	30-60mm
	0.63	325	205	670	1025	60-180mm
SBC/56	0.56	315	175	510	1225	10-30mm
	0.56	340	190	560	1135	30-60mm
	0.56	365	205	620	1035	60-180mm
SBC/50	0.5	350	175	476	1224	10-30mm
	0.5	380	190	535	1130	30-60mm
	0.5	410	205	590	1020	60-180mm
SBC/385	0.385	455	175	415	1180	10-30mm
	0.385	495	190	465	1080	30-60mm
	0.385	530	205	505	985	60-180mm
SBC/296	0.296	590	175	360	1100	10-30mm
	0.296	640	190	400	995	30-60mm
	0.296	695	205	440	890	60-180mm
Sample 3:	**Engineering brick**					
EBC/63	0.63	280	175	530	1210	10-30mm
	0.63	305	190	580	1125	30-60mm
	0.63	325	205	660	1010	60-180mm
EBC/56	0.56	315	175	500	1205	10-30mm
	0.56	340	190	550	1120	30-60mm
	0.56	365	205	610	1020	60-180mm

EBC/50	0.5	350	175	470	1205	10-30mm
	0.5	380	190	520	1100	30-60mm
	0.5	410	205	580	1005	60-180mm
EBC/385	0.385	455	175	410	1160	10-30mm
	0.385	495	190	455	1060	30-60mm
	0.385	530	205	500	965	60-180mm
EBC/296	0.296	590	175	350	1085	10-30mm
	0.296	640	190	390	980	30-60mm
Design	0.296	695	205	430	875	60-180mm
Actual	0.296	775	230	395	800	60-180mm
Sample 4:	**Gravel**					
GC/63	0.63	220	140	600	1365	10-30mm
	0.63	255	160	650	1260	30-60mm
	0.63	280	175	740	1130	60-180mm
GC/56	0.56	250	140	570	1365	10-30mm
	0.56	285	160	620	1260	30-60mm
	0.56	310	175	690	1150	60-180mm
GC/50	0.5	280	140	535	1370	10-30mm
	0.5	320	160	590	1260	30-60mm
	0.5	350	175	655	1145	60-180mm
GC/385	0.385	365	140	475	1345	10-30mm
	0.385	415	160	525	1225	30-60mm
	0.385	455	175	575	1120	60-180mm
GC/296	0.296	475	140	420	1290	10-30mm
	0.296	540	160	465	1160	30-60mm
Design	0.296	590	175	515	1045	60-180mm
Actual	0.296	695	205	465	960	60-180mm

Table 3.2: Mix design for maximum aggregate size 37.5mm. (quantities per m^3, to nearest 5kg)

quantity of water of 15kg/m^3 increases the workability by about 30mm of slump and hence a corresponding increase of 20 to 30kg/m^3 of cement for w/c ratios from 0.63 to 0.5 and 35 to 50kg/m^3 for w/c from 0.385 to 0.296 to maintain a constant w/c ratio in the same mix. The increase of 15kg/m^3 of water to improve workability by about 30mm of slump and corresponding increase of cement to maintain w/c ratio is accompanied by 8 to 11% increase in the quantity of fines and similar decrease in quantity of coarse aggregates required to maintain constant wet density. The aggregates were considered to be in the saturated surface dry state and moisture content of fines was determined at regular intervals during the experimental testing.

The angular shape and honeycombed texture of brick aggregates have associated problems of low workability, hence increased compaction effort. Extremely low workabilities had been experienced by previous researchers on brick aggregate concrete. Hence mixes with low workability of 10 to 30mm slump were not attempted in the experimental investigation. Mixes with high workability with 60 to 180mm slump tend to become uneconomic because of higher cement content along with associated problems of increased shrinkage and creep. Medium workability mixes with slump values between 30 and 60mm were selected for experimental investigation since they could be compacted with optimum effort and were relatively economical.

The workability was observed to be towards the lower limits mostly (i.e 30mm) reducing to about 15mm in a few cases. Table 3.3 gives the properties of the fresh concrete. If the brick aggregates are not saturated before mixing, workability reduces to quite an extent in first about fifteen minutes due to absorption of water by aggregates to become fully saturated hence reducing the w/c ratio and increasing the strength of concrete. Retempering with about

AGGREGATE TYPE	RELATIVE DENSITY	MIX	WATER CEMENT RATIO	AGGREGATE CEMENT RATIO	SLUMP mm	FRESH COMPACTED DENSITY kg/m^3
1. London brick	1.8592	LBC/63	0.63	5.11	30	2121.48
		LBC/56	0.56	4.47	30	2154.10
		LBC/50	0.50	3.89	34	2142.22
		LBC/385	0.385	2.76	31	2154.10
		LBC/296	0.296	1.35	49	2148.10
2. Sandlime brick	2.3325	SBC/63	0.63	5.69	30	2186.67
		SBC/56	0.56	4.99	46	2195.56
		SBC/50	0.50	4.38	16	2219.00
		SBC/385	0.385	3.12	60	2287.00
		SBC/296	0.296	1.57	49	2272.60
3. Engineering brick	2.3164	EBC/63	0.63	5.59	nil	2290.00
		EBC/56	0.56	4.91	30	2240.00
		EBC/50	0.50	4.26	15	2222.20
		EBC/385	0.385	3.06	34	2290.40
		EBC/296	0.296	1.54	46	2305.18
4. Gravel	2.49	GC/63	0.63	7.49	35	2489.00
		GC/56	0.56	6.60	35	2423.70
		GC/50	0.50	5.78	65	2391.10
		GC/385	0.385	4.22	100	2456.30
		GC/296	0.296	2.05	105	2383.84

Table 3.3: Properties of fresh concrete.

5% water to improve workability in the event of loss of workability in the first ten to fifteen minutes does not affect the strength of brick aggregate concrete since, loss of workability is mostly due to absorption of water by brick aggregate to become fully saturated. One concrete mixer was used throughout the experimental investigation and similarly the same vibrating table was used for the compaction of test specimens.

3.3. FRESH DENSITY

Relative densities of aggregates from normal construction bricks(LBC), sandlime bricks and engineering'B' bricks varied from 1.86 to 2.33 and were too low hence the estimated wet density of fully compacted concrete could not be obtained from 'Design of Normal Concrete Mixes' for further estimating the quantities of fine and coarse aggregates. An approximate value of wet density of fully compacted concrete was therefore taken for the first trial mix and a correction was applied after obtaining the actual wet density of the fully compacted fresh concrete from first trial mix. An average percentage of sand was taken from the maximum and minimum percentages permitted by the design method.

The required characteristic mean strengths were achieved almost in the first trial mix. Sufficient water was sprayed on the brick aggregates before mixing so as to bring them to nearly saturated surface dry state.

An average compaction time of three minutes was observed to be optimal and mixes with workabilities of 30 to 50mm slump were observed to achieve maximum compaction. However, mixes with workabilities of 50 to 100mm slump could achieve maximum compaction in about two minutes whereas mixes with slump values between 15 to 30mm required about four minutes to compact fully at medium to high vibrating speeds.

The average fresh compacted density of normal construction brick aggregate concrete was observed to be around 2140kg/m^3 and that of sandlime brick aggregate concrete was around 2235kg/m^3. The fresh compacted density of engineering brick aggregate concrete was found to be around an average of 2250kg/m^3 whereas that of the control mix with Thames Valley gravel as coarse aggregate was around 2425kg/m^3.

No bleeding was observed in the mixes, possibly because of the absorption of water by brick aggregates and also because of lower workability. No segregation was observed in brick aggregate concrete.

Concrete with normal construction brick aggregate and sandlime brick aggregate developed compressive strengths of 46N/mm^2 and 44N/mm^2 respectively for w/c ratio of 0.385 and strength of control mix of 54N/mm^2. The compressive strength of concrete with normal construction brick and sandlime brick aggregates could not be increased any further by lowering the w/c ratio because of the lower crushing strengths of the bricks from which these aggregates were obtained.

For w/c ratio of 0.296 and characteristic strength of gravel aggregate concrete of 65N/mm^2 highly workable mixes with slump values between 60 to 180mm were used due to higher cement content and percentage of fines and reduced quantity of coarse aggregates. The quantity of water had to be further increased by about 10% of the design value to increase workability since higher quantities of cement and fines required more water to wet their surfaces. The increase in strength was, however, observed to be too little as compared to the increase in quantity of cement in the case of concrete with normal construction brick and sandlime brick aggregate. Concrete made from engineering

'B' brick aggregates posed little problems with workability and compressive strength was observed to be much higher as compared to a similar normal concrete.

3.4. CONCLUSIONS

Prewetting of porous brick aggregates is neccessary to avoid loss of workability soon after mixing. Retempering with about 5% water to improve workability in the event of loss of workability in the first ten to fifteen minutes does not affect the strength of brick aggregate concrete. Due to different bulk densities of brick aggregate and sand, fresh concrete tends to segregate on compaction if higher workability is achieved, however it may be avoided by drier consistencies. Unit weight of fresh, compacted brick aggregate concrete is about 7 to 12% lower than normal weight concrete. Use of brick aggregate from softer bricks or highly fractured aggregates may crush during the process of mixing or compaction of concrete thereby further reducing the workability.

Design of normal concrete mixes by the method given by Road Note 4[1] of the Department of Environment, Great Britain considers properties and surface characteristics of aggregates and has been used initially to obtain the w/c ratio and water content of mixes. Relative densities of aggregates from normal construction bricks(LBC), sandlime bricks and engineering'B' bricks varied from 1.86 to 2.33 and were too low hence the estimated wet density of fully compacted concrete could not be obtained from 'Design of

Normal Concrete Mixes'. For further estimating the quantities of fine and coarse aggregates an approximate value of wet density of fully compacted concrete was therefore taken for the first trial mix and a correction was applied after obtaining the actual wet density of the fully compacted fresh concrete from first trial mix. The following relationship proved useful for estimating fully compacted wet density of concrete with all types of brick aggregates except normal construction brick aggregate due to its very low relative density :

Fresh compacted density = 975 * RD

where RD is relative density of aggregate subject to a minimum value of 2.2.

Mix design for low workability (i.e. 10 to 30mm slump) is impractical for brick aggregates. Medium workability mixes with slumps of 30 to 60mm are possible. It was observed that by maintaining a fines content between 29 and 33% of the total aggregates results in workabilities within the desired range, where fines are of medium grading. Brick aggregates obtained by crushing bricks with maximum average compressive strength of $20N/mm^2$ should not be used for concrete with a compressive strength of over $35N/mm^2$. It is recommended that the following design method for design of mixes with brick aggregates be followed:

Step 1. Select w/c ratio against the desired strength from Figure 3.1 (Design Chart)

Note: For crushed brick aggregate obtained from bricks with crushing strength of $40 N/mm^2$ or more, increase the w/c ratio obtained from Figure 3.1 by 30%.

Step 2. Determine free water content from Table 3.4

MAXIMUM SIZE	MEDIUM WORKABILITY	HIGH WORKABILITY
40mm	$190 kg/m^3$	$205 kg/m^3$
20mm	$210 kg/m^3$	$225 kg/m^3$

Table 3.4. Free water content

Step 3. Determine cement content from w/c ratio and free water content.

$$\text{Cement content} = \frac{\text{Free water content}}{\text{w/c ratio}}$$

Step 4. Determine total aggregate content.

To determine total aggregate content, an estimate of wet, compacted density is made from following:

Fresh compacted density = 975 * RD

where RD is relative density of aggregate subject to a minimum value of 2.2.

Calculate total aggregate content from:

Total aggregate = wet compacted density - cement - water

Step 5. Determine fine and coarse aggregate contents.

Fine aggregates = %fines * Total aggregate content

Coarse aggregates = Total aggregate content - fine aggregates

Use 33 to 29% fines (medium grading), higher value for higher w/c ratio and lower for lower w/c ratio varying from 0.7 to 0.3 respectively. Use of fine sand tends to increase the free water content whereas coarse sand tends to further reduce workability.

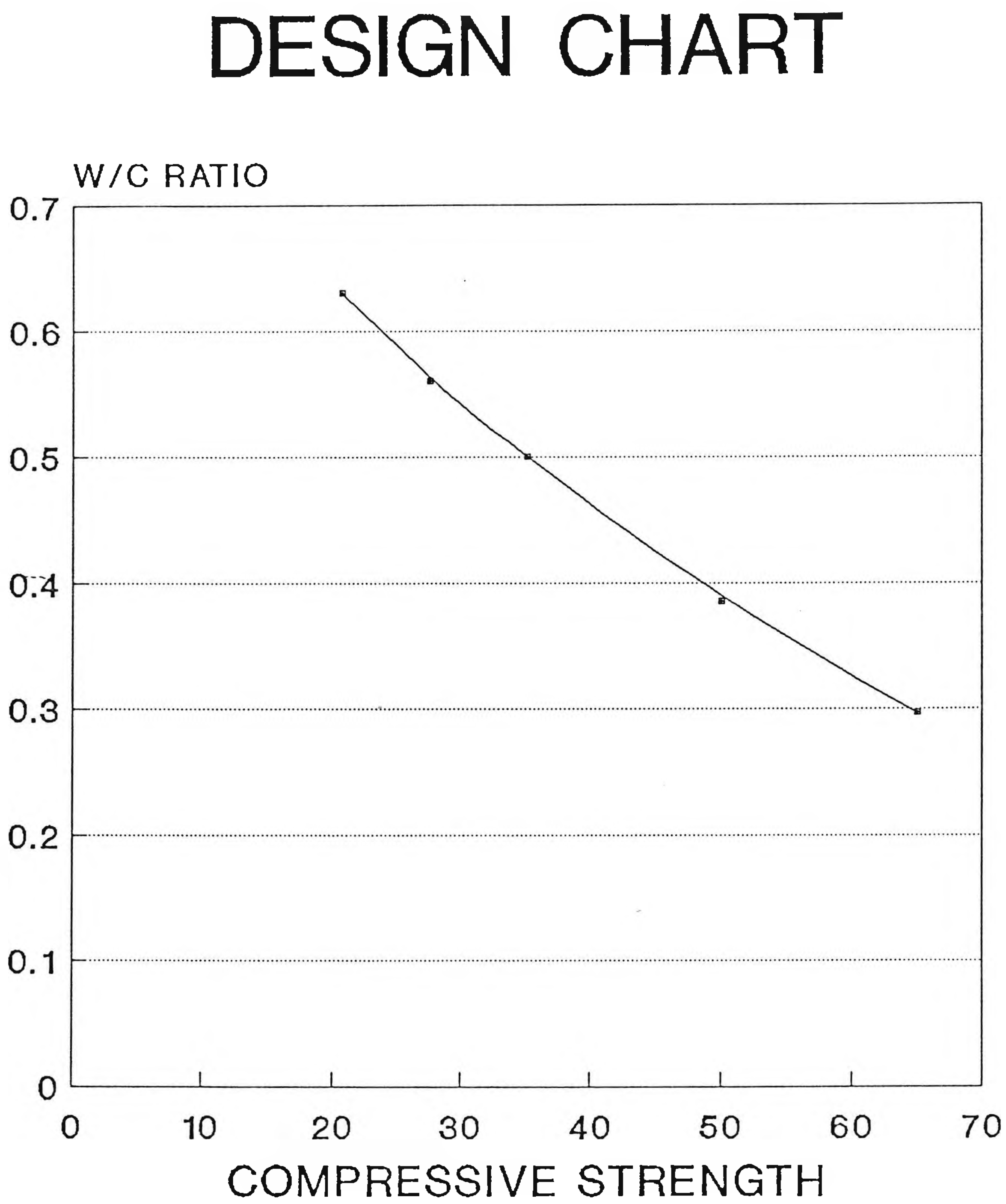


Figure 3.1:Design Chart - Characteristic Strength vs w/c ratio

CHAPTER 4

CONCRETE WITH CRUSHED BRICK COARSE AGGREGATES

This chapter covers determination of the mechanical properties of concrete with different types of selected crushed brick aggregates and the values are compared with the values for specimen of control mix made from concrete with Thames Valley gravel as aggregate and having the same w/c ratio. As well as comparing the values of properties of concrete with different types of brick aggregates and gravel, assessment of different causes of the variation in behaviour was made.
The tests carried out to investigate the mechanical properties of concrete with brick aggregates include compressive strength tests on cubes at 7 and 28 days, cylinder strength tests and tests for evaluating splitting tensile and flexural strengths. Stress/strain behaviour was studied on cylinders thereby evaluating static moduli of elasticity. Dynamic moduli were evaluated on the basis of longitudinal resonant frequencies. Saturated and dry densities were evaluated for each type of concrete. Ultrasonic pulse velocity tests were also carried out to assess the possibility of evaluation of properties by non-destructive testing. Tests were also conducted to assess the coefficients of thermal expansion for concrete with different types of crushed brick aggregates.

4.1. GENERAL

Specimens of five selected strengths of brick aggregate concrete were prepared for experimental investigation. Different types of brick aggregates used were normal construction brick(LBC) aggregate, sandlime brick aggregate and engineering 'B' brick aggregate. The concrete specimens used as standard to carry out comparative study were prepared by using Thames Valley gravel. Water/cement ratio, quality of water, curing conditions and test methods were kept constant for all specimen so as to aid a realistic comparative study by maintaining characteristics of paste constant and replacing gravel with different types of crushed brick aggregates only. All specimen were cured by immersion in water at 20^{0}C in a curing tank for 28 days as specified by BS 1881: Part 111: 1983. Tables 4.1 and 4.2 give the properties of different types of concretes.

TYPE OF AGGREG-ATE	MIX	COMP.STRENGTH 7DAYS N/mm^2	28DAYS N/mm^2	TENSILE STRENGTH N/mm^2	FLEXURAL STRENGTH N/mm^2	ELASTIC DYNAMIC N/mm^2	MODULUS STATIC N/mm^2
London brick	LBC/63	28.92	33.30	2.39	3.93	18551.3	8753.4
	LBC/56	31.50	36.40	2.44	3.03	23546.9	10087.3
	LBC/50	33.78	38.35	2.97	4.40	23812.8	11063.4
	LBC/385	42.44	46.37	2.53	4.92	24101.9	11417.7
	LBC/296	46.07	47.72	-	-	-	-
Sandlime brick	SBC/63	30.22	33.44	2.93	4.43	22125.8	8348.1
	SBC/56	27.70	35.30	2.59	4.64	23556.7	8511.4
	SBC/50	32.69	36.33	2.16	4.13	25737.6	10086.9
	SBC/385	40.92	43.93	3.04	4.80	25517.7	10710.5
	SBC/296	47.13	49.08	-	-	-	-
Enginee-ring brick	EBC/63	36.69	48.59	4.07	6.20	33190.8	13375.6
	EBC/56	45.33	55.62	4.51	5.27	32384.6	15080.0
	EBC/50	59.05	64.46	4.79	5.33	33763.8	15108.6
	EBC/385	61.00	71.00	3.13	5.47	33562.4	17636.2
	EBC/296	75.29	80.98	3.63	6.52	34143.0	20272.3
Gravel	GC/63	22.58	27.27	2.75	3.98	45296.6	18910.5
	GC/56	27.19	33.58	2.96	3.90	45531.1	22506.3
	GC/50	36.83	41.34	3.25	4.41	46922.8	23480.2
	GC/385	46.49	53.81	3.47	5.33	47557.8	24033.5
	GC/296	57.94	64.90	3.81	5.94	49825.5	27292.9

Table 4.1 : Properties of concrete with brick aggregates.

4.2. COMPRESSIVE STRENGTH

150*150*150mm cubes were moulded as specified by BS 1881: Part 108: 1983 and 150mm diameter, 300mm long cylinders were moulded as per BS 1881: Part 110: 1983. Cubes were tested for compressive strength at 7 days and 28 days whereas cylinders were tested for compressive strength at 28 days only. Testing for compressive strength was carried out as per BS 1881: Part 116: 1983 and a loading rate of

0.4N/mm^2 was applied for all tests.

TYPE OF AGGREGATE	MIX	DENSITY OF HARDENED CONCRETE (kg/m^3) dry	saturated	PULSE VELOCITY km/s
London brick	LBC/63	1979.26	2122.96	3.39
	LBC/56	1987.56	2123.56	3.67
	LBC/50	2013.00	2139.30	3.80
	LBC/385	2017.78	2142.22	3.96
Sandlime brick	SBC/63	2045.00	2184.80	3.61
	SBC/56	2070.52	2210.40	3.82
	SBC/50	2097.30	2231.11	3.87
	SBC/385	2108.44	2241.44	3.89
Engineering brick	EBC/63	2176.30	2284.15	4.00
	EBC/56	2191.30	2296.30	4.07
	EBC/50	2233.19	2309.63	4.12
	EBC/385	2297.18	2331.26	4.14
	EBC/296	2307.81	2340.41	4.21
Gravel	GC/63	2316.44	2408.60	4.48
	GC/56	2357.32	2414.51	4.64
	GC/50	2403.15	2454.80	4.76
	GC/385	2411.10	2457.70	4.79
	GC/296	2416.26	2459.81	4.94

Table 4.2. Properties of concrete with brick aggregates.

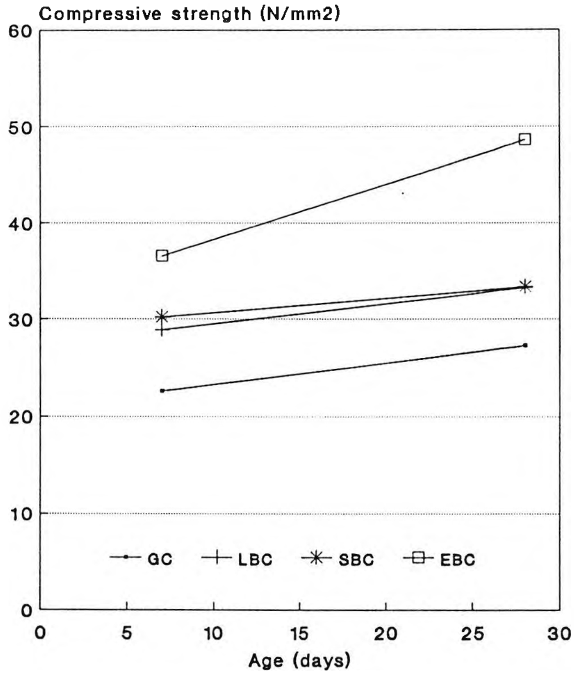
Compressive strength tests on cubes at 7 days and 28 days showed that the rate of development of strength of brick aggregate concrete was similar to normal aggregate concrete. It was observed that brick aggregate concrete developed 85 to 90% of 28 day strength in 7 days in the case of concrete with aggregates from normal construction brick(LBC) and sandlime brick, higher value being for lower w/c ratio where higher amounts of cement are used. In the case of concrete with engineering 'B' brick aggregates, 75 to 90 % of the 28 day strength was achieved in 7 days. Control mix with Thames Valley gravel as coarse aggregate was also observed to develop strength at similar rates.

Figures 4.1 to 4.3 give the relation between 7 and 28 day compressive strengths of concrete with different types of coarse aggregates.

For mixes with w/c ratio from 0.63 to 0.50 and similar to 28 days characteristic strengths of 20.7 to 35N/mm^2 for gravel concrete, it was observed that concrete with normal construction brick(LBC) aggregate and sandlime brick aggregate developed adequate average compressive strength, similar to normal concrete. In the case of concrete with engineering brick aggregates, the average strength observed was between 30 to 45 % higher than the target mean strength and 55 to 75% higher than the average compressive strengths achieved for concrete with gravel aggregate.

For mixes similar to characteristic strength of 50N/mm^2 for gravel aggregate and w/c ratio of 0.385, concrete with normal construction brick(LBC) aggregate developed an average 28 day compressive strength of 46N/mm^2 whereas concrete with sandlime brick aggregate developed an average 28 day strength of 44N/mm^2 compared to 54N/mm^2 for the control mix. This failure to develop adequate strength of concrete with normal construction brick aggregate and concrete with sandlime brick aggregate is due to lower compressive strengths of about 20 and 15N/mm^2 of bricks, respectively, from which they have been obtained. 46 to 48% of coarse aggregates were present in the concrete by mass hence at higher concrete strengths the effect of lower aggregate strength is pronounced. On observing the actual

W/C RATIO 0.63



W/C RATIO 0.56

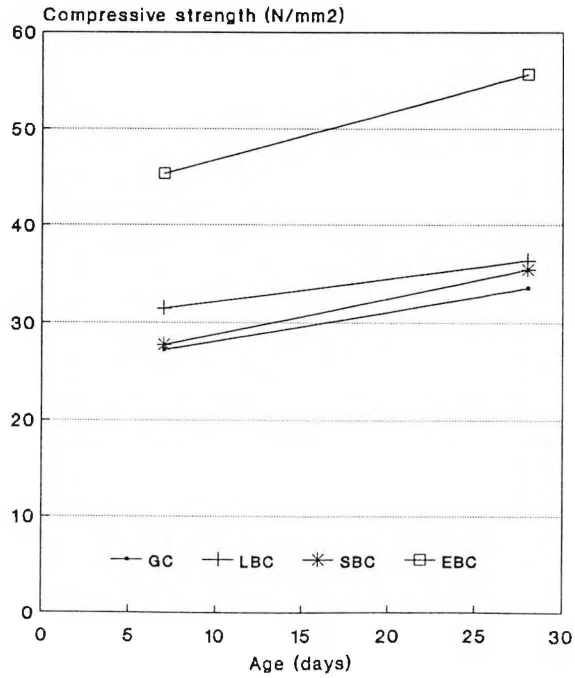
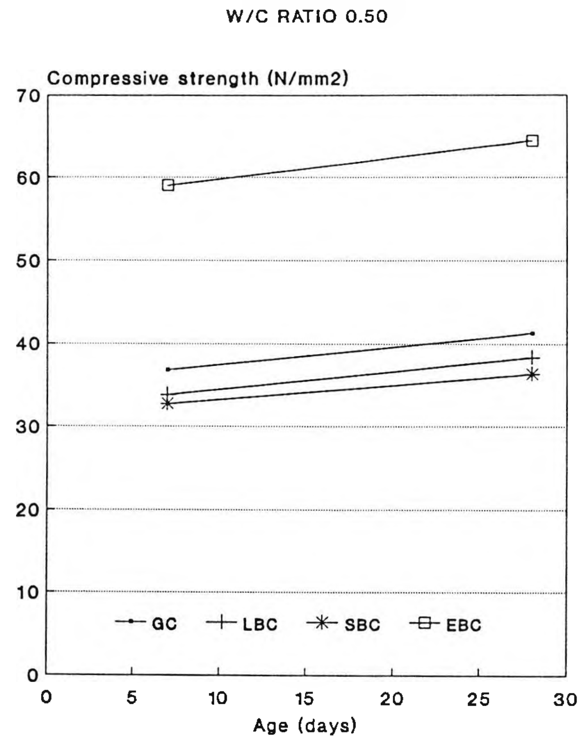


Figure 4.1: Strength development - Water/cement ratio 0.63
Strength development - Water/cement ratio 0.56



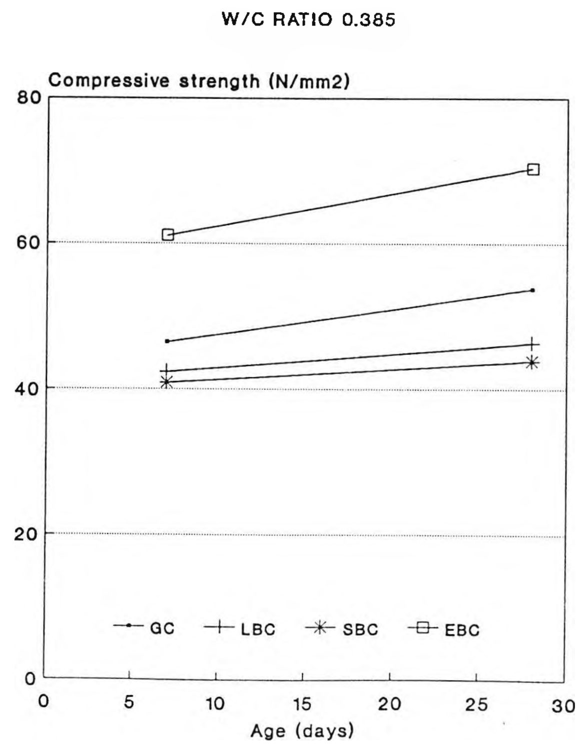


Figure 4.2: Strength development - Water/cement ratio 0.50
Strength development - Water/cement ratio 0.385

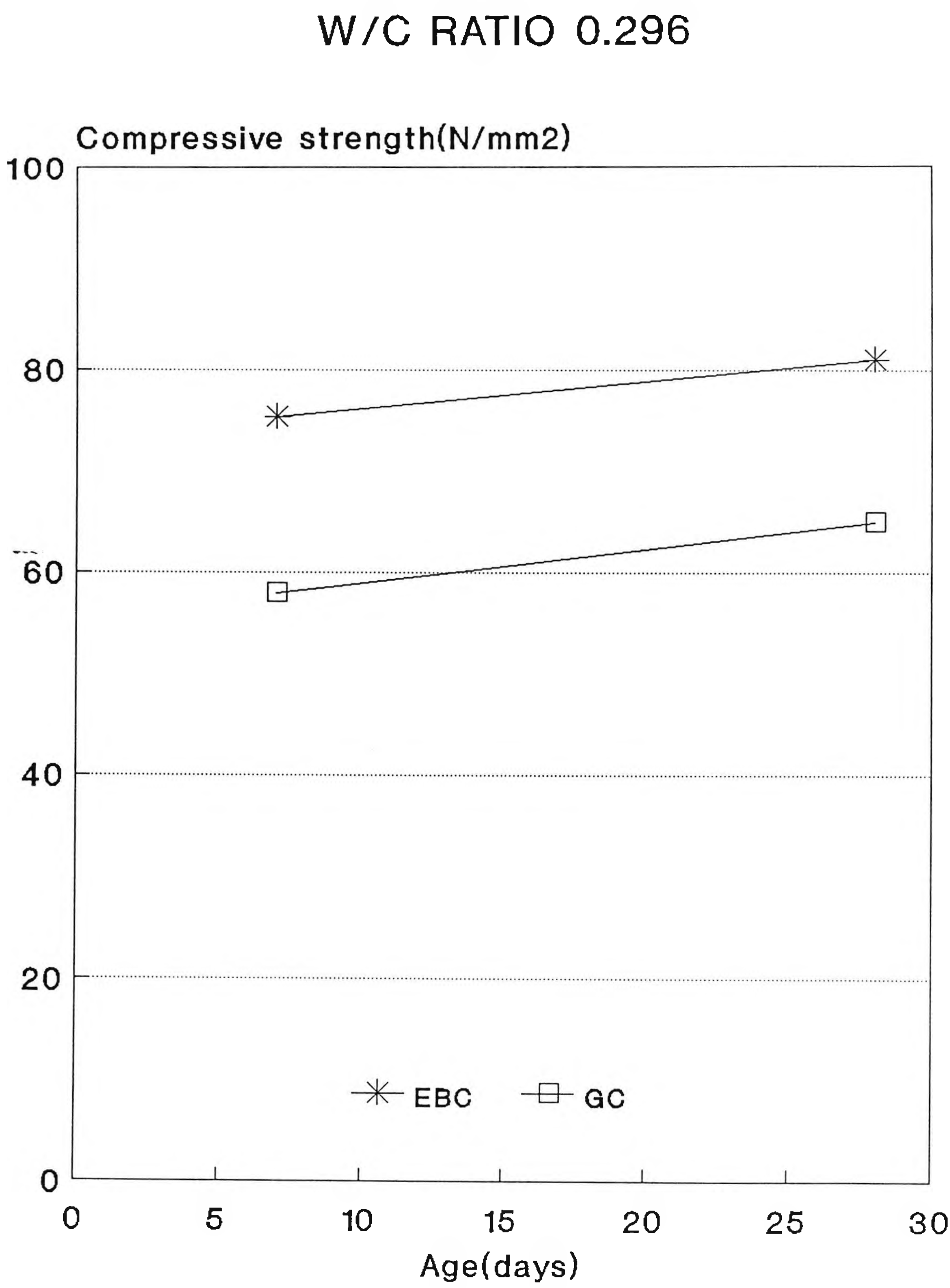


Figure 4.3: Strength development - Water/cement ratio 0.296

strengths achieved by concrete with w/c ratio of 0.296 and mixes similar to gravel concrete with characteristic strength of 65N/mm^2, it can be stated that a redesign of mix with slight lowering of w/c ratio would not bring the compressive strength up to the desired limit in the case of concrete with normal construction brick(LBC) aggregate nor it would be possible in the case of concrete with sandlime brick aggregate where a large increase in the amount of cement has a minor effect on strength of concrete, hence making it uneconomic.

Concrete with engineering brick aggregate and with w/c ratio of 0.385 developed an average 28 day strength of 70N/mm^2, which is 30% higher than the control mix. For w/c ratio of 0.296 concrete with engineering brick aggregates developed average 28 day compressive strength of 80.98N/mm^2 which is about 24% higher than the control mix.

Figure 4.4 gives the typical failure of cubes made from concrete with brick aggregates. It can be observed from the failure pattern that failure cracks pass through the brick aggregates thereby splitting the aggregates along with mortar unlike concrete with gravel aggregate where failure cracks pass through the mortar and around the gravel particles showing bond failure at aggregate-paste interface. Figure 4.5 gives the relation between compressive strength and w/c ratio of concretes with different aggregates.

Table 4.3 gives the variation of average compressive

Figure 4.4. Typical failure of cubes of brick aggregate concrete

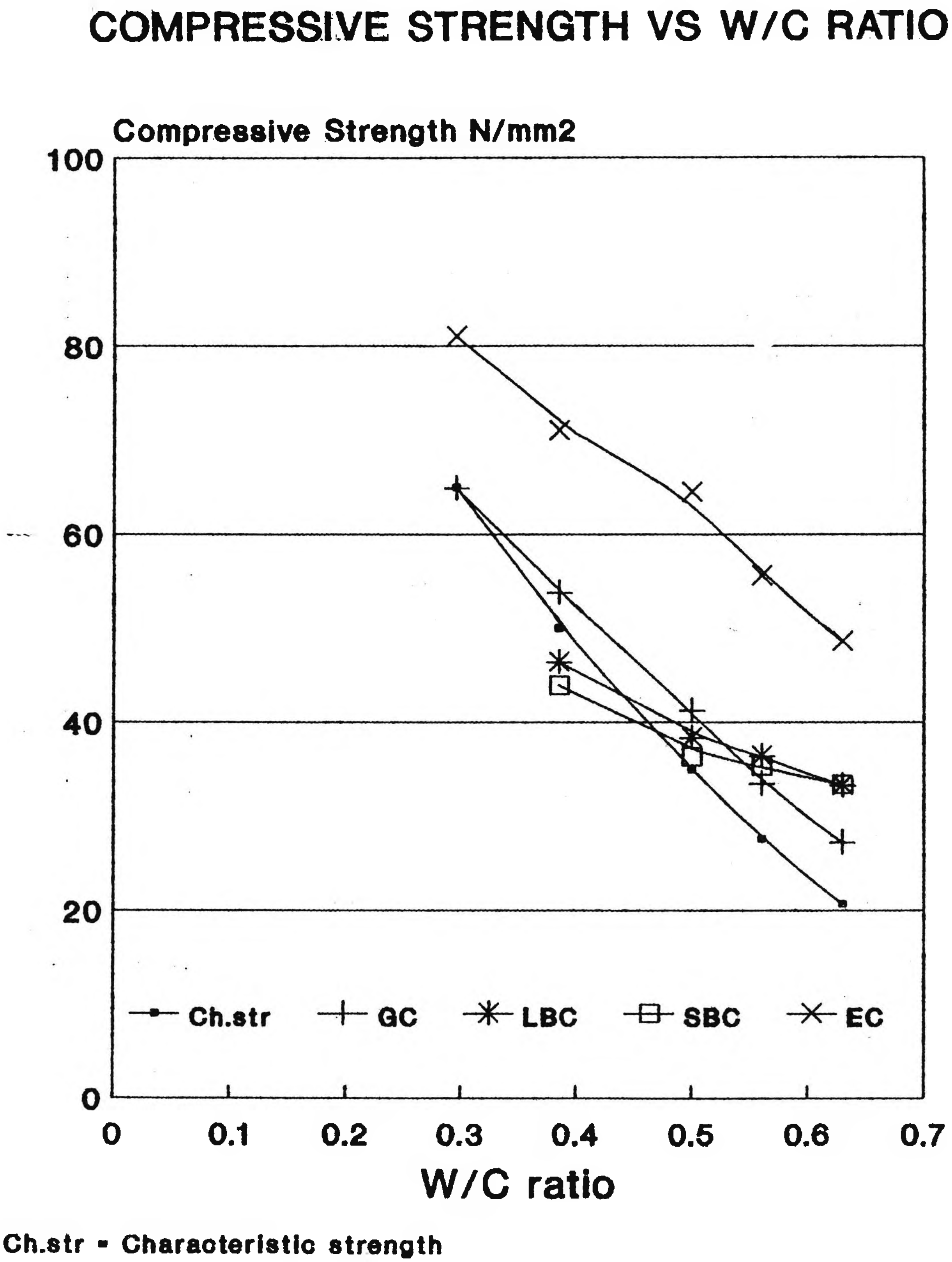


Figure 4.5. Compressive strength vs w/c ratio

strength and the standard deviation for concrete with brick aggregates. The standard deviation is calculated for the lowest compressive strength of cubes observed in the laboratory testing by the help of following equation[1]:

$$s = \sqrt{\frac{\Sigma (x - m)^2}{n - 1}}$$

where s = standard deviation

x = lowest compressive strength

m = mean compressive strength

n = number of specimen tested

TYPE OF AGGREGATE	MIX	AVERAGE STRENGTH N/mm^2	STANDARD DEVIATION %
London brick	LBC/63	33.30	1.41
	LBC/56	36.40	1.44
	LBC/50	38.35	1.60
	LBC/385	46.37	1.66
Sandlime brick	SBC/63	33.44	1.32
	SBC/56	35.30	1.41
	SBC/50	36.33	1.45
	SBC/385	43.93	1.52
Engineer-ing brick	EBC/63	48.59	1.06
	EBC/56	55.62	1.29
	EBC/50	64.46	1.41
	EBC/385	70.31	1.38
	EBC/296	80.98	1.42
Gravel	GC/63	27.27	1.41
	GC/56	33.58	1.39
	GC/50	41.34	1.42
	GC/385	53.81	1.54
	GC/296	64.90	1.42

Table 4.3: Variation of compressive strengths.

A total of nine specimen from three different batches were tested. The variation in compressive strength was observed to be about 5N/mm^2 for the lowest compressive strength achieved in the laboratory as compared to mean compressive strength of cubes for concrete with normal construction brick and sandlime brick aggregate. Variation in compressive strength for concrete with engineering brick aggregate was 4N/mm^2 as compared to the usual value of 4 to 6N/mm^2 for concrete with gravel aggregate[1]. Hence standard deviation for concrete with brick aggregates is similar to normal concrete.

Table 4.4 gives the 28 day compressive strengths of cubes and cylinders for concrete with different types of brick aggregates.

TYPE OF AGGREGATE	MIX	CUBE STRENGTH fcu N/mm^2	CYLINDER STRENGTH N/mm^2	%fcu
London brick	LBC/63	33.30	18.68	56.0
	LBC/56	36.40	20.65	56.7
	LBC/50	38.35	22.76	59.9
	LBC/385	46.37	29.58	63.8
Sandlime brick	SBC/63	33.44	16.05	48.0
	SBC/56	35.30	17.58	49.8
	SBC/50	36.33	18.50	50.9
	SBC/385	43.93	31.43	71.5
Engineering brick	EBC/63	48.59	25.60	52.7
	EBC/56	55.62	32.82	59.0
	EBC/50	64.46	37.67	58.4
	EBC/385	70.31	52.90	75.3
	EBC/296	80.98	62.85	77.6
Gravel	GC/63	27.27	18.54	68
	GC/56	33.58	23.50	70
	GC/50	41.34	29.31	70.6
	GC/385	53.81	37.98	70.6
	GC/296	64.90	46.73	72

Table 4.4: Cube and cylinder strengths of different concretes.

On testing cylinders for 28 days compressive strength, it was observed that cylinder strength varied from 48 to 77% of cube strength for concrete with brick aggregates as compared to 60 to 84% for concrete with Thames Valley gravel as coarse aggregate.

Average cylinder strength for concrete with normal construction brick(LBC) aggregate was observed to be 59% of the cube strength whereas it is 55.05% for concrete with sandlime brick aggregate and 64.60% for concrete with engineering brick aggregate. Cylinder strength for concrete with engineering brick aggregates mostly remained higher than the characteristic compressive strength of similar mixes with gravel aggregates. Average cylinder strength for concrete with Thames Valley gravel was observed to be 70% of the average cube strength which is lower than roughly 80% normally expected ratio of cylinder strength to cube strength for normal concretes, due to the round shape of gravel aggregate.

Figure 4.6 and 4.7 shows the failure in compression of cylinders of concrete with Thames Valley gravel and engineering brick aggregates. The failure of cylinder with gravel aggregate was observed to be due to failure of mortar and mortar-gravel bond near the point of application of compressive load whereas cylinder with engineering brick aggregate shows failure due to chipping of vertical layers of mortar along with brick aggregates from near the centre of cylinder extending towards the loaded edges, as is also

Figure 4.6. Cylinder made from concrete with engineering brick aggregate after failure in compression.

Figure 4.7. Cylinder made from concrete with Thames Valley gravel aggregate after failure in compression.

evident by few vertical cracks in the figure. Hence failure pattern of cylinders of concrete with brick aggregates suggests that the failure of cylinders in uniaxial compression is initiated by the failure of brick aggregates in tension. The lower tensile strength of crushed brick aggregates lowers the cylinder strength of concrete with crushed brick aggregates.

4.3. TENSILE STRENGTH

Splitting tensile strength tests were carried out on specimen to determine the splitting tensile strength of concrete with brick aggregates as per BS 1881: Part 117: 1983. 150mm diameter, 150mm long cylinders were cast and cured for 28 days as per BS 1881: Part 111: 1983.

Table 4.5 gives the relationship between compressive and splitting tensile strengths for concrete with crushed brick and gravel aggregates. The splitting tensile strength of concrete with normal construction brick(LBC) aggregate was observed to vary from 2.16 to 2.97N/mm^2 i.e 7.18 to 5.46% of the 28 day compressive strength, reducing with increase in average compressive strength. Similarly, in the case of concrete with sandlime brick aggregate, the splitting tensile strength was observed to vary from 2.16 to 3.04N/mm^2 i.e 8.76 to 5.95%. In the case of concrete with engineering brick aggregate splitting tensile strength was observed to vary from 4.79 to 3.13N/mm^2 i.e 8.38 to 4.41%. In case of the control mix with Thames Valley gravel as coarse aggregate, the splitting tensile strength varied

TYPE OF AGGREGATE	MIX	COMP.STRENGTH 28DAYS f_c N/mm^2	TENSILE STRENGTH f_t N/mm^2	RATIO f_t/f_c %	STANDARD DEVIATION %
London brick	LBC/63	33.30	2.39	7.18	0.98
	LBC/56	36.40	2.44	6.70	1.41
	LBC/50	38.35	2.97	7.74	1.53
	LBC/385	46.37	2.53	5.46	1.22
Sandlime brick	SBC/63	33.44	2.93	8.76	0.92
	SBC/56	35.30	2.59	7.34	1.06
	SBC/50	36.33	2.16	5.95	2.01
	SBC/385	43.93	3.04	6.92	1.89
Engineering brick	EBC/63	48.59	4.07	8.38	1.54
	EBC/56	55.62	4.51	8.11	1.06
	EBC/50	64.46	4.79	7.43	0.98
	EBC/385	71.00	3.13	4.41	1.21
	EBC/296	80.98	3.63	4.48	1.07
Gravel	GC/63	27.27	2.75	10.08	1.51
	GC/56	33.58	2.96	8.81	1.05
	GC/50	41.34	3.25	7.86	0.93
	GC/385	53.81	3.47	6.45	1.02
	GC/296	64.90	3.81	5.87	0.98

Table 4.5: Relationship between compressive and splitting tensile strengths.

from 3.81 to 2.75N/mm^2 i.e 10 to 5.87% of the 28 day compressive strength, reducing with increase in average compressive strength. Hence concrete with engineering brick aggregate has a splitting tensile strength about 20% higher on average as compared to the splitting tensile strength of concrete with Thames Valley gravel whereas concrete with normal construction brick (LBC) aggregate and sandlime brick aggregate have tensile splitting strengths which are, on average, 18% and 22% lower than for concrete with gravel aggregate.

It was observed that splitting tensile failure across the section of test cylinders occurred by a crack through the mortar and through the aggregate particles in case of concrete with brick aggregates as shown in Figure 4.8. Thus the brick aggregate particles failed in tension rather than in bond between the mortar and aggregates. The failure crack propagated through the mortar and around the gravel particles in case of control mix with Thames Valley gravel as coarse aggregate. No gravel particles were observed to fail in tension but tensile failure occurred along the bond surface between the mortar and rounded gravel particles as shown in Figure 4.9.

Reduced tensile strength of concrete with normal construction brick aggregate and sandlime brick aggregate is due to lower tensile strength of their aggregates varying from $1.14N/mm^2$ for normal construction brick to $0.85N/mm^2$ for sandlime brick as compared to tensile strength of $2.07N/mm^2$ for engineering bricks. These results were obtained in the laboratory. Ultimate tensile strength for natural aggregates varies between 1.38 and $13.8N/mm^2$[86].

4.4. FLEXURAL STRENGTH

150*150*750mm beams were cast for determining the flexural strength of concrete with brick aggregates, vide BS 1881: Part 109: 1983. Test beams were cured for 28 days before testing, vide BS 1881: Part 111: 1983. Test for flexural strength was carried out with third point loading (BS 1881: Part 118: 1983).

It was observed that the flexural strength of concrete with

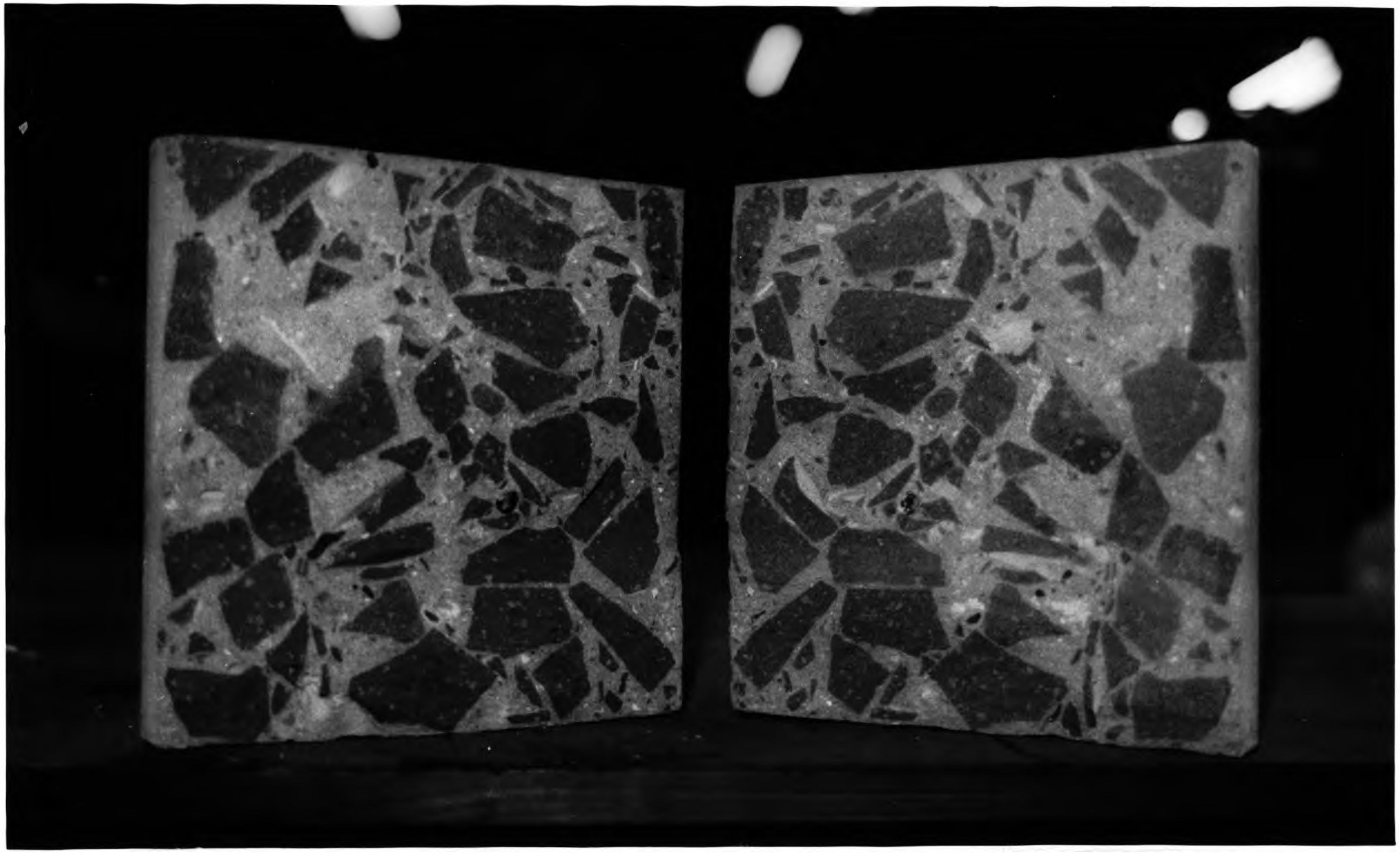


Figure 4.8. Splitting tensile failure of concrete with engineering brick aggregate.

Figure 4.9. Splitting tensile failure of concrete with Thames Valley gravel.

TYPE OF AGGREGATE	MIX	COMP. STRENGTH 28DAYS f_c N/mm^2	FLEXURAL STRENGTH f_f N/mm^2	RATIO f_f/f_c	STANDARD DEVIATION %
London brick	LBC/63	33.30	3.93	11.80	0.69
	LBC/56	36.40	3.03	8.32	0.73
	LBC/50	38.35	4.40	11.47	0.58
	LBC/385	46.37	4.92	10.61	0.88
Sandlime brick	SBC/63	33.44	4.43	13.25	0.47
	SBC/56	35.30	4.64	13.14	0.71
	SBC/50	36.33	4.13	11.37	0.92
	SBC/385	43.93	4.80	10.93	0.87
Engineering brick	EBC/63	48.59	6.20	12.76	0.77
	EBC/56	55.62	5.27	9.48	0.89
	EBC/50	64.46	5.33	8.27	0.92
	EBC/385	71.00	5.47	7.70	0.88
	EBC/296	80.98	6.52	8.05	0.69
Gravel	GC/63	27.27	3.98	14.59	0.73
	GC/56	33.58	3.90	11.61	0.84
	GC/50	41.34	4.41	10.66	0.96
	GC/385	53.81	5.33	9.91	0.79
	GC/296	64.90	5.94	9.15	0.67

Table 4.6 : Relationship between compressive and flexural strengths.

normal construction brick aggregate(LBC) varied from 3.03 to 4.92N/mm^2 i.e 8.32 to 11.80% of the 28 day compressive strength. For concrete with sandlime brick aggregate, the flexural strength varied from 4.13 to 4.80N/mm^2 i.e 10.93 to 13.25% of the 28 day compressive strength and for concrete with engineering brick aggregates flexural strength varied from 5.33 to 6.52N/mm^2 i.e 7.7 to 12.76% of the 28 day compressive strength. Flexural strength for concrete with Thames Valley gravel as coarse aggregate varied from 3.90 to 7.33N/mm^2 i.e 9.15 to 14.59% of the 28 day compressive strength.

Hence average flexural strength values for concrete with brick aggregates are almost similar to concrete with Thames Valley gravel.

It was observed that failure in flexure across the section of test beams occurred by a crack through the mortar and through the aggregate particles in the case of concrete with brick aggregates, that is, tensile failure of the brick aggregates as shown in Figure 4.10. The failure crack propagated through the mortar and around the gravel particles in case of control mix with Thames Valley gravel as coarse aggregate. No gravel particles were observed to fail in tension but failure occurred along the bond surface between the mortar and rounded gravel particles. Figure 4.11 shows the flexural failure of beams made from concrete with Thames Valley gravel.

4.5. STRESS/STRAIN BEHAVIOUR

The stress/strain behaviour of brick aggregate concretes and concrete with Thames Valley gravel were studied on 150mm diameter, 300mm long cylinders up to failure. Increments of load were applied and strains measured for each increment of load up to the failure of specimen. Figures 4.12 to 4.14 give the stress/strain relationship of different types of concretes for different w/c ratios. It was observed that the curves representing the stress/strain behaviour of concrete with normal construction brick and sandlime brick aggregate were similar to the stress/strain curves for concrete with similar w/c ratio and with Thames Valley gravel as coarse aggregates. However, the

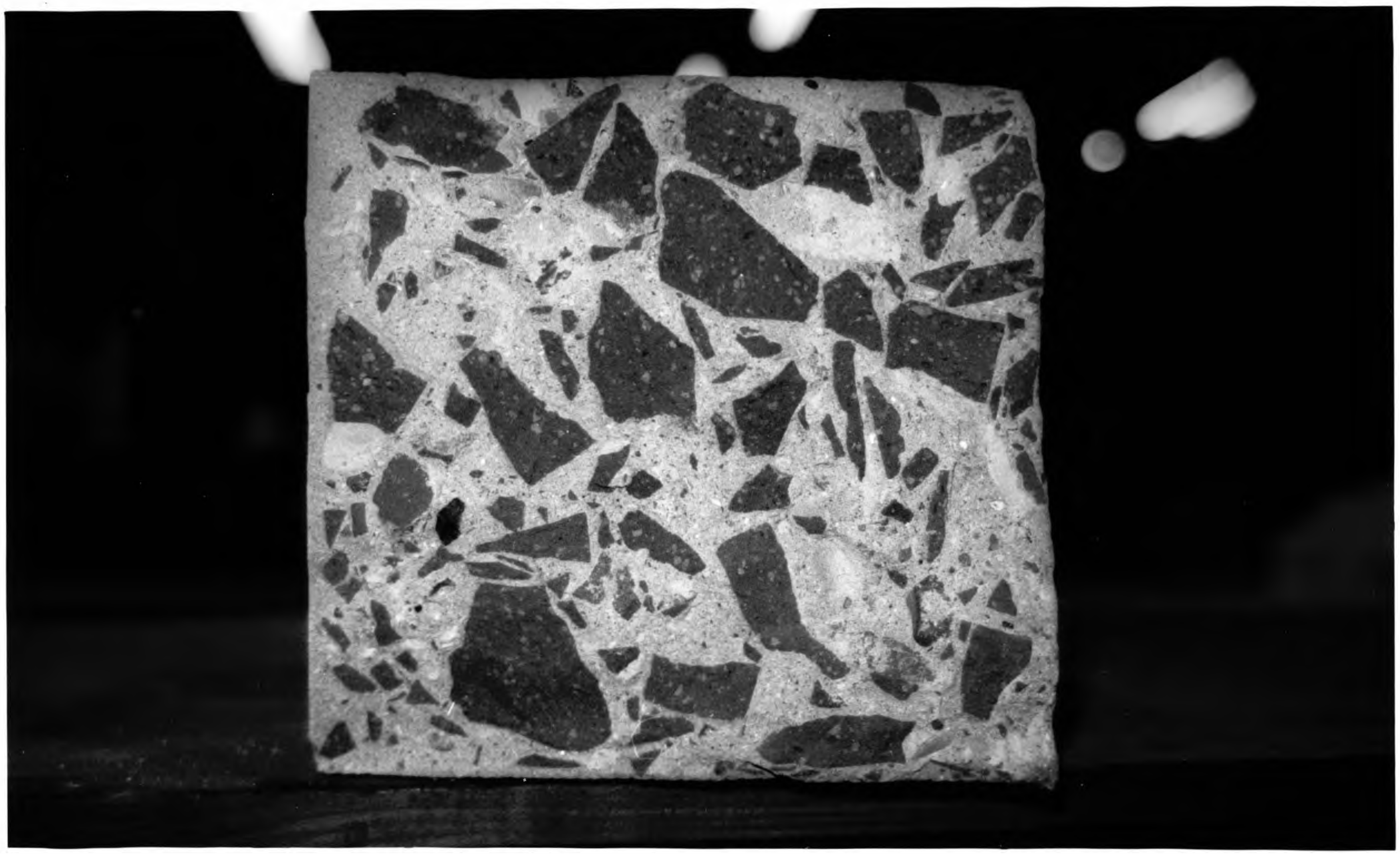
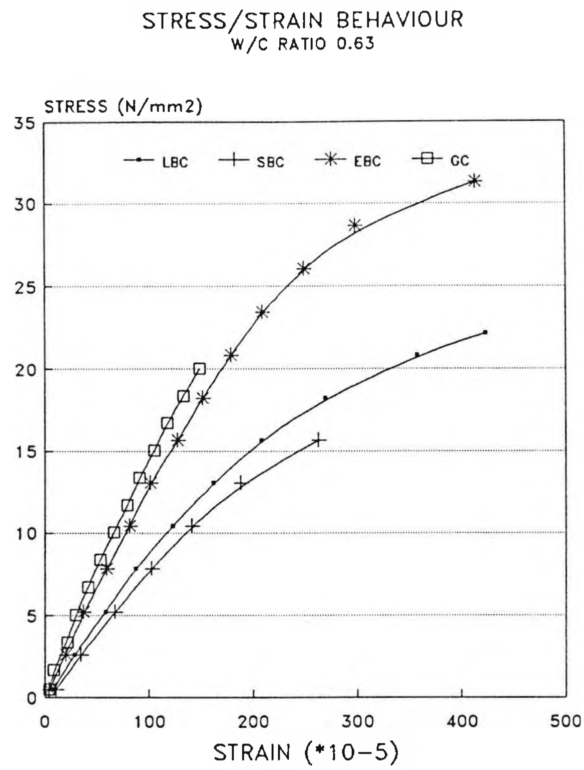


Figure 4.10. Ends of beams failed in flexure showing failure for concrete with engineering brick aggregate.

Figure 4.11. Ends of beams failed in flexure showing failure for concrete with Thames Valley gravel.



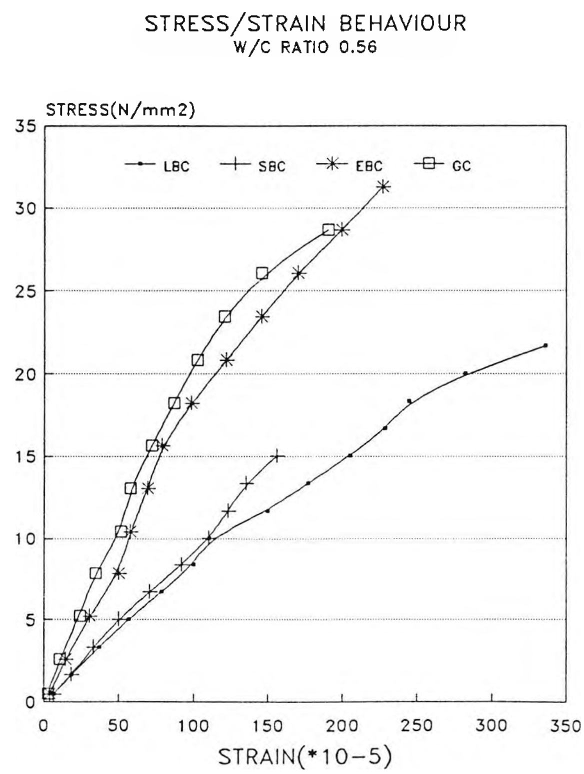
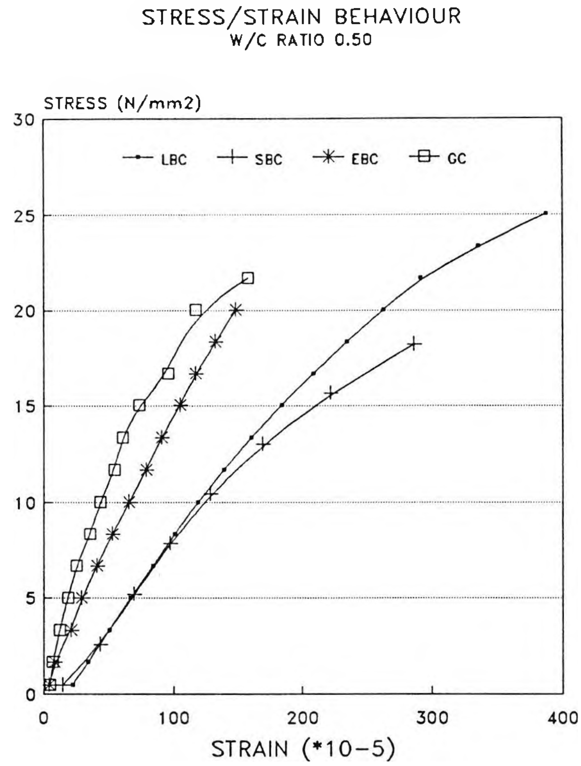


Figure 4.12. Stress/strain behaviour - w/c ratio 0.63
Stress/strain behaviour - w/c ratio 0.56



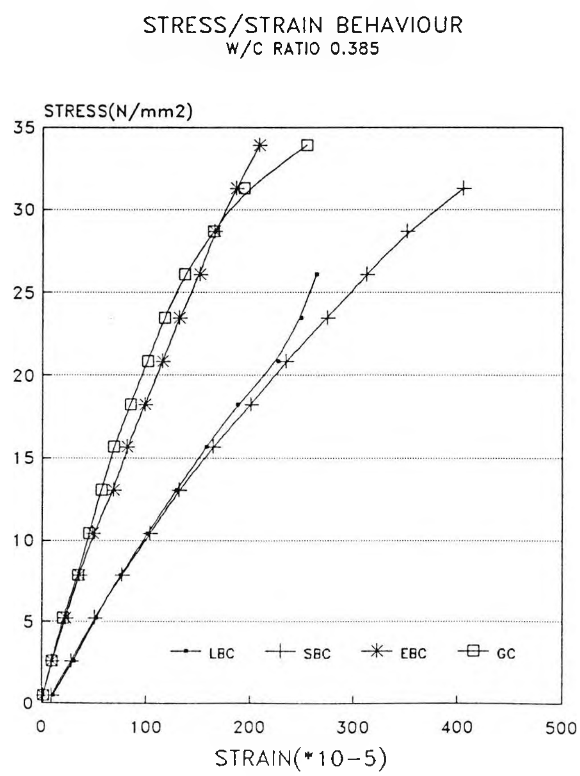


Figure 4.13. Stress/strain behaviour - w/c ratio 0.50
Stress/strain behaviour - w/c ratio 0.385

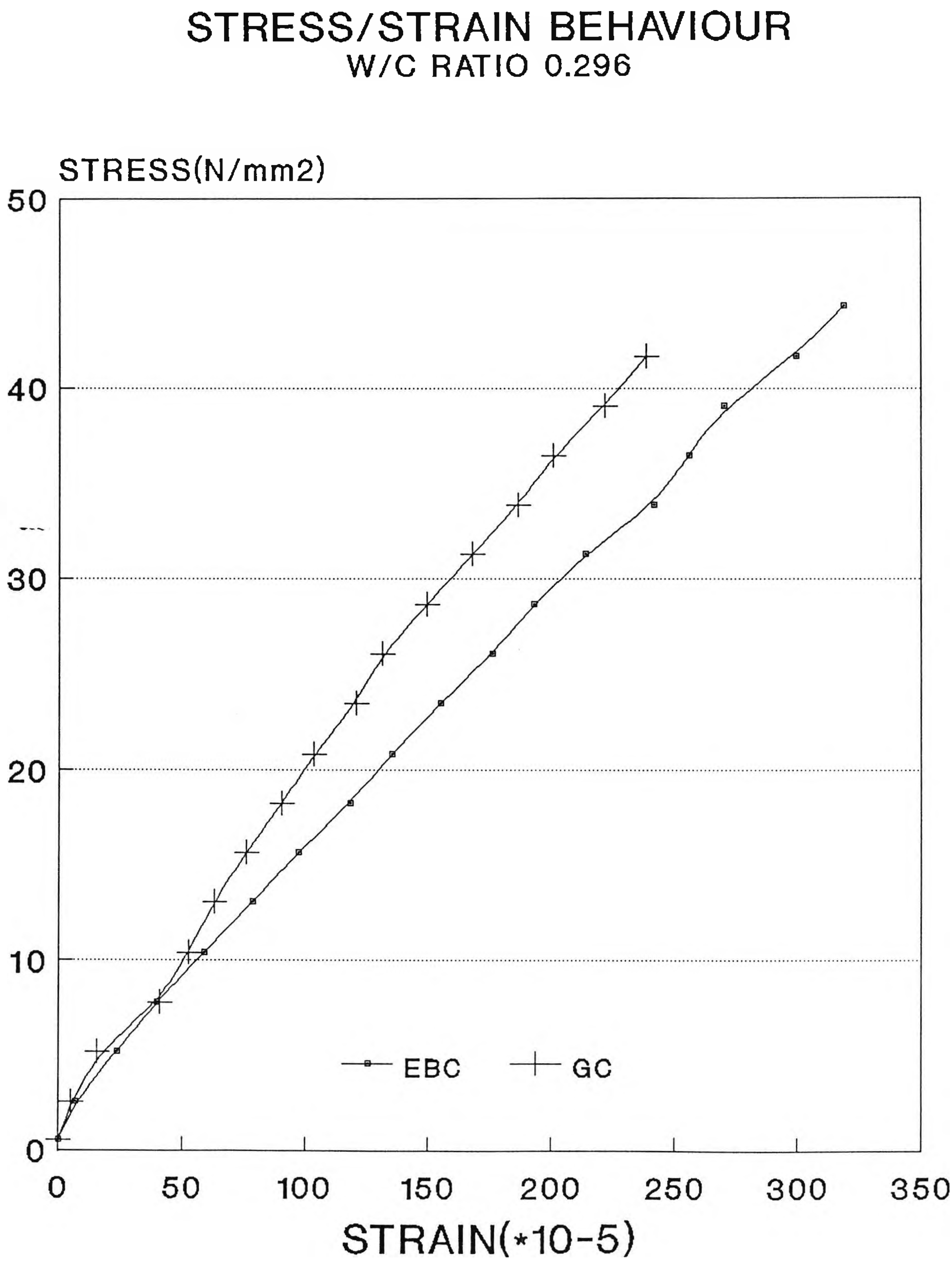


Figure 4.14. Stress/strain behaviour - w/c ratio 0.296

stress/strain curve for concrete with engineering brick aggregates tend to be linear with reduction in w/c ratio, as compared to concrete with same w/c ratios and with gravel aggregate. This is because of the higher compressive strengths of concrete with engineering brick aggregate as compared to concrete with gravel aggregate.

Highest values of compressive strain at failure were observed in the case of concrete with normal construction brick aggregates with average value of $381*10^{-5}$. Lower strains at failure were observed in the case of concrete with sandlime brick aggregates and engineering brick aggregates with average values of $270*10^{-5}$ and $230*10^{-5}$ respectively and the lowest failure strains were observed for concrete with Thames Valley gravel aggregate with average value of $210*10^{-5}$. Hence average failure strains for concrete with normal construction brick, sandlime brick and engineering brick aggregates were observed to be 83%, 28.5% and 10% higher, respectively, as compared to concrete with Thames Valley gravel. Limiting strain in compression for normal concrete varies from $2*10^{-3}$ to $4*10^{-3}$ for compressive strengths between 70 and $14N/mm^2$ whereas value used in structural design is $3.5*10^{-3}$. The values of strains at failure for concrete with crushed brick aggregates lie within the limiting strain values in compression. Higher strains in concrete with brick aggregates are due to lower elastic modulus of brick aggregates.

4.6. MODULUS OF ELASTICITY

4.6.1. Static modulus of elasticity

150mm diameter, 300mm long cylinders were prepared for determining the static modulus of elasticity in compression. Preparation of the sample and testing was carried out as per BS 1881: Part 121: 1983. The specimen were cured for 28 days as specified in BS 1881: Part 111: 1983. Table 4.7 gives the values of static moduli of elasticity observed during the investigations.

TYPE OF AGGREGATE	MIX	COMP. STRENGTH 28DAYS N/mm^2	STATIC MODULUS OF ELASTICITY N/mm^2
London brick	LBC/63	33.30	8753.4
	LBC/56	36.40	10087.3
	LBC/50	38.35	11063.4
	LBC/385	46.37	11417.7
Sandlime brick	SBC/63	35.30	8348.1
	SBC/56	33.44	8511.4
	SBC/50	36.33	10086.9
	SBC/385	43.93	10710.5
Engineering brick	EBC/63	48.59	13375.6
	EBC/56	55.62	15080.0
	EBC/50	64.46	15108.6
	EBC/385	71.00	17636.2
	EBC/296	80.98	20272.3
Gravel	GC/63	27.27	18910.5
	GC/56	33.58	22506.3
	GC/50	41.34	23480.2
	GC/385	53.81	24033.5
	GC/296	64.90	27292.9

Table 4.7: Relationship between compressive strength and static modulus of elasticity.

The specimen were fully saturated when tested for modulus of elasticity. The static modulus of elasticity for wet specimen is higher by 3000 to 4000N/mm^2 as compared to dry specimen whereas compressive strength of dry specimen is higher than wet ones[12].

For w/c ratio varying from 0.63 to 0.296, the static modulus of elasticity in the case of concrete with normal construction brick(LBC) aggregates was observed to vary from 8753 to 11417N/mm^2. Similarly the static modulus of elasticity for concrete with sandlime brick aggregates varied from 8348 to 10710N/mm^2 whereas values for concrete with engineering brick aggregates varied from 13375 to 20272N/mm^2. The static modulus of elasticity for concrete with Thames Valley gravel was observed to vary from 18910 to 27292N/mm^2. Values of static modulus of elasticity were observed to increase with increase in the compressive strength of concrete. Hence the average static modulus of elasticity for concrete with normal construction brick aggregate, sandlime brick aggregate, engineering brick aggregate and Thames Valley gravel aggregate is 10330.45, 9414.23, 16598.18 and 23047.49N/mm^2.

The average static modulus of elasticity for concrete with normal construction brick(LBC) aggregate, sandlime brick aggregate and engineering brick aggregate is 55%, 59% and 28% lower respectively as compared to concrete with Thames Valley gravel.

The static modulus of elasticity is observed to increase with increase in strength of brick aggregates. Static modulus of elasticity of bricks ranges from 3500N/mm^2 for low strength bricks to 34000N/mm^2 for high strength bricks whereas static modulus of elasticity for hardened cement paste varies from 6900N/mm^2 to 27600N/mm^2 depending upon w/c ratio. Static modulus of elasticity for natural aggregates varies from 34500N/mm^2 to 69000N/mm^2[86]. Lower static modulus of elasticity of concrete with brick aggregates is due to the lower tensile strength and lower modulus of elasticity of brick aggregates as compared to gravel. Very high values of static modulus of elasticity of aggregates tend to increase the static modulus of concrete. The decrease in static modulus of elasticity of concrete with brick aggregates depends upon the static modulus of elasticity of the bricks from which the aggregates have been obtained.

ACI Code 318-83 gives the value of static modulus of elasticity for normal weight concrete by the expression:

E_c (GPa) = $4.70 f_{cyl}^{0.5}$ where f_{cyl} is cylinder strength (MPa)

For concrete with normal construction brick aggregate, sandlime brick aggregate and engineering brick aggregate respectively, following equations for average static modulus of elasticity are observed to be reasonably accurate within $\pm 10\%$:

$$E_c \text{ (GPa)} = 2.11 f_{cyl}^{0.5}$$

$$E_c \text{ (GPa)} = 1.927 f_{cyl}^{0.5}$$

$$E_c \text{ (GPa)} = 3.384 f_{cyl}^{0.5}$$

4.6.2. Dynamic modulus of elasticity

Test beams 150*150*750mm were cast for carrying out the dynamic modulus of elasticity tests. The specimens were cured for 28 days as specified by BS 1881: Part 111: 1983. The dynamic modulus of elasticity was evaluated as per BS 1881: Part 5: 1970. Table 4.8 gives the variation in dynamic modulus of elasticity for specimens tested in the laboratory.

TYPE OF AGGREGATE	**MIX**	**COMP. STRENGTH 28DAYS** N/mm^2	**DYNAMIC MODULUS OF ELASTICITY** N/mm^2
London brick	LBC/63	33.30	18551.3
	LBC/56	36.40	23546.9
	LBC/50	38.35	23812.8
	LBC/385	46.37	24101.9
Sandlime brick	SBC/63	33.44	22125.8
	SBC/56	35.30	23556.7
	SBC/50	36.33	25737.6
	SBC/385	43.93	25517.7
Engineering brick	EBC/63	48.59	33190.8
	EBC/56	55.62	32384.6
	EBC/50	64.46	33763.8
	EBC/385	71.00	33562.4
	EBC/296	80.98	34143.0
Gravel	GC/63	27.27	45296.6
	GC/56	33.58	45531.1
	GC/50	41.34	46922.8
	GC/385	53.81	47557.8
	GC/296	64.90	49825.5

Table 4.8: Relationship between compressive strength and dynamic modulus of elasticity.

Average resonant frequencies observed for concrete with normal construction brick aggregate, sandlime brick aggregate and engineering brick aggregate were observed to be about 26%, 25% and 13% lower than for concrete with Thames Valley gravel aggregate with an average value of 2965Hz. Resonant frequencies were observed to increase with decrease in w/c ratio.

For w/c ratio reducing from 0.63 to 0.296, the dynamic modulus of elasticity for concrete with normal construction brick increased from 18551 to 24101N/mm^2 whereas concrete with sandlime brick aggregate increased from 22125 to 25737N/mm^2. Values for dynamic modulus for concrete with engineering brick aggregate increased from 33190 to 34143N/mm^2 against values of 45531 to 49825N/mm^2 for concrete with Thames Valley gravel. Hence the average dynamic modulus for concrete with normal construction brick aggregate, sandlime brick aggregate and engineering brick aggregate is 47, 51 and 70% respectively of the value for concrete with Thames Valley gravel aggregate. Lower relative densities of brick aggregates reduce the resonant frequencies thereby reducing the dynamic modulus for concrete with crushed brick aggregates. The dynamic modulus for concrete with crushed brick aggregates increased with increase in strength and density of brick aggregate.

4.7. ULTRASONIC PULSE VELOCITY

Ultrasonic pulse velocity tests for the brick aggregate concrete specimen were carried out as per BS 1881: Part 203: 1986. 150mm cubes were cured for 28 days as per BS 1881: Part 111: 1983 before testing for the pulse velocity. It was observed that pulse velocity could be determined quite accurately across two opposite moulded faces of cubes since complete transducer and receiver surface could be made to contact the complete surface of the cubes, the surface of specimen being quite smooth. However it was difficult to obtain complete contact between the transducer or the receiver surface with the unmoulded face of the cubes due to surface unevenness resulting in increased timings observed for the pulses to travel through the specimen. These increases were not due to the variation in quality of concrete but rather to the variation in air gap due to reduced contact between the transducer/receiver surface and the unmoulded cube surface. Hence the average of pulse velocities across the two moulded surfaces only were used. Pulse velocity at right angles to the direction of compaction can be about 2% higher than the velocity in the direction of compaction of specimen due to tendency of aligning of initial flaws at right angles to the direction of compaction, because of poor bonding of cement paste to the underside of aggregates(86).

Slightly lower (<2%) values of pulse velocities were observed near the top surface of cubes made from different types of brick aggregates concrete as compared to middle and bottom which is possibly due to the presence of more water voids near the top surface due to upward movement of water during compaction. Occasionally segregation could also be a cause of this variation.

Pulse velocities observed for concrete specimens with different types of crushed brick aggregates as well as with gravel aggregate and with w/c ratio ranging from 0.63 to 0.296 are given in Table 4.9.

TYPE OF AGGREGATE	MIX	COMP.STRENGTH 28DAYS N/mm^2	ELASTIC DYNAMIC N/mm^2	MODULUS STATIC N/mm^2	PULSE VELOCITY km/s
London brick	LBC/63	33.30	18551.3	8753.4	3.39
	LBC/56	36.40	23546.9	10087.3	3.67
	LBC/50	38.35	23812.8	11063.4	3.80
	LBC/385	46.37	24101.9	11417.7	3.96
Sandlime brick	SBC/63	33.44	22125.8	8348.1	3.61
	SBC/56	35.30	23556.7	8511.4	3.82
	SBC/50	36.33	25737.6	10086.9	3.87
	SBC/385	43.93	25517.7	10710.5	3.89
Engineering brick	EBC/63	48.59	33190.8	13375.6	4.00
	EBC/56	55.62	32384.6	15080.0	4.07
	EBC/50	64.46	33763.8	15108.6	4.12
	EBC/385	71.00	33562.4	17636.2	4.14
	EBC/296	80.98	34143.0	20272.3	4.21
Gravel	GC/63	27.27	45296.6	18910.5	4.48
	GC/56	33.58	45531.1	22506.3	4.64
	GC/50	41.34	46922.8	23480.2	4.76
	GC/385	53.81	47557.8	24033.5	4.79
	GC/296	64.90	49825.5	27292.9	4.94

Table 4.9: Relationship between compressive strength, moduli of elasticity and ultrasonic pulse velocity.

The average pulse velocity across concrete with normal construction brick(LBC) aggregate was observed to be 3.7km/s whereas average pulse velocity across concrete with sandlime brick aggregate was observed to be 3.8km/s. Similarly the average pulse velocity across concrete with engineering brick aggregate was observed to be 4.12km/s. For concrete with Thames Valley gravel as coarse aggregate average pulse velocity was observed to be 4.67km/s. Hence pulse velocity in the case of concrete with normal construction brick(LBC) aggregate, sandlime brick aggregate and engineering brick aggregate was observed to be 20, 18.5 and 12% lower as compared to pulse velocity in concrete with Thames Valley gravel aggregate.

Lower velocities for concrete with crushed brick aggregates are due to lower density and high porosity of brick aggregates. The velocity of ultrasonic pulses was observed to increase with the increase in density of brick aggregates.

Values obtained from BS 1881: Part 203: 1986 are given in Table 4.10. It was observed that pulse velocities, static moduli and dynamic moduli of elasticity obtained from experimental investigations did not correlate with the values given in BS 1881: Part 203: 1986 for concrete with

PULSE VELOCITY km/s	**DYNAMIC MODULUS** N/mm^2	**STATIC MODULUS** N/mm^2
3.6	24000	13000
3.8	26000	15000
4.0	29000	18000
4.2	32000	22000
4.4	36000	27000
4.6	42000	34000
4.8	49000	43000
5.0	58000	52000

Table 4.10: Empirical relationship between moduli of elasticity and pulse velocity.

different types of brick aggregates as well as Thames Valley gravel. Table 4.11 gives the average experimental values and empirical values for the static and dynamic moduli of elasticity for different concretes. The lower density brick aggregates with lots of internal fractures due to crushing are a source of larger variation of pulse velocities.

Measured values of static modulus of elasticity for

TYPE OF CONCRETE	PULSE VELOCITY km/s	EMPIRICAL MODULI STATIC N/mm^2	DYNAMIC N/mm^2	EXPERIMENTAL MODULI STATIC N/mm^2	DYNAMIC N/mm^2
London brick aggregate concrete	3.7	14000	25000	10330	22503
Sandlime brick aggregate concrete	3.8	15000	26000	9414	24234
Engineering brick aggregate concrete	4.12	20000	30500	16598	33225
Thames Valley gravel aggregate concrete	4.67	37150	44450	23047	47459

Table 4.11: Comparison of empirical and experimental Moduli of elasticity by pulse velocity measurements.

concrete with normal construction brick, sandlime brick and engineering brick aggregates are 26, 37 and 17% lower respectively, than the empirical values whereas measured value of static modulus of elasticity for concrete with gravel aggregate is 38% lower than the empirical value given by BS.

Similarly measured values of dynamic modulus of elasticity for concrete with normal construction brick and sandlime brick aggregates are 10% and 6.8% lower respectively, than the empirical values whereas measured value of dynamic modulus of elasticity for concrete with engineering brick and gravel aggregate are 9% and 6.7% higher than the empirical values given by BS.

4.8. DENSITY OF HARDENED CONCRETE

Densities of hardened concrete were obtained by weighing the specimens (cubes) accurately at the end of the 28 days curing period to obtain the saturated weight and measuring the dimensions accurately to obtain the volume of test cubes as per BS 1881: Part 114: 1983. The cubes were reweighed after heating them at 105°C +/- 5°C for 48 hours, to calculate the dry densities and absorption. Table 4.12 gives the densities of concrete with different types of brick aggregates as well as concrete with gravel aggregate, for different w/c ratios investigated.

TYPE OF AGGREGATE	MIX	DENSITY OF HARDENED CONCRETE (kg/m^3) dry	saturated
London brick	LBC/63	1979.26	2122.96
	LBC/56	1987.56	2123.56
	LBC/50	2013.00	2139.30
	LBC/385	2017.78	2142.22
Sandlime brick	SBC/63	2045.00	2184.80
	SBC/56	2070.52	2210.40
	SBC/50	2097.30	2231.11
	SBC/385	2108.44	2241.44
Engineering brick	EBC/63	2176.30	2284.15
	EBC/56	2191.30	2296.30
	EBC/50	2233.19	2309.63
	EBC/385	2297.18	2331.26
	EBC/296	2307.81	2340.41
Gravel	GC/63	2316.44	2408.60
	GC/56	2357.32	2414.51
	GC/50	2403.15	2454.80
	GC/385	2411.10	2457.70
	GC/296	2416.26	2459.81

Table 4.12: Densities of concretes with different aggregates.

The average saturated and dry densities for concrete with normal construction brick aggregates were observed to be 2132kg/m^3 and 1999kg/m^3 respectively. Average values of saturated and dry densities for concrete with sandlime brick aggregate were observed to be 2217 and 2080kg/m^3

respectively whereas for concrete with engineering brick aggregates the values were 2312 and 2241kg/m^3. The average saturated and dry densities for concrete with Thames Valley gravel were observed to be 2438 and 2386kg/m^3. Hence densities of concrete with normal construction brick, sandlime brick and engineering brick aggregates are 12.6, 9 and 5% lower as compared to the density of concrete with gravel aggregate. The density of concrete with brick aggregates was observed to increase with increase in the density of brick aggregates.

On saturating another set of specimen and drying under the similar conditions as for obtaining the densities, average absorption for concrete with normal construction brick, sandlime brick and engineering brick aggregates were observed to be 6.75, 6.7 and 3.65% respectively. Average absorption for concrete with Thames Valley gravel was observed to be around 3%. The higher absorption of concrete with normal construction brick aggregates is due to higher absorption of bricks from which these aggregates are obtained. The lower absorption of concrete with engineering brick aggregate is due to lower absorption of engineering bricks whereas least absorption of concrete with gravel aggregate is due to low absorption of gravel aggregate.

4.9. COEFFICIENT OF THERMAL EXPANSION

Experiments to monitor the variation in length with increase/decrease in temperatures were monitored for concrete with brick aggregates and with Thames Valley gravel for w/c ratio of 0.63 and the specimens were fully saturated at the time of test.

Prismatic specimen 100*100*500mm were cast with thermistors inside them to monitor inside temperatures during testing. The specimen were cured in water at 20°C for 28 days after which they were tested. Demec strain gauge was used for measuring the length changes during heating/cooling. The specimens were heated in an oven from 19°C to 100°C and the temperature inside the specimen along with changes in length were observed at intervals. Similarly the specimen were cooled from 19°C to -30°C in a refrigerating unit and variation in length was measured along with the inside temperature of the specimen at regular intervals.

Table 4.13 and Figure 4.15 show the variation in length with change in temperature for different concretes.

TEMPERATURE (°C)	EXPANSION/ CONTRACTION ($*10^{-4}$mm)	TEMPERATURE (°C)	EXPANSION/ CONTRACTION ($*10^{-4}$mm)
Sample 1. LBC W/C RATIO 0.63		**Sample 3. EBC W/C RATIO 0.63**	
94	+6.19	97	+7.29
61	+3.94	63	+4.32
42	+2.69	43	+2.92
19	0.00	19	0.00
0	-1.87	-2	-1.40
-21	-3.07	-26	-3.17
Coefficient=$8.052*10^{-6}$ per °C		Coefficient=$8.504*10^{-6}$ per °C	
Sample 2. SBC W/C RATIO 0.63		**Sample 4. GC W/C RATIO 0.63**	
97	+11.19	101	+10.84
61	+6.48	67	+6.62
41	+4.03	48	+4.17
19	0.00	19	0.00
-1	-2.59	-3	-2.45
-25	-4.80	-27	-5.09
Coefficient=$1.311*10^{-5}$ per °C		Coefficient=$1.245*10^{-5}$ per °C	

Table 4.13. Variation in length with temperature change.

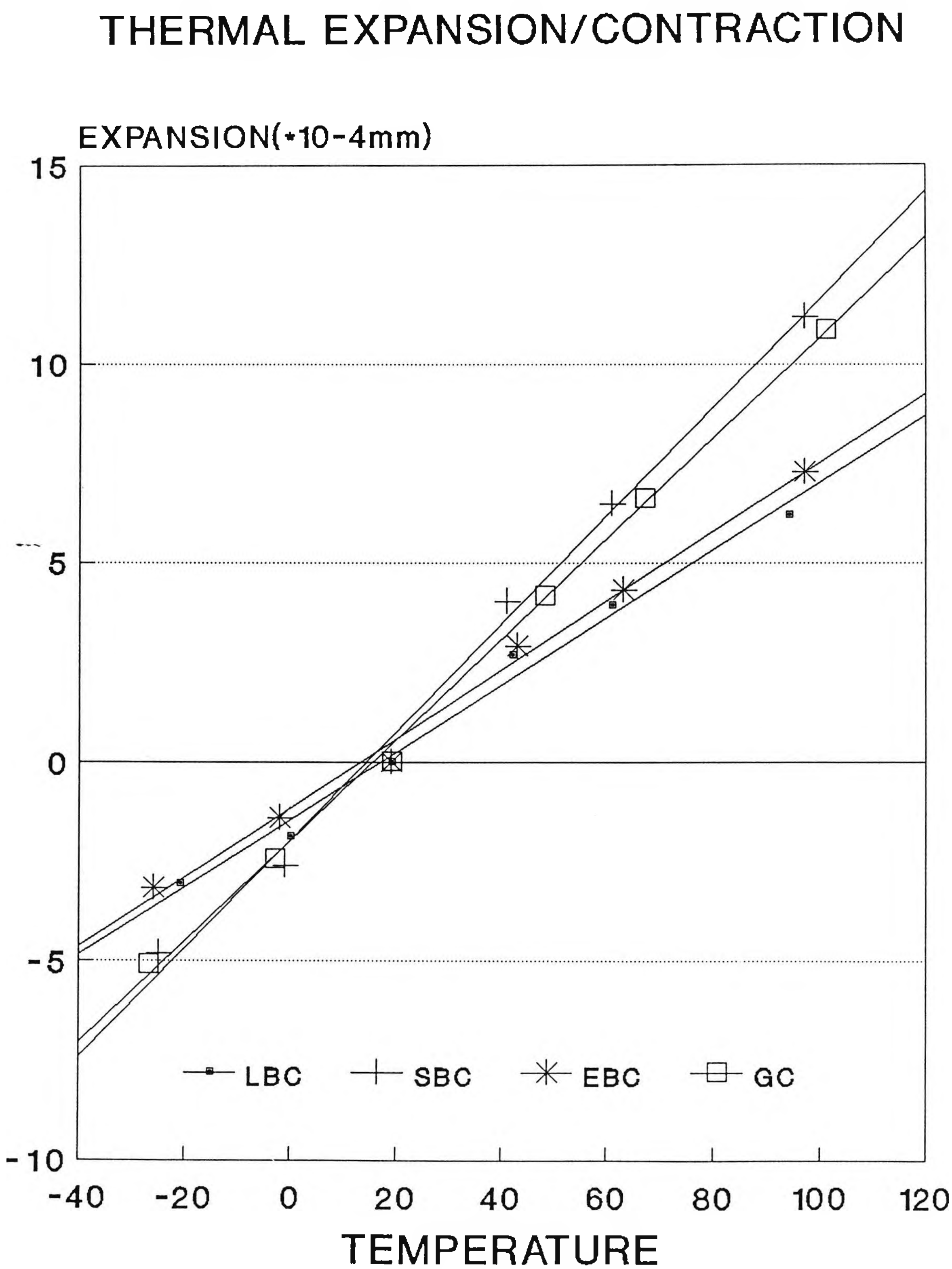


Figure 4.15. Variation in length with temperature change.

Thermal expansion of concrete with crushed brick aggregates was observed to be linear in the temperature range of -27°C to 100°C, similar to concrete with gravel aggregate. No variation in coefficient of thermal expansion was observed for temperatures less than 20°C, unlike concrete with limestone aggregates which shows highly reduced coefficient of thermal expansion at temperatures below 20°C as compared to much higher values above 20°C.

The coefficient of thermal expansion for concrete with normal construction brick, sandlime brick and engineering brick aggregates were observed to be $8.052*10^{-6}$ per °C, $1.311*10^{-5}$ per °C and $8.504*10^{-6}$ per °C respectively as compared to coefficient of thermal expansion of concrete with gravel aggregate of $1.245*10^{-5}$ per °C. Hence the coefficient of thermal expansion for concrete with sandlime brick aggregate was observed to be 5% higher than concrete with Thames Valley gravel whereas coefficient of thermal expansion of normal construction brick aggregate and engineering brick aggregate were observed to be 35 and 32% lower respectively as compared to concrete with gravel aggregate.

The coefficient of thermal expansion of cement paste varies from 12 to $20*10^{-6}$ per °C depending on the moisture condition. Coefficient of thermal expansion for natural aggregates varies from 6 to $12*10^{-6}$ per °C[86]. The coefficient of thermal expansion for clay bricks varies from 3 to $5.6*10^{-6}$ per °C whereas for gravel it is $12*10^{-6}$

per °C. Hence the aggregates, with lower coefficient of thermal expansion, tend to restrain cement paste with higher values for coefficient of thermal expansion. The lower values of coefficients of thermal expansion of concrete with normal construction brick and engineering brick aggregates is due to lower coefficient of thermal expansion for bricks from which these aggregates were obtained. Higher coefficient of thermal expansion for concrete with sandlime brick aggregate is due to higher coefficient of thermal expansion of sandlime bricks. Sandlime bricks are made from a mixture of sand and lime both of which have higher coefficients of thermal expansion.

4.10. CONCLUSIONS

Brick aggregate concrete cannot be easily designed using the Road Note 4 method given in 'Design of Normal Concrete Mixes'. A design method has been suggested in chapter 3 and using this the required characteristic compressive strength can be achieved almost in the first mix.

Prewetting of aggregates is necessary before mixing to avoid any appreciable loss of workability after mixing. Workability for brick aggregate concrete is reduced by more than half of the design values but improvement of workability is possible by slight alterations in the quantities of materials.

Table 4.14 summarises the mechanical properties of concrete with different types of crushed brick aggregates and control mix of concrete with gravel aggregates already given previously in this chapter.

MIX	COMP STR N/mm^2	TENSILE STR N/mm^2	FLEXURAL STR N/mm^2	ELASTIC MODULUS DYNAMIC N/mm^2	ELASTIC MODULUS STATIC N/mm^2	DENSITY kg/m^3 saturated	PULSE VELOCITY km/s
LBC/63	33.30	2.39	3.93	18551.3	8753.4	2122.96	3.39
LBC/56	36.40	2.44	3.03	23546.9	10087.3	2123.56	3.67
LBC/50	38.35	2.97	4.40	23812.8	11063.4	2139.30	3.80
LBC/385	46.37	2.53	4.92	24101.9	11417.7	2142.22	3.96
LBC/296	47.72	-	-	-	-		
SBC/63	33.44	2.93	4.43	22125.8	8348.1	2184.80	3.61
SBC/56	35.30	2.59	4.64	23556.7	8511.4	2210.40	3.82
SBC/50	36.33	2.16	4.13	25737.6	10086.9	2231.11	3.87
SBC/385	43.93	3.04	4.80	25517.7	10710.5	2241.44	3.89
SBC/296	49.08	-	-	-	-		
EBC/63	48.59	4.07	6.20	33190.8	13375.6	2284.15	4.00
EBC/56	55.62	4.51	5.27	32384.6	15080.0	2296.30	4.07
EBC/50	64.46	4.79	5.33	33763.8	15108.6	2309.63	4.12
EBC/385	71.00	3.13	5.47	33562.4	17636.2	2331.26	4.14
EBC/296	80.98	3.63	6.52	34143.0	20272.3	2340.41	4.21
GC/63	27.27	2.75	3.98	45296.6	18910.5	2408.60	4.48
GC/56	33.58	2.96	3.90	45531.1	22506.3	2414.51	4.64
GC/50	41.34	3.25	4.41	46922.8	23480.2	2454.80	4.76
GC/385	53.81	3.47	5.33	47557.8	24033.5	2457.70	4.79
GC/296	64.90	3.81	5.94	49825.5	27292.9	2459.81	4.94

Coefficient of thermal expansion
a. LBC/63 = $8.052*10^{-6}$ per °C
b. SBC/63 = $1.311*10^{-5}$ per °C
c. EBC/63 = $8.504*10^{-6}$ per °C
a. GC/63 = $1.245*10^{-5}$ per °C

Table 4.14 : Summary - properties of concrete with different types of crushed brick and gravel aggregates.

Density of concrete with normal construction brick, sandlime brick and engineering brick aggregates is 12.6, 9 and 5% lower, respectively, as compared to normal concrete with hardened density of 2400kg/m^3. Density of concrete with brick aggregates increases with increase in the density of brick aggregates. Lower densities for concrete with brick aggregates are due to lower densities of brick aggregates as compared to gravel aggregate.

It has been shown that brick aggregate concrete of satisfactory strength can be produced. The compressive strength of brick aggregate concrete depends upon the crushing strength of the bricks from which the aggregates have been obtained. Aggregates obtained from normal construction bricks and sandlime bricks with crushing strength of 20 and 15N/mm^2 respectively can be satisfactorily used for concrete with maximum characteristic strength of 35N/mm^2. Average cylinder strengths developed by concrete with brick aggregates was observed to be 10% lower as compared to concrete with gravel aggregate.

Concrete with engineering brick aggregates obtained from engineering 'B' bricks with crushing strength of 40N/mm^2 developed 25 to 30% higher compressive strength as compared with normal concrete. For w/c ratio of 0.296 concrete with engineering brick aggregates developed 80.9N/mm^2. Such high strengths are otherwise difficult to achieve without the use of workability aids. Higher compressive strengths for concrete with engineering brick aggregate were due to higher crushing strength of engineering bricks from which these aggregates were obtained and due to better bonding and interlocking of aggregates with the cement paste due to irregular shape and texture.

Concrete with normal construction brick (LBC) aggregate and sandlime brick aggregate have on the average 18% and 22%, respectively, lower splitting tensile strength as compared to concrete with Thames Valley gravel whereas concrete with engineering brick aggregate has an average of about 20% higher splitting tensile strength. Hence the splitting tensile strength increases with the increase in crushing strength of the bricks from which the aggregates have been obtained along with better bonding and interlocking of brick aggregates with the cement paste. Lower splitting tensile strengths of concrete with normal construction brick and sandlime brick aggregates are due to lower tensile strengths of the normal construction bricks and sandlime bricks from which these aggregates were obtained. The tensile strength of normal construction brick, sandlime brick and engineering brick was observed to be 1.14N/mm^2, 0.85N/mm^2 and 2.07N/mm^2 respectively.

Similarly average flexural strength values for concrete with normal construction brick and sandlime brick aggregates were 13.5 and 5%, respectively, lower than concrete with gravel aggregate whereas concrete with engineering brick aggregates had 22% higher flexural strength as compared to concrete with gravel aggregate. The reasons for this variation in values of flexural strength are similar to the reasons for variation in splitting tensile strengths given previously.

Average strains on failure for w/c ratio from 0.63 to 0.269 for concrete with normal construction brick, sandlime brick and engineering brick aggregates were observed to be 83%, 28.5% and 10% higher, respectively, as compared to concrete with Thames Valley gravel.

The average static modulus of elasticity for concrete with normal construction brick(LBC) aggregate, sandlime brick aggregate and engineering brick aggregate is 55%, 59 and 28% lower, respectively, as compared to concrete with Thames Valley gravel. The average dynamic modulus for concrete with normal construction brick aggregate, sandlime brick aggregate and engineering brick aggregate is 26, 25 and 13%, respectively, lower than the value for concrete with Thames Valley gravel aggregate.

Coefficient of thermal expansion for concrete with sandlime brick aggregate was observed to be 5% higher than concrete with Thames Valley gravel whereas coefficient of thermal expansion of normal construction brick aggregate and engineering brick aggregate were observed to be 35 and 32% lower, respectively, as compared with the value for concrete with gravel aggregate. The lower coefficient of thermal expansion of normal construction brick aggregate and engineering brick aggregate along with the greater strain capacity at failure explains higher fire resistance of such concrete as compared to concrete with Thames Valley gravel.

A comparison made on the basis of similar compressive strengths selected from Table 4.14 is given in Table 4.15. For similar compressive strength, concrete with normal

MIX	COMP STR N/mm^2	TENSILE STR N/mm^2	FLEXURAL STR N/mm^2	ELASTIC MODULUS DYNAMIC N/mm^2	STATIC N/mm^2	DENSITY kg/m^3 saturated	PULSE VELOCITY km/s
LBC/63	33.30	2.39	3.93	18551.3	8753.4	2122.96	3.39
SBC/63	33.44	2.93	4.43	22125.8	8348.1	2184.80	3.61
GC/56	33.58	2.96	3.90	45531.1	22506.3	2414.51	4.64
EBC/56	55.62	4.51	5.27	32384.6	15080.0	2296.30	4.07
GC/385	53.81	3.47	5.33	47557.8	24033.5	2457.70	4.79
EBC/50	64.46	4.79	5.33	33763.8	15108.6	2309.63	4.12
GC/296	64.90	3.81	5.94	49825.5	27292.9	2459.81	4.94

Table 4.15. Comparison of concrete on the basis of similar compressive strengths.

construction brick has about 12% higher w/c ratio, 20% lower tensile strength, similar flexural strength, 59% lower dynamic modulus, 60% lower static modulus and 12% lower densities as compared to concrete with gravel. Similarly concrete with sandlime brick has about 12% higher w/c ratio, almost similar tensile strength, 13% higher flexural strength, 51% lower dynamic modulus, about 62% lower static modulus and 10% lower densities as compared to concrete with gravel.

For similar compressive strength, concrete with engineering brick has about 55% higher w/c ratio, about 25% higher tensile strength, about 10% lower flexural strength, 30% lower dynamic modulus, 45% lower static modulus and 7% lower densities as compared to concrete with gravel.

4.11. RECOMMENDATIONS

Concrete with normal construction brick and sandlime brick aggregate has 12 to 9% lower density as compared to normal concrete which is beneficial since it reduces the dead load of the structure. The lower modulus of elasticity of concrete with normal construction brick aggregate and sandlime brick aggregate as compared to normal concrete can result into higher deflections. The lower tensile and flexural strengths could lead to increased cracking in tension and flexure although higher failure strain capability of concrete with normal construction brick and sandlime brick aggregates may tend to reduce the number of cracks.

Concrete with brick aggregates from normal construction brick and sandlime brick is suitable for most structural applications where the compressive strength required is up to $40N/mm^2$. The structural elements of low rise buildings will normally fall within this category. Concrete structures such as walkways and foundations of light buildings which are continually supported and have no deflection problems can also be made from concrete with normal construction brick and sandlime brick aggregates. Concrete with normal construction brick aggregate has the advantage of having 35% lower coefficient of thermal expansion which, combined with its higher limiting strain capability, can be useful in reducing damage to beams and columns in case of fire.

Concrete with brick aggregates from engineering bricks has 5% lower density as compared to normal concrete which reduces the dead weight of the structure. Higher w/c ratio for concrete with engineering brick aggregates and thus the implied lower cement content makes it more economic than normal concrete. A 32% lower static modulus of elasticity for concrete with engineering brick aggregates may result in slightly larger deflections than normal concrete whereas the higher tensile and flexural strength along with higher failure strains for concrete with engineering brick aggregate help in reducing cracking of structures in tension or flexure. Hence concrete with brick aggregates from engineering bricks is suitable for all structural uses. Concrete with engineering brick aggregate has 32% lower coefficient of thermal expansion as compared to normal concrete hence it will provide a better fire resistance.

CHAPTER 5

TIME DEPENDENT PROPERTIES OF CONCRETE WITH CRUSHED BRICK COARSE AGGREGATES

This chapter deals with investigations carried out to assess the shrinkage and creep properties of concrete with different types of crushed brick aggregates. A brief discussion on structure of concrete and the mechanism of shrinkage and creep are given in section 5.1, followed by the details and results of tests carried out for shrinkage and creep of concrete with crushed brick aggregates. Shrinkage and creep values are also compared with the values obtained from similar tests on specimens of concrete with gravel aggregate.

5.1. GENERAL

The hydration of cement produces a coherent mass composed primarily of poorly crystallised colloidal reaction products together with some non-colloidal products principally $Ca(OH)_2$. Cement gel occupies little more than twice as much space as the cement from which it is derived hence occupying the space of cement particles and some or all of the interstitial space initially filled with water. The cement gel exists in dense masses which mostly starts developing on $Ca(OH)_2$ crystals formed soon after hydration commences. Most bodies of cement gel have a laminar structure which could be more or less tubular and concentric except at outer parts where the contours of the laminae adapt to the interstitial spaces between bodies of cement gel. The interstitial spaces left between the laminae are voids and correspond to capillary spaces. The mean size of gel bodies is 5000Å, which is smaller, the denser the paste, and interstitial spaces reduces progressively and finally at w/c ratio of 0.4, gel bodies merge with each other to form a continous mass, hence very little or no capillary space exists in such pastes on maturity. Laminae of cement gel are probably sheets of colloidal tobermorite with an average thickness of 30Å. The spaces between laminae are of gel pores with average width of 15Å. Cross links between laminae are assumed to be $Ca(OH)_2$ crystals, since cement gel exhibits limited swelling capability. Cement gel bodies behave as colloids because of their extreme thinness of about 30Å.

Studies by electron microscopy revealed that the diameter of one molecule of adsorbed water was 2.63Å. The maximum thickness of the adsorbed layer on an open surface in saturated conditions was found to be five molecules thick. Hence spaces in cement gel less than ten molecular diameters cannot accommodate all adsorbed water at saturation humidity. Since average spacing in cement gel is 15Å, many spaces will be less than the average spacing. Below saturation pressure, the thickness of adsorbed layer on open surfaces depends on the ambient vapour pressure varying from 0.76 times at 5% relative humidity to 5 times at 100% relative humidity(86).

Solid surfaces experience forces of attraction between them which depend on the distance and the medium between them. The magnitude of the van der Waals forces varies inversely as the fourth or fifth power of the inter-particle distances between the tobermorite crystals. The thickness of adsorbed layer of water changes the magnitude of these forces of mutual attraction thereby exerting pressure on confining surfaces.

The time-dependant deformational behaviour of loaded and unloaded hardened cement paste shows distinct similarity between creep and shrinkage. Both these processes are governed by movement or migration of various types of water. Reversible creep is similar to reversible shrinkage whereas irreversible creep is similar to irreversible shrinkage. A number of hypotheses exist on mechanism of shrinkage and creep in concrete. The mechanism of shrinkage suggested by Powers[86] is discussed below.

Shrinkage occurs when water is lost by evaporation through the exposed surfaces. The adsorbed films are depleted of water resulting into film tension. The resulting hydrostatic tension due to film tension tends to draw water from the surrounding cavities. Reduction in the thickness of adsorbed layer hence results into increased forces of attraction between the solid surfaces resulting into shrinkage. Hence shrinkage is greater the greater the capillary porosity.

The vapour pressure in a saturated specimen is lower than that of pure water due to presence of alkali in the specimen. On evaporation of water from the specimen, the concentration of alkali increases. Hence vapour pressure decreases due to increase in concentration of alkali as well as due to increase in hydrostatic tension. The increase in concentration of alkali increases the permeability of drying concrete although porosity is decreasing due to closing of some channels. It is likely that first drying connects initially isolated channels and subsequent drying empties larger cavities[86].

Irreversible shrinkage is due to closing of some pores in first drying resulting in diminished internal surface area and reduced porosity. The gel bodies are thought to undergo irreversible compression whereas interstitial spaces open up forming new inter-connecting passages. Therefore the specimen cannot be resaturated again to the same degree as before drying resulting into irreversible shrinkage. Hence any subsequent shrinkage after resaturation is always smaller than the first shrinkage[86].

For concrete with normal weight aggregates, swelling is ten to twenty times smaller than shrinkage whereas it can be twenty to eighty percent of shrinkage, for lightweight concretes. Whilst in the plastic state, cement paste undergoes a volumetric contraction of about 1% of the volume of cement content due to loss of water due to evaporation or by suction of water by drier concrete below. This is termed as plastic shrinkage. Autogenous shrinkage occurs due to loss of water used up in hydration process and is very small in the range of 50 to $100*10^{-6}$. Carbonation shrinkage occurs due to formation of carbonic acid which reacts with $Ca(OH)_2$ to form $CaCO_3$ resulting in shrinkage of concrete. Deposition of $CaCO_3$ reduces permeability whereas release of water on decomposition of $Ca(OH)_2$ aids hydration resulting in slight increase in strength[12]. Carbonation shrinkage and autogenous shrinkage are due to chemical processes and are not considered in shrinkage due to physical processes not affecting the chemical composition of solids.

Shrinkage is considerably reduced by increased aggregates percentages and improved gradings. Higher w/c ratio increases shrinkage by providing higher capillary water content thereby accelerating the contraction process. Higher percentage of capillaries and voids associated with high w/c ratios tend to reduce the rigidity of the solid matrix thereby reducing its capacity to resist contraction of cement gel on shrinkage[86].

Basic creep occurs under sustained load. As explained by Ishai[86], under sustained load compressed liquid begins to diffuse and migrate from areas of high pressure to low pressure areas within concrete. Under uniform pressure, transfer of load takes place from the liquid phase to the solid phase. The pressure on capillary water and gel water disappears in few weeks time. The part of creep deformation governed by migration of capillary and gel water is reversible. On unloading, creep deformation is recovered completely with some delay due to the viscous resistance of the confined liquid. This mechanism is known as creep recovery.

The creep process which takes place in the inter-crystalline and intra-crystalline spaces and the adsorbed water present in these spaces is prolonged and slow. The applied loading causes a decrease in the interparticle spaces leading to irrecoverable creep. The compacting or squeezing mechanism continues long after the recoverable creep process has terminated and leads to creep deformation proceeding for years.

Increase in w/c ratio increases creep. Creep is reduced as the percentage of aggregate increases provided it is harder than the cement paste. The affect of mineral type of the aggregate on creep is not clear and has not been widely investigated[86].

5.2. SHRINKAGE

Shrinkage tests were carried out in accordance with RILEM Recommendation CPC 9 Measurement of shrinkage and swelling. 100*100*500mm prismatic specimen of concrete with different types of crushed brick aggregates and with gravel aggregate with w/c ratios of 0.63, 0.50, 0.385 and 0.296 were cast with metallic gauge points for measuring shrinkage using 8 inch Demec gauge. The specimen were cured in water at 20°C for 28 days before the start of test. The gauge length of the prisms were then accurately measured and specimens stored in a conditioning room with temperature controlled at 20°C and relative humidity at 65% for a period of ninety days after which the gauge length was again measured accurately to enable the shrinkage to be calculated. Table 5.1 gives the shrinkage values observed for concrete with different brick aggregates as well as control mix. Figure 5.1 shows a specimen ready for shrinkage test.

SAMPLE	MIX	SHRINKAGE($*10^{-4}$) 90 DAYS
London brick Concrete	LBC/63	2.400
	LBC/50	4.368
Sandlime brick Concrete	SBC/63	6.672
	SBC/50	7.150
Engineering brick Concrete	EBC/63	0.816
	EBC/50	1.230
	EBC/385	7.824
	EBC/296	8.125
Gravel Concrete	GC/63	0.500
	GC/50	1.176
	GC/385	2.976
	GC/296	2.112

Table 5.1. Shrinkage values for different concretes.

The shrinkage of concrete with normal construction brick aggregate was observed to be four to five times higher than concrete with Thames Valley gravel whereas concrete with sandlime brick showed seven to ten times greater shrinkage. Concrete with engineering brick aggregates was observed to vary between a half to twice the value of shrinkage for concrete with Thames Valley gravel.

It was observed that shrinkage increased with increase in cement content. The increased values of shrinkage for concrete with brick aggregates are due to higher absorption of the brick aggregates like 20% for normal construction brick aggregate, 10% for sandlime brick aggregate and 3% for engineering brick aggregate along with lower modulus of

Figure 5.1. Specimen prepared for shrinkage test.

elasticity as compared to gravel. Increased shrinkage for concrete with brick aggregates is also due to the property of brick aggregates to expand on saturation and contract on drying compared to negligible contraction on drying of Thames Valley gravel aggregates.

Shrinkage value for hardened cement paste varies from 2000 to $3000*10^{-6}$ whereas shrinkage is negligible for natural aggregates. Bricks tend to contract on drying and contraction varies from 0.02 to 0.07%.

5.3. CREEP UNDER UNIAXIAL COMPRESSION

Tests for creep in uniaxial compression were carried out in accordance with RILEM Recommendation. Prisms 100*100*500mm were cast and cured in water at 20°C for 28 days before loading. The temperature was maintained at 20°C and humidity at 65% for the entire period of one year. A constant load of 40% of the ultimate load of the weakest concrete i.e concrete with sandlime brick aggregates was maintained on all specimen to observe the relative values of creep for concrete with different types of brick aggregates.

Figure 5.2 shows a specimen fixed in creep frame for testing. Table 5.2 gives the creep strains observed during the test, for concrete with different aggregates. Figure 5.3 shows the performance of concrete with different aggregates with regards to creep.

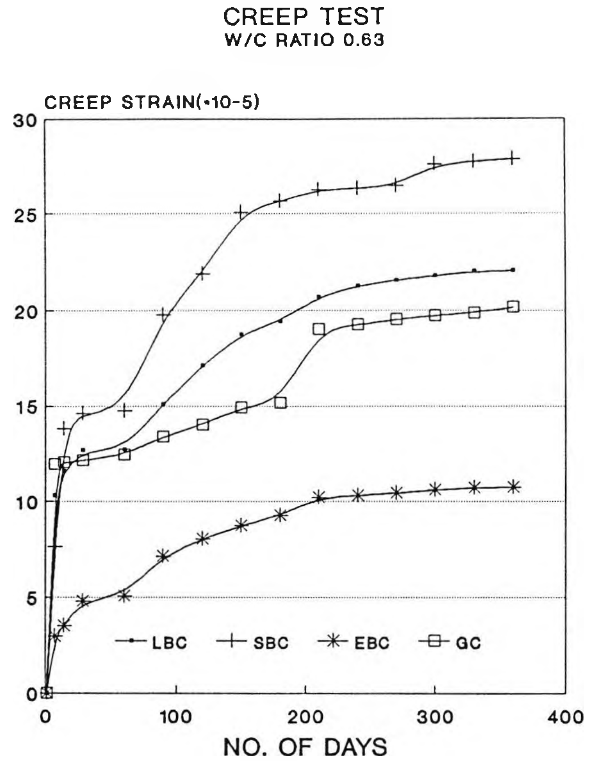
It was observed that almost 70 to 85% of one year creep value was attained within the first six months. The creep

DURATION	CREEP READINGS($*10^{-5}$)			
	LBC	SBC	EBC	GC
i. W/C Ratio 0.63				
Day 1	0.0000	0.0000	0.0000	0.0000
Week 1	10.300	7.6330	3.0000	11.933
Week 2	11.567	13.833	3.5330	12.033
Week 4	12.667	14.633	4.8000	12.133
Month2	12.700	14.767	5.0670	12.433
Month3	15.100	19.767	7.1330	13.400
Month4	17.133	21.900	8.0330	14.033
Month5	18.767	25.067	8.7330	14.933
Month6	19.433	25.667	9.2670	15.167
Month7	20.700	26.267	10.200	19.033
Month8	21.266	26.340	10.312	19.249
Month9	21.567	26.467	10.433	19.533
Month10	21.790	27.614	10.610	19.735
Month11	22.022	27.766	10.716	19.866
Month12	22.067	27.872	10.741	20.156
CREEP STRAINS AFTER ONE YEAR	$2.207*10^{-4}$	$2.787*10^{-4}$	$1.074*10^{-4}$	$2.016*10^{-4}$
ii. W/C Ratio 0.50				
Day 1	0.0000	0.0000	0.000	0.000
Week 1	3.3100	2.1240	1.467	1.166
Week 2	3.8000	2.6340	1.502	2.600
Week 4	5.0000	4.2340	1.767	3.533
Month2	6.1000	6.8670	2.167	4.633
Month3	6.9670	9.0670	2.404	5.566
Month4	7.5670	9.6670	2.829	5.833
Month5	8.0670	9.6670	3.313	6.166
Month6	8.3220	9.8910	3.784	6.500
Month7	8.6000	10.200	4.031	6.966
Month8	9.1890	10.634	4.310	7.339
Month9	9.4340	11.126	4.594	7.680
Month10	9.8510	12.201	4.877	7.805
Month11	10.109	12.382	5.089	7.968
Month12	10.210	12.428	5.373	8.065
CREEP STRAINS AFTER ONE YEAR	$1.021*10^{-4}$	$1.243*10^{-4}$	$5.373*10^{-5}$	$8.065*10^{-5}$

Table 5.2. Creep strains for different concretes.

Note: LBC is normal construction brick(LBC) aggregate concrete.
SBC is sandlime brick aggregate concrete.
EBC is engineering brick aggregate concrete.
GC is Thames Valley gravel aggregate concrete.

Figure 5.2. Specimen fixed for creep testing.



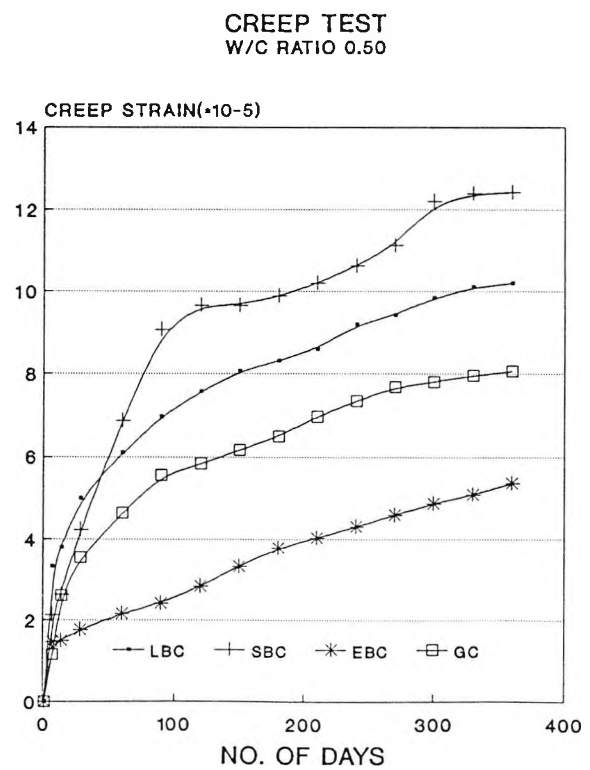


Figure 5.3. Creep of different concretes vs time.

strain values for concrete with normal construction brick, sandlime brick, engineering brick and Thames Valley gravel aggregates were observed to be $2.207*10^{-4}$, $2.787*10^{-4}$, $1.074*10^{-4}$ and $2.016*10^{-4}$ respectively, for w/c ratio of 0.63 and $1.021*10^{-4}$, $1.243*10^{-4}$, $5.373*10^{-5}$, $8.065*10^{-5}$ respectively, for w/c ratio of 0.5. Hence the average creep strain for concrete with normal construction brick aggregates was observed to be from 9.5 to 26.6% higher than concrete with Thames Valley gravel. Creep strains for concrete with sandlime brick aggregate were observed to vary from 38.2 to 54% higher than concrete with Thames Valley gravel. Concrete with engineering bricks developed from 33 to 46% lower creep strains as compared to concrete with Thames Valley gravel.

5.4. CONCLUSIONS

5.4.1. SHRINKAGE

Shrinkage for concrete with normal construction brick aggregate was observed to be four to five times higher than concrete with Thames Valley gravel whereas concrete with sandlime brick showed seven to ten times greater shrinkage. Concrete with engineering brick aggregates was observed to vary between a half to twice the value of shrinkage for concrete with Thames Valley gravel.

Shrinkage increased with increase in cement content. The increased values of shrinkage for concrete with brick aggregates is due to the higher absorption of the brick aggregates, 20% for normal construction brick aggregate, 10% for sandlime brick aggregate and 3% for engineering brick aggregate, along with the lower modulus of elasticity as compared to gravel. Increased shrinkage of concrete with brick aggregates is also due to the tendency of brick aggregates to expand on saturation and contract on drying compared to negligible contraction on drying of Thames Valley gravel aggregates.

5.4.2. CREEP UNDER UNIAXIAL COMPRESSION

Average creep strains for concrete with normal construction brick aggregates were observed to be about 18% higher than those for concrete with Thames Valley gravel. Creep strains for concrete with sandlime brick aggregate were observed to be approximately 46% higher than concrete with Thames Valley gravel. Concrete with engineering bricks developed an average of 39% lower creep strains as compared to concrete with Thames Valley gravel.

The larger creep strains developed by concretes with normal construction brick aggregates are due to high porosity, lower modulus of elasticity and lower strength of their aggregates whereas the lower creep strains produced in concrete with engineering brick aggregates appear to be due to almost 30% higher compressive strengths shown by its specimen during strength tests.

PART 3

DURABILITY OF CONCRETE WITH CRUSHED BRICK COARSE AGGREGATES

This part covers the investigations on durability of concrete with different types of crushed brick aggregate. It comprises of three chapters.

Chapter 6 deals with permeability investigations. This chapter discusses permeability along with factors affecting permeability, the nature and sizes of pores in concrete and factors affecting the size and distribution of pores. Transport mechanisms in concrete are briefly discussed followed by a survey of the existing methods of testing permeability. Results of the selected permeability tests carried out are then evaluated for the performance of concrete with crushed brick aggregates.

Chapter 7 covers the investigations on frost resistance of concrete with different types of crushed brick aggregates. A general discussion on frost resistance, its effects on concrete and factors affecting frost resistance is followed by a study of the mechanism of frost action in aggregates, cement paste and the overall effects. A survey of the available methods of testing frost resistance of aggregates and concrete is carried out. Discussion of the performance of concrete with different types of crushed brick aggregates in frost resistance testing is followed by concluding remarks.

Chapter 8 covers an investigation of sulphate resistance of concrete with different types of crushed brick aggregates. A general discussion on sulphate resistance is followed by a study of the mechanism of sulphate damage. A brief survey of the available test methods for testing the sulphate resistance of concrete with crushed brick aggregates is carried out. Results obtained from the sulphate resistance test on concrete with different types of crushed brick aggregates are discussed followed by conclusions.

Three specimens from three different batches were tested to assess each property hence the values given for each property represent an average of a total of nine specimens. For Voltage Driven Chloride Diffusion Test in permeability testing, one specimen from three different batches was tested resulting into a total of three specimens for each type of mix.

CHAPTER 6

PERMEABILITY

This chapter discusses the permeability characteristics of concrete. Section 6.1 gives a general discussion on permeability including factors affecting permeability, the nature and sizes of pores present in the cement paste and factors affecting the pore size and distribution in concrete. Transport mechanisms in concrete are discussed in section 6.2. A brief survey of existing permeability tests on concrete is carried out in section 6.3. The tests selected for permeability testing of concrete with crushed brick aggregates were ISAT and Voltage driven chloride diffusion test. In addition, capillary rise test was selected to investigate the pore sizes of different bricks which were used for concrete with crushed brick aggregate. This test facilitated the understanding of the frost resistance of concrete with crushed brick aggregates. The performance of concrete with different crushed brick aggregates is given in section 6.5.

6.1. GENERAL

Combined transportation of heat, moisture and chemical substances, within the concrete mass and in exchange with the surroundings, and parameters controlling these transport mechanisms constitute the principle elements of durability. Hardened cement paste and the aggregates in concrete are a porous mass with a number of pores. The size and distribution of pores are the main factor controlling the durability of concrete. The presence of water or moisture is the single and most important factor controlling various deterioration mechanisms, excluding mechanical deterioration. The transport of water within the concrete is determined by the pore type, size and distribution and by micro and macro cracks. Controlling the nature and distribution of cracks becomes an essential task in creating durable concrete structures [13,34]. The resistance of concrete to chemical and physical influences is considerably reduced by a larger quantity of capillary pores.

Permeability is the quality which governs the ease with which liquids and gases travel through concrete. This property is of interest in the case of air and other gases and for the watertightness of structures such as sewage tanks, gas purifiers, water retaining structures and pressure vessels in nuclear reactors. In the case of gas permeability, steady conditions are reached in hours as compared to days for water permeability. The extremely fine texture and very small size of the gel pores of cement gel reduces greatly its permeability compared with a porosity of around 28% for concrete with normal weight aggregate. Permeability of the hardened cement paste is dependent on the capillary porosity and pore size distribution because of the presence of the larger capillary pores. Capillary porosity depends upon the w/c ratio and degree of hydration. Permeability reduces greatly with reduction in w/c ratio, specially below 0.6 when the capillaries become largely discontinous and segmented[12]. Figures 6.1 and 6.2 show the relationship between permeability and w/c ratio and reduction in permeability of cement paste with the progress in hydration.

Powers[34] classified pores in the cement paste as gel

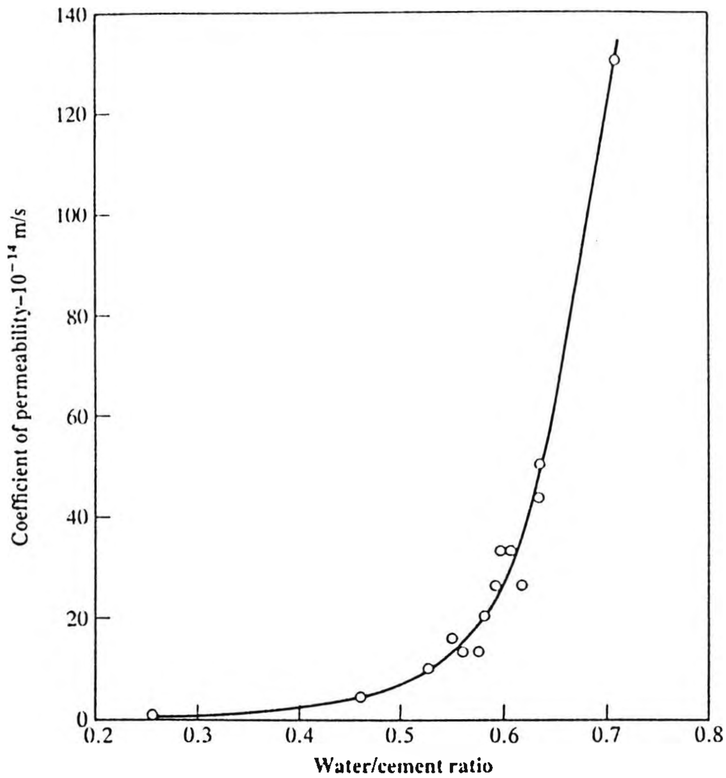


Figure 6.1. Relation between permeability and w/c ratio for mature cement pastes (93% of hydrated cement).
(Ref: Powers, Copeland, Hayes and Mann
Permeability of Portland cement paste
ACI Journal, Nov, 1954)

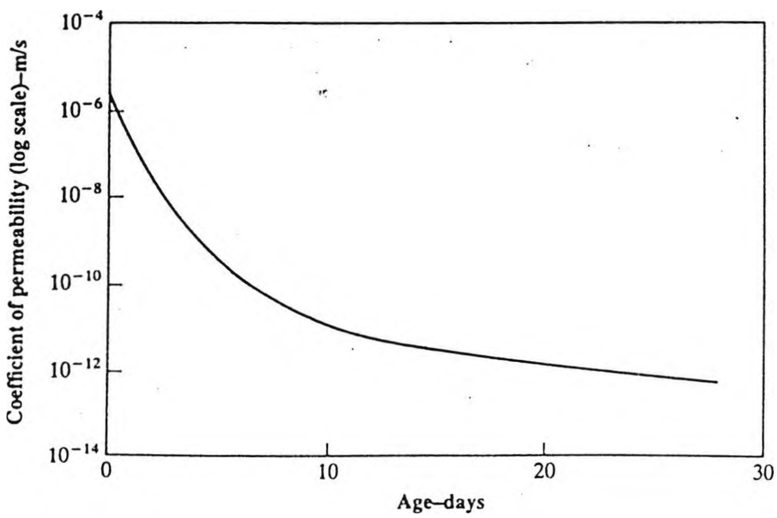


Figure 6.2. Reduction in permeability of cement paste with progress in hydration.
(Ref: Powers, Copeland, Hayes and Mann
Permeability of Portland cement paste
ACI Journal, Nov, 1954)

pores with less than 10nm diameter, capillary pores with pore sizes varying between 10 to 10,000nm diameter and air voids with diameter larger than 10,000nm.

Iupac[34] classified pore sizes into:

Micro pores with less than 2.5nm diameter,

Meso pores with diameters between 2.5 and 50nm,

Macro pores with diameters between 50 and 10,000nm,

Air voids with diameters larger than 10,000nm.

Large mesopores and macropores form part of the capillary system.

For capillaries with radii generally larger than 10^{-2}mm, a viscous, laminar flow of water is most probable whereas for pore radii between 10^{-2} to 10^{-4}mm, capillarity by means of surface tension of menisci is likely. For capillary radii less than 10^{-4}mm liquid conduction is through diffusion only[35].

Using mercury intrusion porosimetry (MIP), the size and distribution of pores down to the largest gel pores can be measured whereas sorption techniques must be used to measure the meso and micropores[34]. Gel pores are associated with the formation of hydration products while capillary pores are considered to be the remnants of water filled space[34]. Moist curing segments the capillaries in a short period. Moist curing interrupted with a period of drying will also decrease the permeability by segmenting the capillaries due to minute shrinkage cracks around the aggregate particles, especially the larger ones. The permeability of steam cured concrete is generally higher than moist cured concrete. Dense concrete with the use of well graded aggregate aids the attainment of lower permeabilities. ACI 301-75 specifies a maximum w/c ratio of 0.48 for watertight structural concrete for fresh water and 0.44 for sea water(12).

Use of more porous aggregates increases the permeability of concrete. Water and gas permeabilities are reduced with increase in lateral pressure(21). The pore size distribution is strongly influenced by the curing temperature, higher temperatures increasing the volume of large mesopores hence increasing the permeability. Drying of concrete changes the pore size distribution thereby increasing the coefficient of permeability. Mineral admixtures like fly ash, slag and silica fume increase the durability by refining the pore structure of concrete. Pozzolanic reaction readily develops a discontinous pore system. Increased temperatures increase pozzolanic reaction and reduce water flow. The pronounced reduction in pore size in pastes containing silica fume is due to its high pozzolanic reactivity and small size which allows it to pack efficiently between cement grains, hence subdividing the space.

The use of water reducing agents reduces the w/c ratio hence reducing the permeability. The more uniform dispersion of cement grains due to water reducing agents is likely to result in a more uniform pore structure with smaller pore sizes thereby reducing permeability[34]. The cement-aggregate interface is generally more porous than the paste and this is even more likely if bond cracking occurs under local stresses caused by thermal mismatch between paste and aggregate or restraint of paste shrinkage by aggregate[34].

In marine environments and particularly submerged zones, skin effects can cause rapid reduction in permeability over initial few months[16].

Carbon dioxide is consumed in chemical reaction of carbonation of concrete. In the presence of moisture, CO_2 forms carbonic acid, which reacts with $Ca(OH)_2$ to form $CaCO_3$, resulting into carbonation shrinkage. Consumption of CO_2 reduces its concentration hence CO_2 diffuses in concrete. Similarly oxygen also diffuses into concrete when it is being consumed in corrosion of reinforcement. Chloride ion penetration reduces greatly with decrease in w/c ratio. Weight gain of conventional concrete and concrete with admixtures increased by about 100% as w/c increased from 0.35 to 0.54[27]. Latex modified concrete and concrete with high range water reducing admixtures provide excellent performance in greatly reducing the ingress of chloride ions[27].

6.2. TRANSPORT MECHANISMS IN CONCRETE

Transport mechanisms in concrete are given below in order according to the extent which water travels within concrete:

a. Adsorption

In adsorption, molecules of water adhere to the pore surfaces due to surface energy. The thickness of the film depends upon the degree of humidity within the pores. The ratio between the surface area and volume of pores increases with decreasing pore radius, hence the quantity of water adsorbed relative to the pore volume will also increase until, at a certain limiting value of pore radius, the pore is completely filled with water. This is called capillary condensation[13]. As a result of the high percentage and very small radii of the gel pores, concrete will have a comparatively higher water content even if the relative humidity of the surrounding air is low. Increasing humidity of air will then cause larger pores to be filled with water until saturation, where diffusion of gases will be practically negligible[13]. The effect of capillary suction depends upon the surface energy of the pore surface. The height of capillary rise in vertical capillaries is determined by an equilibrium between the binding forces of the surface and the weight of water column in the capillary. Suction in a horizontal direction depends upon excess of water present on concrete surface and the duration of this situation. Adsorption of water by capillary suction is at a considerably higher rate than the quantity of water lost through evaporation[13].

In physical adsorption the molecules of water are held to the concrete surfaces by the help of Van der Waal's forces whereas in chemical adsorption the molecules of water adhere as a result of chemical forces[16].

b. Diffusion

Diffusion is the process where liquid, gas or ions can pass through concrete under the action of a concentration gradient and is defined for particular material by its diffusion coefficient or diffusivity value[16]. Diffusion comes into play where other water transport mechanisms approach equilibrium[13].

After initial adsorption onto the thinner surfaces of concrete, water vapour passes through the concrete by diffusion expressed by the Fick's first law[16]:

$$J = - D \frac{\delta c}{\delta l}$$

where J is the mass transport rate
c is the concentration
l is the flow path

$\frac{\partial c}{\delta l}$ is the concentration gradient

D is the diffusion coefficient

With the increase in relative humidity inside the concrete, water starts condensing within the pore necks which shortens the paths and water flow occurs in thin liquid films. Due to increasing relative humidity or the presence of an external source of water, the meniscus is formed within the capillary. Forces induced due to pressure differentials across the meniscus induce flow through the capillary resulting in partially saturated liquid flow. When the pore system is completely saturated and sufficient pressure head exists, saturated liquid flow takes place which is governed by the Darcy's Law for steady state flow[16]:

$$v = Q/A = - Ki = - K \frac{\partial h}{\partial l} \qquad (1)$$

where v is the apparent velocity of flow

Q is the flow rate

A is the cross sectional area of flow

i is the hydraulic gradient

∂h is the head loss over a flow path of length ∂l

K is the coefficient of permeability, hydraulic conductivity, seepage coefficient or effective permeability

Flow through capillary pores is assumed to be mostly laminar flow through porous media governed by Darcy's equation.

Ions such as chlorides diffuse through the free water within the porous structure which is most effective in fully saturated state although it continues during the other stages of liquid transfer through concrete[12].

6.3. PERMEABILITY TESTS ON CONCRETE

A brief survey of all the available test methods was carried out from which ultimately two test methods were selected for investigating the permeability of concrete with crushed brick aggregates and one test method was selected to investigate the pore sizes of bricks used for crushing to aggregate. Table 6.1 shows the test methods available.

PERMEABILITY TESTS ON CONCRETE	
TESTS	**SECTION**
1. IN-SITU TESTS	6.3.1
a. **ISAT** *	6.3.1.1
b. Water Absorption test	6.3.1.2
c. Figg method	6.3.1.3
d. Pressure applied surface permeability	6.3.1.4
e. Depth of carbonation	6.3.1.5
f. Ionic diffusion by electrical measurement	6.3.1.6
g. Drill hole permeability test	6.3.1.7
h. Testing of completed structures	6.3.1.8
2. LABORATORY TESTS	6.3.2
a. Absorption tests	6.3.2.1
i. Shallow immersion	6.3.2.1.1
ii. **Capillary rise** *	6.3.2.1.2
b. Pressure induced flow - liquids	6.3.2.2
i. Measurement by flow	6.3.2.2.1
ii. Measurement by penetration	6.3.2.2.2
c. Pressure induced flow - gases	6.3.2.3
d. Gas diffusion	6.3.2.4
e. Water vapour diffusion	6.3.2.5
f. **Ionic diffusion** *	6.3.2.6
3. OTHER METHODS	6.3.3
a. Radiation attenuation	6.3.3.1
b. Resistivity	6.3.3.2
c. High pressure techniques	6.3.3.3
d. Transient pressure pulse and pressure decay	6.3.3.4
e. Osmotic pressure	6.3.3.5

Table 6.1. Permeability tests for concrete.
(* shows the test methods selected).

The test method should be chosen to be appropriate to the predominant mechanisms acting on concrete under consideration. The surface or immediate surface characteristics can be assessed by ISAT or Figg tests. Water permeability and ion/gas diffusion tests can also be selected for the risk one wishes to investigate[17].
For marine structures, the ones fully submerged in water may require a pressure differential permeability test or

ionic diffusion test whereas structures subjected to high humidity conditions may require gas or water vapour diffusion. Structures subjected to water occasionally or offshore structures in the tidal/splash zones may require an absorption or water vapour/ionic diffusion test[18].

The results in the case of in-situ tests are affected by uncontrollable factors like initial moisture content and surface conditions of concrete along with the weather conditions. Adjustments to the results from varying moisture content may have to be considered. The advantage of site tests is that they do not disfigure the concrete surface to any large extent, in contrast to the large core holes to be repaired when samples are taken for laboratory tests. These tests mostly give the permeability index rather than true permeability[16,18].

A number of in-situ tests may also be carried out in the laboratory but specific laboratory tests are designed to specifically measure permeability of concrete in the laboratory. Better results on measurement of permeability in the laboratory are due to possibility of precise size of the sample required for the test, which can be cut from the structure or is precast, and the possibility of getting the moisture content of the sample to a standard condition since moisture condition of concrete at the time of test will affect the absorption values significantly.

6.3.1. In-situ tests

These tests are carried out in-situ on the surface of concrete or in small shallow holes drilled into the concrete surface. Following tests are available for in-situ testing:

a. ISAT.

b. Water Absorption test.

c. Figg method.

d. Pressure applied surface permeability.

e. Depth of carbonation.

f. Ionic diffusion by electrical measurement.

g. Drill hole permeability test.

h. Testing of completed structures.

6.3.1.1. Initial surface absorption test (ISAT)

This test measures the rate at which water is absorbed from the surface of concrete and is of interest in relation to the durability of concrete as regards to rusting of embedded steel, frost resistance and weathering. BS 1881: Part 5: 1970 specifies ISAT.

6.3.1.2. Water absorption test

This test involves weighing of oven dried and saturated specimen which are sawn, cut or drilled. Saturation period for specimen is specified for this test. The absorption is then measured as a percentage of dry weight. It is very indirect in assessing the permeability but its major advantage is that it is very simple and cheap(17).

6.3.1.3. Figg method(16)

This method investigates the immediate surface characteristics of concrete and bypasses any surface effects. Measurements taken in this test are considered relatively insensitive to the actual head of water since capillary suction is the dominant mode of transfer of water. Air can also be used in place of water . Advantage of using air permeation is that the test can be repeated a number of times. Reasonable correlations between the measurements on time and the compressive strength and water/cement ratio were observed by Figg. The aggregate type appears to affect the results along with disturbances in the aggregate-matrix bond due to drilling of test holes. The test is useful for comparative purposes but it only tests very small area(17).

6.3.1.4. Pressure-applied surface permeability

A number of tests similar to ISAT have been developed by different researchers. The equipment used in these tests is portable and can be used in-situ.

Montgomery and Adams(16) developed a rig which is glued to the concrete surface by adhesives. Water is then applied to the concrete surface under constant pressure and volume of water absorbed is monitored. Coefficient of permeability may then be calculated. Since use of this method has not been extensive hence it is difficult to assess its advantage over ISAT, however, less complications in setting up of the equipment and results in the form of coefficients of permeability enabling easier comparisons are advantageous. Destructive gluing to the concrete may damage the concrete surface.

Another similar test developed by Steinart[16] approximates to ISAT under high pressure. Water is pressurised by compressed air and its volume penetrating concrete surface is recorded.

6.3.1.5. Depth of carbonation

This test gives an assessment of concrete permeability to carbon dioxide. Carbonation is reaction of carbon dioxide with the hydrated cement compounds. It proceeds from surface inwards and depends on the rate of movement of carbon dioxide through concrete. Measuring the position of carbonation front may give an assessment of concrete permeability to carbon dioxide. A standard test procedure has been proposed by RILEM CPC - 18.

6.3.1.6. Ionic diffusion by electrical measurement

Permeability of concrete to chloride can be measured by a portable instrument developed by US Portland Cement Association. The amount of electrical charge passed during the six hour application of current gives a measure of concrete permeability. Results from this test correlate with those from AASHTO T 259-80 method. Interpretation of results in tests with technique of applying voltage is difficult due to a lack of understanding of the mechanism of ion transport through concrete[16].

6.3.1.7. Drill hole permeability test

This method is considered as an extension to the Figg method to examine concrete at greater depths and has been used in the construction of roller compacted concrete dams in Japan and USA[16]. Pressure recovery data obtained from this test is used to assess the permeability of concrete.

6.3.1.8. Testing of completed structures

Testing of concrete pipes, structures like offshore oil platform caissons and nuclear containment vessels is carried out on site. BS 5911: Part 1 specifies a hydrostatic test method and compliance requirement.

6.3.2. LABORATORY TESTS

Various test methods are categorised on the basis of the transport mechanism involved, i.e.

a. Absorption of water

b. Permeation of gas/water due to pressure gradient

c. Diffusion of gas/water/ions due to concentration gradient

Laboratory tests available for testing permeability of concrete are :

a. Absorption tests

   i. Shallow immersion

   ii. Capillary rise

b. Pressure induced flow - liquids

   i. Measurement by flow

   ii. Measurement by penetration

c. Pressure induced flow - gases

d. Gas diffusion

e. Water vapour diffusion

f. Ionic diffusion

6.3.2.1. Absorption tests

In absorption tests measurements of voids filled or partially filled with water under specific conditions of immersion and time interval are observed. Absorption tests are relatively simple and quick and provide a means of obtaining the permeability index of concrete rather than the true permeability. Different types of absorption tests are[16]:

6.3.2.1.1. Shallow immersion:

Water absorption is measured by drying the specimen to constant weight, immersing it in water for a specific time and measuring its increase in weight as a percentage of dry weight. BS 1881: Part 122 specifies the details for an absorption test. BS 5911: Part 1 discusses a similar test for precast concrete pipes and fittings.

6.3.2.1.2. Capillary rise

This test involves placing a sample with one surface just in contact with water and the height or weight of water absorbed by capillary rise is measured. A relationship between capillary rise, pore radius and time has been developed by Fagerlund, hence capillary rise can be used to give an indication of the mean pore radius of the specimen as shown in Figure 6.3. Porosity can also be measured by plotting the height of capillary rise against weight gain of the sample per unit area as shown in Figure 6.4. Water penetration reduces with the increase in grade of concrete and increased period of moist curing. RILEM CPC13 specifies a test method for capillary rise[16].

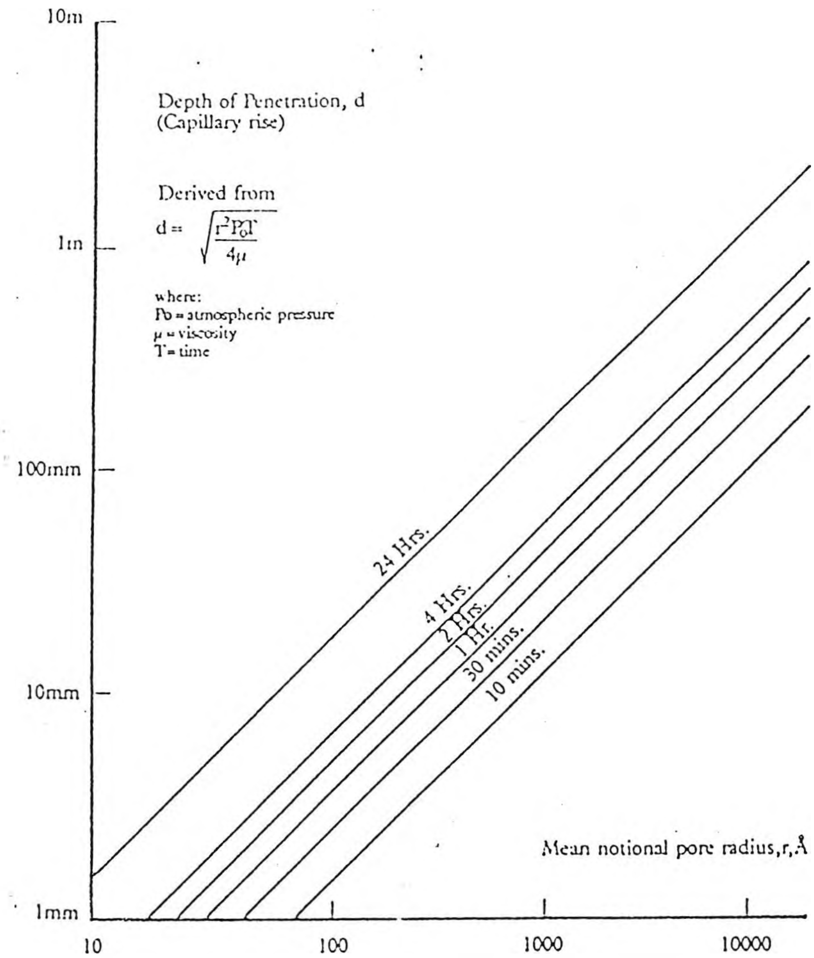


Figure 6.3. Assessment of mean notional pore radius from capillary rise tests.(Ref: Concrete Society Report No. 31)

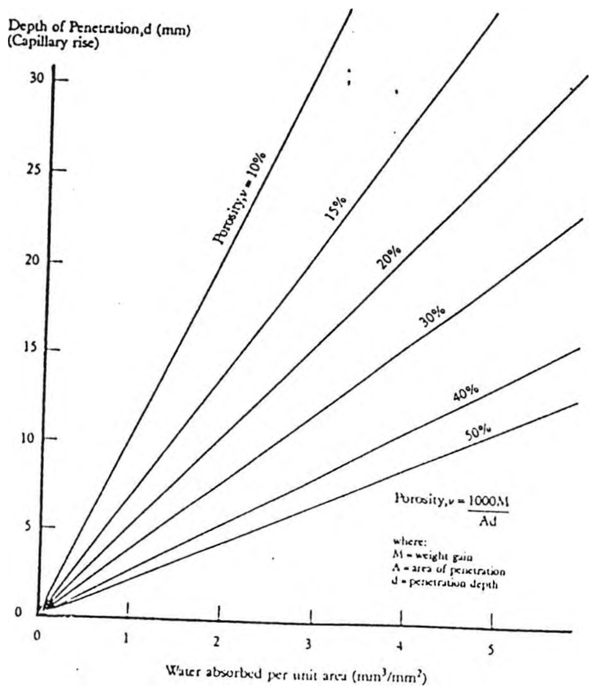


Figure 6.4. Estimating porosity from capillary rise test results.(Ref: Concrete Society Report No. 31)

6.3.2.2. Pressure induced flow - Liquids

Two methods exist i.e. measurement by flow and measurement by penetration. As far as practicality is concerned, the depth of penetration after a given time is the preferred method as it keeps the test duration short, however, as far as scientific value is concerned, flow rate is more meaningful even though the test may take longer[17].

6.3.2.2.1. Measurement by flow

Darcy's equation is used to measure direct permeability of concrete i.e.:

$$Q = \frac{kA\ (P_1 - P_2)}{\mu L}$$

where L is the length of the sample,
A is its cross section area,
P_1 and P_2 are the measured liquid pressures at inlet and outlet faces of the sample and
μ is the viscosity of the fluid.

Various test cells of varying designs and test methods are used employing both small and large pressure heads. The test cells used are similar in principle to the tri-axial cell used for soils and rocks but dimensions have to be different since concrete permeability is quite lower than soils and rock[16].

6.3.2.2.2. Measurement by penetration

For dense, low permeability concrete measuring the depth of penetration is a more practical method. Water under pressure is applied to one face of the test specimen for a specified time period and the the specimen is split open and the depth of penetration observed visually. Although some doubts could be raised on the accuracy of detecting the water penetration front, this method is specified in German Standard DIN 1048 and International Standard ISO 7031.

6.3.2.3. Pressure induced flow - gases

Gas penetration into concrete is important for durability of reinforced concrete and to evaluate gas tightness of concrete storage vessels. Darcy's law is used to measure flow of gases through concrete. The value of permeability obtained from measurements on gas is higher than liquid due to gas slippage around the corners. Gas permeability depends upon the type of gas used and its mean pressure. Due to lower viscosities, higher rates of flow and hence earlier establishing of steady state conditions are achieved. The tests can also be repeated a number of times in a short period. Oxygen, nitrogen and air are commonly used for permeability measurements(16). Methods of curing, drying procedures and actual moisture conditions inside concrete at the time of test are so variable that comparisons of different reported data is difficult to make.

6.3.2.4. Gas diffusion

Studies on gas diffusion in concrete have been carried out. Oxygen diffusion measurements are relevant to problems of reinforcement corrosion in concrete whereas carbon dioxide diffusion is relevant to carbonation of concrete. Length of cure, moisture content and drying of specimen before test affect its diffusion coefficient.

6.3.2.5. Water vapour diffusion

Water vapour diffusion through concrete is measured by different methods. In Dry cup method the specimen is placed in a chamber having known vapour pressure to come to an equilibrium state. The specimen is later connected to a desiccant which absorbs the moisture from the specimen. The cup is weighed at regular intervals to monitor the attainment of a steady state. By storing the specimen in conditions of different relative humidity, diffusion rates against vapour pressure may be obtained which give a good indication of concrete performance[16]. This method is practical for small specimens due to limitations on weighing very large specimens accurately.

The rate of drying of concrete spheres has also been used to obtain diffusivity of water vapour. Another similar method is the inverted dry cup with water on the other side. These are the most pertinent conditions in practice but have not been studied in detail yet[16].

6.3.2.6. Ionic diffusion

Ions diffuse through concrete due to differences in ion concentration and are often independent of pressure gradient. Diffusion of chloride ions in particular through concrete is important with regard to corrosion of reinforcement[16,28]. Ionic concentration is measured at specified time intervals and the diffusion coefficient is calculated from Fick's first law. Three methods mostly used for determining ionic diffusion are:

a. Incremental samples are taken from different depths by drilling and the chloride content of each increment is measured. Samples may be obtained from different depths from a core drilled from a structure. This is a widely used method, particularly on marine structures. The diffusion coefficient may vary with time, in which case the values obtained by Fick's first law may be misleading[16].

b. Ionic diffusion is measured with a concentration difference between two faces of cores removed from a structure. One side of the tank is usually filled with an appropriate salt solution and the rate of diffusion is monitored by periodically measuring the ion concentration in water on the other side of the tank. The time taken to achieve steady state conditions depends upon the concentration difference but they may be of the order of one month. In cases where the ion under consideration is already present in significant quantity in the pore solution, more sophisticated techniques have to be employed. Monitoring of sulphate ion using radioactive sulphate solutions has been studied.

Accelerated chloride ion diffusion tests have been devised where voltage is applied to accelerate the process. Voltage driven chloride diffusion (VDCD) test cell developed at Imperial college, London[23] is discussed in section 6.4. This test takes about one week to reach a steady state and temperature rise during the test has been found to be negligible hence diffusion remaining the major transportation mechanism. The results obtained from the VDCD test have been found to correlate well with the chloride ion diffusion coefficients calculated from long term tests.

Another simple potential difference (PD)test[25] provides a chloride diffusion index within ten days. The test utilises small applied potential difference of 10 volts dc to accelerate transport of chloride ions through concrete. Fick's first law is applied to calculate the diffusion index from the PD (potential difference) test and coefficient of chloride diffusion is obtained from CD (chloride diffusion) test. A close relationship between the diffusion index and chloride diffusion coefficient has been observed. A number of PD and CD tests can be undertaken simultaneously.

c. Ionic diffusion is measured by change in electrical properties resulting from changes in concentration. AASHTO T 277-831[19,22] uses this technique. A potential difference of 60 volts dc is applied across the specimen for 6 hours and amount of current passed, in coulombs, is recorded. The amount of current passed is then compared with typical chloride permeability values given to assess its permeability to chloride ions[22].

6.3.3. OTHER METHODS

6.3.3.1. Radiation attenuation

Gamma ray back scatter technique is useful in giving a general idea on porosity and quality of concrete but the relationship with permeability has not yet been established[16].

6.3.3.2. Resistivity

Research is being conducted to relate permeability to electrical resistivity of concrete by applying 9 volts, 1000Hz a.c. to 50mm thick concrete slice. Results are expressed as 'formation factor' being the ratio of resistivity of concrete to resistivity of pore solution[16].

6.3.3.3. High pressure techniques

A high pressure test developed by Portland Cement Association involves forcing water at a pressure of 300 bar and measuring the rate at which water enters into a 150mm diameter, 300mm high cylinder. The test takes one to three days and permeability is calculated by Darcy's equation[16].

A number of other pressure systems have also been developed by different researchers/agencies[29,36,37].

6.3.3.4. Transient pressure pulse and pressure decay

Pressure and time are more easily measured than flow rate and velocity, for low permeability situations. Tests are being developed to measure permeability of relatively impermeable rocks (k less than $10^{-18}m^2$) which could possibly be used for underground storage of oils, gases and nuclear waste. A small pore pressure is applied to one end of a jacketed specimen and the change in pressure with time is observed as the pore fluid moves from one reservoir to another through the specimen. Pressure decay of nitrogen gas applied to a cavity in a standard concrete specimen has also been studied(16).

6.3.3.5. Osmotic pressure

Specimen have been subjected to osmotic pressure by allowing strong solution of KOH, NaCl, $CaCl_2$ or Na_2SO_4 (150g/l) to come into contact with one side and distilled water with the other side of specimen. Movement of the meniscus in a capillary is used to measure the rate of flow through the specimen. Results are expressed graphically as solution column height versus time(16).

6.4. METHODS SELECTED FOR PERMEABILITY TESTING

The capillary rise test method was selected to investigate the pore sizes of different types of bricks used for crushing to obtain aggregates for concrete under investigation.

Brick aggregates with lower specific gravity than sand tend to rise upwards and orientate in a horizontal position on compaction. Due to this behaviour of brick aggregates in concrete, the layer of fines formed on the surface of concrete is thinner as compared to normal concrete. Hence, to investigate the surface absorption characteristics of brick aggregates concrete the ISAT test was selected. To investigate the permeability of concrete with brick aggregates to chloride ions, voltage driven chloride test was selected.

oxygen permeability tests would have been desirable but the necessary equipment was not available.

6.4.1. Capillary rise test

The fineness of the capillary pores in concrete causes absorption. Larger capillaries absorb water rapidly whereas smaller capillaries absorb smaller quantity of water. This is a useful indicator of the durability of concrete. Basically a sample is placed with one surface just in contact with water and the height or weight of water absorbed by capillary rise is measured. A relationship between capillary rise, pore radius and time has been developed by Fagerlund, hence capillary rise can be used to give an indication of the mean pore radius of the specimen as shown in Figure 6.3. RILEM CPC13 specifies a test method for capillary rise(16).

The capillary rise test was carried out for normal construction bricks, sandlime bricks and engineering bricks to assess the pore sizes for evaluation of their behaviour towards durability. The regular shape of bricks make this test easier to perform.

6.4.2. Initial surface absorption test

Curing and formwork stripping times can be monitored by this test by the help of measuring surface permeability. Difficulty arises in achieving a watertight seal between the cap and concrete surface and in securing the cap in place without the use of clamps. Modelling clay has proved satisfactory in forming a watertight seal.

ISAT tests were carried out on cubes as per BS 1881: Part 5: 1970. The results were compared with the typical results of ISAT tests given by Concrete Society Technical Report No.31. Figure 6.5 shows the setting up of the ISAT test.

6.4.3. Voltage driven chloride diffusion test

The VDCD test was selected to investigate chloride diffusion through brick aggregate concrete and the control mix. A perspex box was manufactured with two compartments of about 2 litres capacity each. The cell could be split easily into two halves, top and bottom, so that the specimen could be fitted. The gap between the specimen and its compartment in the perspex box is sealed by petroleum jelly and silicon sealant. One compartment was filled with 1M NaCl and the other with 0.3M NaOH. Graphite electrodes were used to apply a voltage of 40 volts dc. The NaOH solution was monitored daily for chloride ion concentration for a period of seven days. Figure 6.6 shows details of the perspex box used for VDCD test.

6.5. PERFORMANCE OF BRICK AGGREGATE CONCRETE

6.5.1. Capillary rise test

Three samples of each type of brick were used for capillary rise test. Table 6.2 gives the pore sizes as observed from the capillary rise tests. Mean notional pore diameter were read against the capillary rise from Figure 6.3.

Largest pore sizes were observed to be in normal construction bricks(LBC) with very high absorption of about 20%. The pore sizes varied between 100 to 1,000 nm.

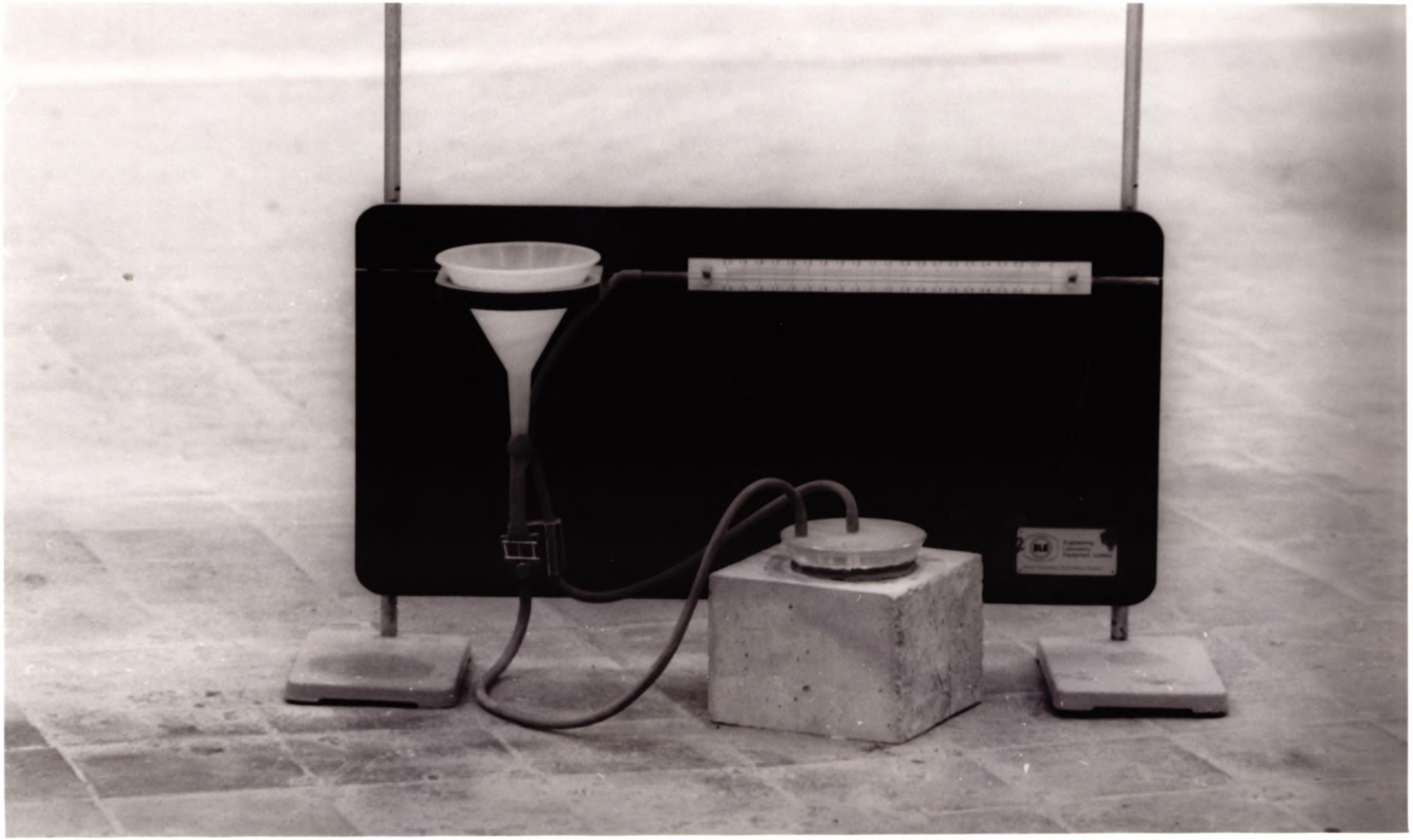
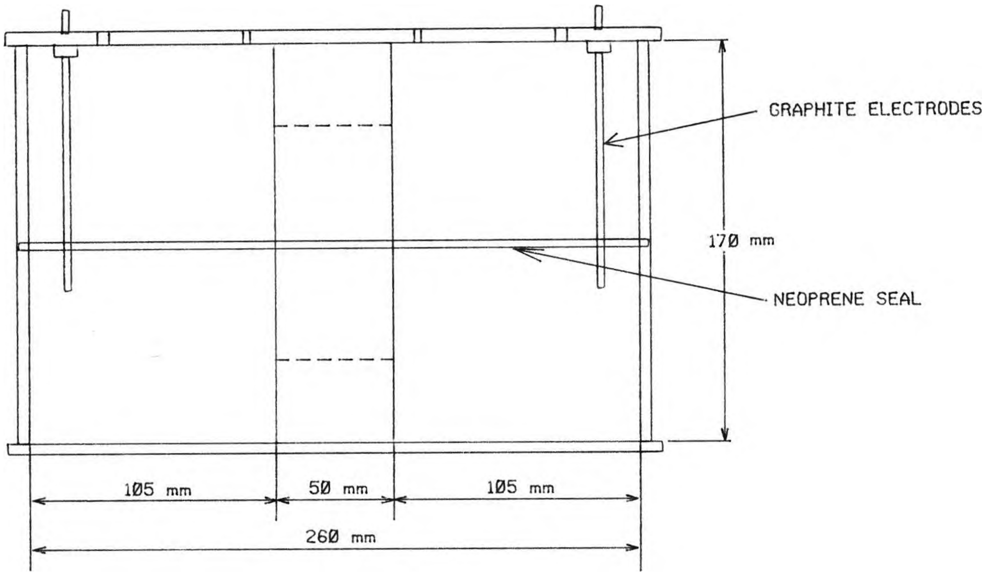
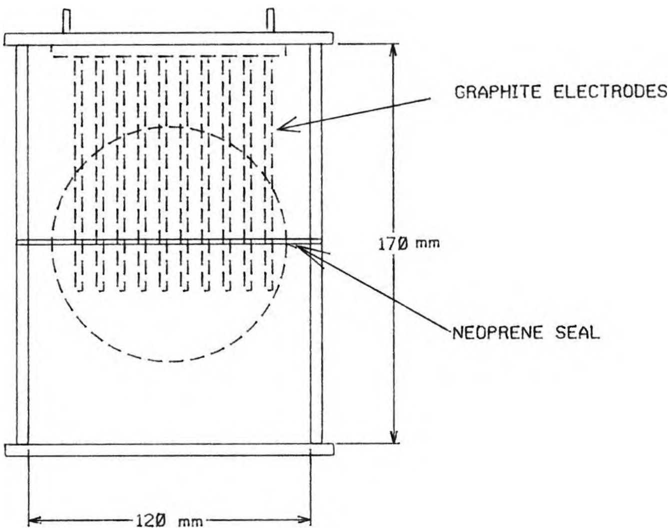


Figure 6.5. Specimen set up for ISAT Test.



ELEVATION



SIDE VIEW

Figure 6.6. Details of perspex box used for VDCD Test.

SAMPLE	CAPILLARY RISE	MEAN PORE SIZE
London brick	Average 18mm	1243.2rÅ i.e.100 to 1000nm
Sandlime brick	Average 5mm	437.5rÅ i.e. 10 to 100nm
Engineering brick	Average 8mm	707.5rÅ i.e. 10 to 100nm

Table 6.2. Results of capillary rise test on bricks.

Sandlime bricks with average absorption of about 10% were observed to have finer pores varying between 10 to 100nm. Similarly engineering bricks with average absorption of 6% were also observed to have fine pores in the range of 10 to 100nm.

6.5.2. Initial surface absorption

This test was carried out in accordance with BS 1881: Part 5: 1970. Table 6.3 gives the details of ISAT tests carried out on concrete with different aggregates. Six specimen of each type of concrete were tested for initial surface absorption.

The results obtained from ISAT were compared with the values given in Concrete Society Report No. 31 reproduced as Table 6.4.

Hence for w/c ratio of 0.63, absorption of concrete with normal construction brick aggregate is initially high in first ten minute, almost three times the value for gravel concrete, thereafter it drops to average values of surface absorption in 30 minutes and later reduces to low values of surface absorption in 1 hour. Concrete with sandlime brick

SAMPLE NO.	MIX	ISAT RESULTS ($ml/m^2/s$) 10MIN	30MIN	1HOUR
1. London brick aggregate concrete	LBC/63	63.00	29.50	9.25
	LBC/56	60.00	26.25	8.00
	LBC/50	34.50	17.50	7.00
2. Sandlime brick aggregate concrete	SBC/63	47.00	16.00	8.00
	SBC/56	38.00	14.00	6.50
	SBC/50	22.00	12.00	6.00
3. Engineering brick aggregate concrete	EBC/63	25.25	13.00	6.50
	EBC/56	24.00	11.00	6.00
	EBC/50	14.00	8.25	5.00
	EBC/385	8.50	6.50	3.50
	EBC/296	6.00	4.00	2.50
4. Gravel concrete	GC/63	19.50	14.00	9.00
	GC/56	19.00	11.50	8.00
	GC/50	15.00	7.00	5.00
	GC/385	8.00	5.00	4.00
	GC/296	5.00	4.25	3.00

Table 6.3. Results of ISAT tests.

ABSORPTION	ISAT RESULTS $ml/m^2/s$ 10 min	30 min	1 hour	2hours
High	>0.50	>0.35	>0.20	>0.15
Average	0.25-0.50	0.17-0.35	0.10-0.20	0.07-0.15
Low	<0.25	<0.17	<0.10	<0.07

Table 6.4. Typical results of ISAT.

aggregate and engineering brick aggregate show average values of surface absorption in the first 10 minutes with concrete with sandlime brick aggregate showing about two and a half times and concrete with engineering brick aggregate showing about 30% higher values of surface absorption than gravel concrete, thereafter dropping to low absorption values in 30 minute and 1 hour readings. Surface absorption for gravel concrete remains throughout the test duration in low range of values. The 1 hour values of surface absorption are similar for concrete with gravel aggregate and normal construction brick aggregate whereas it is about 30% lower for concrete with sandlime brick and engineering brick aggregate.

For w/c ratio of 0.56 following results were obtained :

	10 min	30 min	60 min
LBC/56	60.00	26.25	8.00
SBC/56	38.00	14.00	6.25
EBC/56	24.00	11.00	6.00
GC/56	19.00	11.50	8.00

Hence for w/c ratio of 0.56, absorption of concrete with normal construction brick aggregate is initially high in first ten minute readings, almost three times the value for gravel concrete, thereafter it drops to average values of absorption in 30 minutes and later reduces to low values of surface absorption in 1 hour. Concrete with sandlime brick aggregate shows average values in the first 10 minutes with concrete, almost twice the value for gravel concrete, thereafter dropping to low absorption values in 30 minute and 1 hour readings. Concrete with engineering brick aggregate and gravel aggregate remained throughout the test duration in low range of surface absorption values.

For w/c ratio of 0.50 following results were obtained :

	10 min	30 min	60 min
LBC/50	34.50	17.50	7.00
SBC/50	22.00	12.00	6.00
EBC/50	14.00	8.25	5.00
GC/50	15.00	7.00	5.00

Hence for w/c ratio of 0.50, absorption of concrete with normal construction brick aggregate is initially average in first ten minute readings, almost twice the value for gravel concrete, thereafter it drops to low values of surface absorption in 30 minutes and 1 hour. Concrete with sandlime brick aggregate, engineering brick aggregate and gravel aggregate remained throughout the test duration in low range of surface absorption values.

For w/c ratio of 0.385 following results were obtained :

	10 min	30 min	60 min
EBC/385	8.50	6.50	3.50
GC/385	8.00	5.00	4.00

For w/c ratio of 0.385, absorption of concrete with engineering brick aggregate and gravel aggregate remained throughout the test duration in low range.

For w/c ratio of 0.296 following results were obtained :

	10 min	30 min	60 min
EBC/296	6.00	4.00	2.50
GC/296	5.00	4.25	3.00

For w/c ratio of 0.296, absorption of concrete with engineering brick aggregate and gravel aggregate remained throughout the test duration in very low range.

Hence, for similar w/c ratios, concrete with normal construction brick aggregate shows almost three times the rate of surface absorption as compared to concrete with gravel aggregate whereas concrete with sandlime brick aggregate shows twice the values, in first 30 minutes. The surface absorption rate thereafter becomes steady and is similar for concrete with normal construction brick aggregate, sandlime brick aggregate and gravel aggregate. Concrete with engineering brick aggregate gives similar values of surface absorption as gravel concrete, for similar w/c ratios.

6.5.3. Voltage driven chloride diffusion test

100mm diameter, 50mm thick cores as shown in Figure 6.7 were used for accelerated chloride ion diffusion test. Cores cut from concrete give a more realistic value of diffusion of chloride ions as compared to moulded specimen. The samples were fitted inside the perspex test box and sealed by the help of petroleum jelly. Excessive amount of petroleum jelly at all the joints was used for sealing purposes, hence no leakage was observed throughout the test period. The test equipment is shown in Figure 6.8. Table 6.5 gives the variation in chloride ion concentration with time. Figure 6.9 shows the diffusion rates of chlorides.

Concrete with normal construction brick (LBC) aggregate showed about 42% higher rate of chloride diffusion by the end of seven days as compared to concrete with Thames Valley gravel. The rate of chloride passing through concrete with normal construction brick aggregate was almost three times higher as compared to the rate of chloride diffusion for concrete with gravel in the first three days. The higher rate of current of 0.38A also passed for the same period after which it dropped to 0.26A along

Figure 6.7. Cores used for VDCD test.

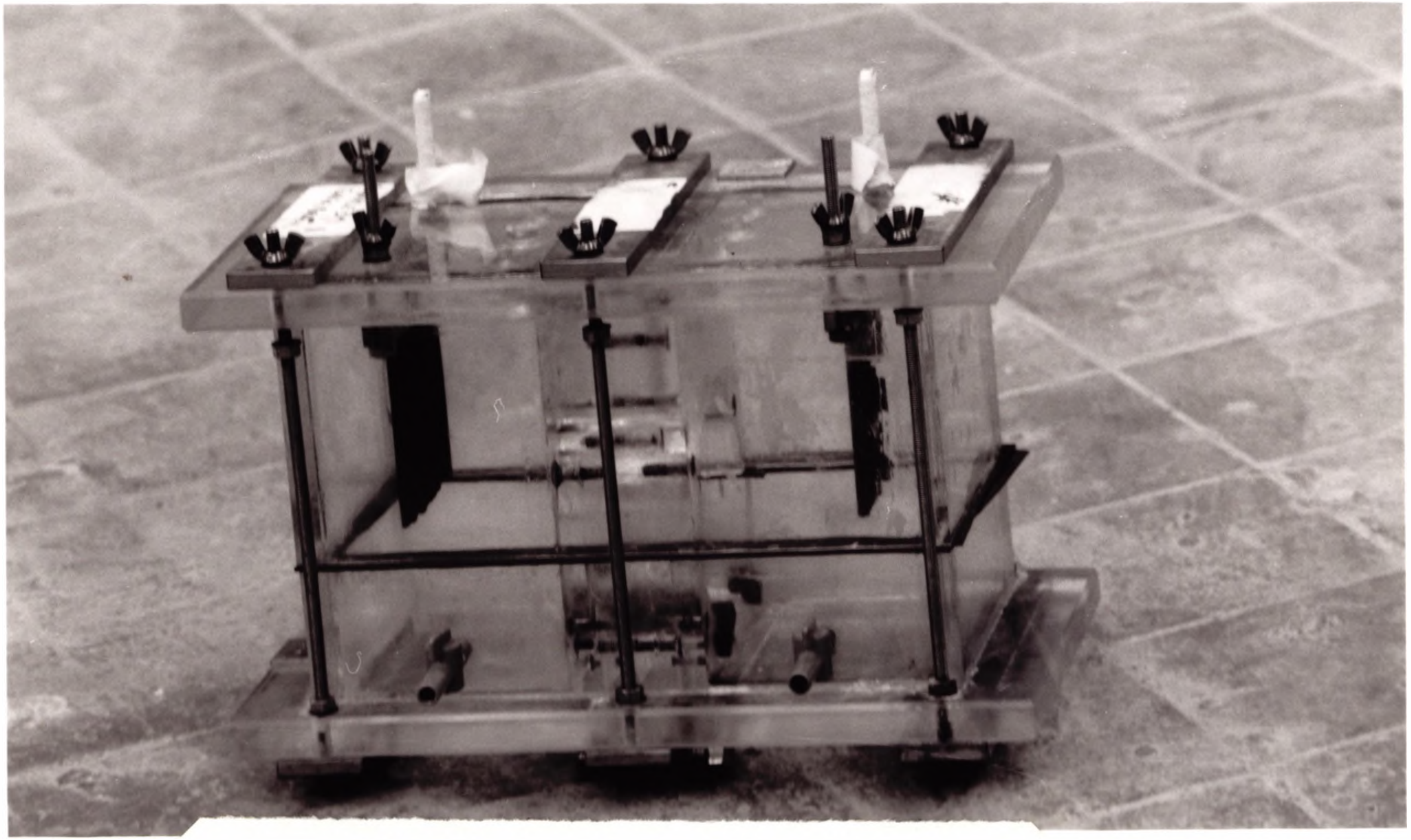


Figure 6.8. VDCD test apparatus.

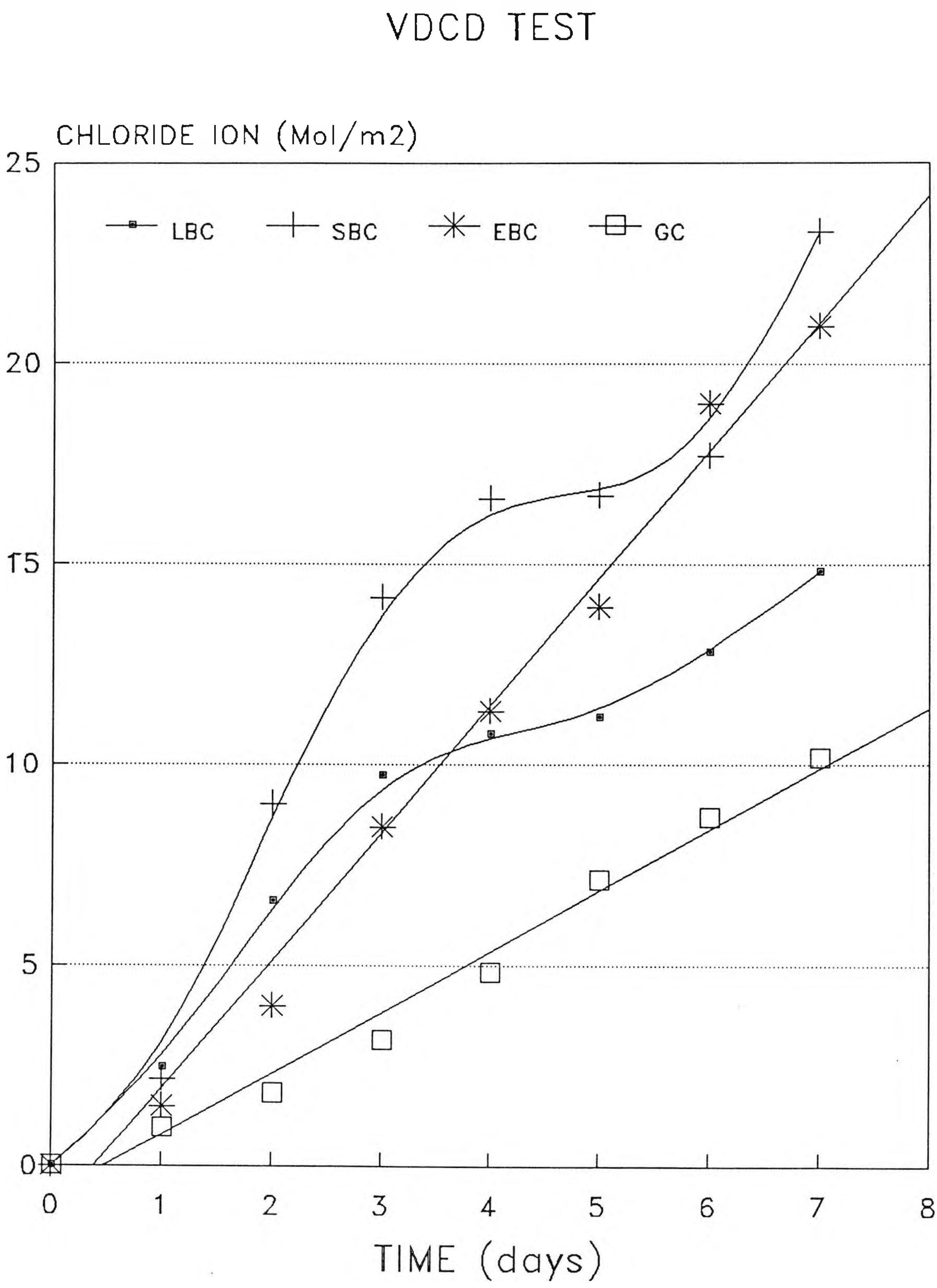


Figure 6.9. Diffusion of chloride ion vs Time

DAY	VOLTAGE	CURRENT	TEMPRATURE(°C) Cl	OH	ROOM	CONCENTRATION mMol/m^2
SAMPLE 1: LBC						
1	40	0.38A	28.3	28.8	22	2462.08
2	40	0.38A	27.8	28.3	22	6590.65
3	40	0.26A	27.0	28.0	22	9707.18
4	40	0.26A	27.5	27.0	23	10762.2
5	40	0.26A	27.5	27.0	20	11165.9
6	40	0.26A	27.5	26.8	22	12806.6
7	40	0.26A	28.3	27.9	23	14812.5
SAMPLE 2: SBC						
1	40	0.38A	30	30	22	2173.96
2	40	0.38A	30	30	22	9005.08
3	40	0.26A	28.0	28.0	22	14163.5
4	40	0.26A	27.5	27.0	23	16641.9
5	40	0.26A	28.0	27.5	20	16714.4
6	40	0.26A	27.3	26.5	22	17710.8
7	40	0.26A	28.2	27.1	23	23269.4
SAMPLE 3: EBC						
1	40	0.22A	27.5	28.0	22	1491.51
2	40	0.22A	28.4	27.7	22	3990.69
3	40	0.22A	27.7	27.0	22	8439.76
4	40	0.20A	27.2	26.6	21	11320.9
5	40	0.20A	27.4	26.6	22	13921.9
6	40	0.20A	27.6	26.7	22	19000.4
7	40	0.20A	28.2	27.7	22	20935.7
SAMPLE 4: GRAVEL						
1	40	0.22A	25.2	25.6	22	945.840
2	40	0.22A	24.8	25.1	22	1120.45
3	40	0.22A	24.7	24.9	22	2437.35
4	40	0.20A	24.2	24.4	21	4823.76
5	40	0.20A	24.3	24.4	22	7111.95
6	40	0.20A	24.5	24.4	22	8676.22
7	40	0.20A	25.1	25.0	22	10149.5

Table 6.5. Results of VDCD test.

with a drop in the diffusion of chloride ions. The rate of diffusion of chloride was observed to be much faster in concrete with normal construction brick aggregate as compared to concrete with gravel possibly due to the presence of almost 0.2375% of chlorides present originally in the normal construction brick aggregates which start diffusing into neutral solution on application of current, as soon as the test is started. It is also easier for the ions to move through the more porous normal construction brick aggregates.

The rate of chloride diffusion through concrete with sandlime brick aggregate concrete was observed to be about two and a quarter times higher than the value for concrete with gravel, after seven days. Diffusion of chloride ion was observed to be at a very high rate for the first four days thereafter it slowed down rapidly for about two days and then increased steeply on the seventh day. Current of 0.38A was observed to pass through the sample for first two days thereafter dropping to 0.26A. The reason for such increased diffusion of chloride ions through concrete with sandlime brick aggregate is not understood.

Concrete with engineering brick aggregates showed a gradual increase in the rate of chloride ion diffusion over a period of seven days similar to concrete with gravel, as shown in Figure 6.9. Amount of current passing through the sample was 0.22A for first two days thereafter reducing to 0.20A for rest of the period of test. Similar amount of current was observed to pass through concrete with gravel. The rate of chloride ion diffusion through concrete with engineering brick aggregate was observed to be almost twice as compared to concrete with gravel aggregates.

The rate of chloride ion diffusion through concrete with Thames Valley gravel was observed to increase gradually over the test period reaching 10149.5 $mMol/m^2$ in seven days. No relationship could be established between the amount of current passing through the samples with the quantity of chloride ions diffusing through them.

6.6. CONCLUSIONS

Capillary rise tests revealed that pore sizes for normal construction bricks(LBC) with very high absorption of about 20% varied between 100 to 1,000 nm. Sandlime bricks with average absorption of about 10% were observed to have finer pores varying between 10 to 100nm. Similarly engineering bricks with average absorption of 6% were also observed to have fine pores in the range of 10 to 100nm.

For similar w/c ratios, concrete with normal construction brick aggregate shows almost three times the rate of surface absorption as compared to concrete with gravel aggregate whereas concrete with sandlime brick aggregate initially shows twice the values of surface absorption thereafter reducing to similar values as of concrete concrete with gravel aggregate. Concrete with engineering brick aggregate gives similar values of surface absorption as gravel concrete, for similar w/c ratios.

Cores cut from concrete were thought to give more realistic value of diffusion of chloride ions as compared to moulded specimen.

The rate of chloride diffusion was observed to be much higher for concrete with normal construction brick aggregate as compared to concrete with gravel possibly due to the presence of almost 0.2375% of chlorides present originally in the normal construction brick aggregates and due to the fact that it is easier for the ions to move through the more porous normal construction brick aggregates.

The rate of chloride diffusion through concrete with sandlime brick aggregate concrete was observed to be about two and a quarter times higher than the value for concrete with gravel, after seven days. Diffusion of chloride ion was observed to be at a very high rate for the first four days.

Concrete with engineering brick aggregates showed a gradual increase in the rate of chloride ion diffusion over a period of seven days similar to concrete with gravel. Similar amount of current was observed to pass through concrete with gravel and engineering brick aggregate. The rate of chloride ion diffusion through concrete with engineering brick aggregate was observed to be almost double than for concrete with gravel aggregates.

CHAPTER 7

FROST RESISTANCE

This chapter considers the frost resistance of concrete with different types of crushed brick aggregates. A general discussion on frost resistance, its effects and factors involved is followed by a description of the mechanism of frost action in concrete in section 7.2. The mechanism of frost action covers freezing in cement paste, freezing in aggregates and overall effects on concrete. A survey of the available frost resistance tests is carried out in section 7.3 which includes frost resistance tests on aggregates as well as concrete. A discussion follows on the available test methods. Tests selected for frost resistance testing of bricks and concrete with crushed brick aggregates are given in section 7.4. Section 7.5 discusses the performance of concrete with different types of crushed brick aggregates. Conclusions are given at the end.

7.1. GENERAL

Exposure of damp concrete to alternate cycles of freezing and thawing is a severe test of concrete quality. Poor quality concretes are certain to fail after a small number of cycles whereas good quality concrete may be undamaged or little damaged after a large number of freezing and thawing cycles. However even very good quality concrete may suffer damage from cyclic freezing under extreme conditions such as when in a saturated or nearly saturated state. In cases where concrete with one face is saturated and the other face is exposed to air, variable behaviour may be exhibited ranging from negligible damage to complete failure. Properly proportioned, placed, finished and cured air entrained concrete may resist cyclic freezing and thawing over a long period of time[15].

The actual amount of water required for hydration of cement is less than one-third the weight of cement but, in practice, excess water has to be added to avoid stiff and unworkable mixes. In concrete slabs, on compaction and later during setting of the concrete, excess water tends to rise upwards thereby diluting the paste at the surface hence weakening the gel structure and making it more porous. The water, whilst channeling towards the surface takes air bubbles along with it which dissipate into the atmosphere but the channels are left open for any ingress of moisture later and result in freeze thaw deterioration with surface scaling(40). Hence finishing plays an important role in frost resistance of concrete.

7.2. MECHANISM OF FROST ACTION

Hardened cement paste and the aggregates in concrete form a porous mass with a number of pores. The size and distribution of pores control the durability of concrete. The size and distribution of pores in the cement paste and in the aggregates in concrete are important for its frost resistance. The size and distribution of pores in concrete help in assessing the ease with which they can be filled by water, the mechanism of transport involved and the porosity and permeability of concrete. Also different pore sizes freeze at different temperatures which is important in designing concrete for frost resistance.

As mentioned in section 6.1, Powers(34) classified pores as gel pores with less than 10nm diameter, capillary pores with pore sizes varying between 10 to 10,000nm diameter and air voids with diameter larger than 10,000nm. Hudec(57) classified pore sizes into the following groups:

a. Force pores are the smallest pores containing solely adsorbed water and can be filled under high humidity conditions only.

b. Micro capillary pores contain adsorbed as well as capillary water. These pores can saturate fully by capillary suction alone. They remain fully saturated in high humidity conditions and are not free draining.

c. Macro capillary pores saturate only partially due to the entrapped capillary air. Only prolonged submersion or vacuum saturation can fully saturate these pores.

d. Large bulk pores containing mostly normal bulk water and air voids are readily saturated and drained provided interconnected.

Iupac(34) classified pore sizes into:

Micro pores with less than 2.5nm diameter,

Meso pores with diameters between 2.5 and 50nm,

Macro pores with diameters between 50 and 10,000nm,

Air voids with diameters larger than 10,000nm.

For capillaries with radii generally larger than 10^{-2}mm, a viscous, laminar flow is most probable whereas for pore radii between 10^{-2} to 10^{-4}mm, capillary rise by means of surface tension of menisci is likely. For capillary radii less than 10^{-4}mm liquid conduction is through diffusion only(35).

Hardened cement paste and aggregate behave differently when subjected to cyclic freezing and thawing(15). Various mechanisms have been put forward by different researchers to explain the action of frost.

These mechanisms are briefly discussed in the following sections as follows:

Freezing in cement paste	7.2.1
Freezing in aggregates (including brick)	7.2.2
Overall effects in aggregates	7.2.3

7.2.1. Freezing in cement paste

On freezing, there is an increase of about 9% in volume. Water present in the cement paste is in the form of a weak alkali solution due to presence of various salts hence its freezing point is lower. In concrete, pores range from very large to very small and the freezing temperatures decrease with decrease in the size of pores hence larger capillary pores freeze much before the smaller gel pores in the cement paste[12,48,15]. This is due to the fact that water in smaller capillaries is under a high pressure as compared to larger ones. Due to very low freezing temperatures in gel pores water in them may not freeze at all. Only one third of the pore water will freeze at a temperature of -30°C and only two third of the pore water will freeze at -60°C[13].

On freezing of the cement paste, water in the larger capillaries starts forming ice crystals after a period of supercooling. Freezing of pure water and the formation of ice crystals results in increased alkali concentration in the rest of the solution thereby creating an osmotic potential. The increase in hydraulic pressure also results from the thermodynamic imbalance between the gel water and ice. The process leads to partial self desiccation of the paste and water from adjacent unfrozen pores starts diffusing into the solution in frozen cavities and cracks hence diluting the solution and resulting in further growth of the ice body (i.e. ice accretion)[12,40,48,15]. When the cavities are filled with ice , further ice accretion exerts dilative pressures on the paste. Failure of the cement paste occurs in cases where the required redistribution of water cannot take place to relieve the dilative pressures, either because the amount of water is too large, cooling rates are too high or the path of migration of water is too long. When water is being drawn out of unfrozen capillaries, the paste tends to shrink[12,48,15].

Air entrainment with appropriately sized and well spaced air bubbles in well compacted and adequately cured mixes with low water/cement ratios increases resistance to cyclic freezing and thawing by providing extra space to expanding ice thereby decreasing the dilative pressures[12,40,48,15].

7.2.2. Freezing in aggregates

The cost of major construction projects is often controlled by the availability of acceptable aggregates. Different researchers have identified different mechanisms of development of D-cracking (i.e. durability cracking) due to frost action in concrete due to its effects on aggregates. D-cracking is a series of closely spaced hairline cracks, crescent shaped, running almost parallel to the free edges and joints of pavement slabs and they often contain calcium hydroxide residue causing dark discoloration of the cracks and surroundings. Such cracking starts at the lower surface of slabs which constantly remains damp, and the aggregates in the region become critically saturated. Hence damage starts due to excessive stresses generated by cycles of freezing and thawing. This crack pattern, which is originally horizontal, later becomes random and turns upwards as it reaches the surface of the slab. This process may take from three to twenty years and lead to complete disintegration of concrete[50].

Reasons given by Cordon[51] for the development of D-cracking were that concrete near the joints and edges is weaker and more susceptible to damage by cyclic freezing and thawing being exposed to moisture and due to stress concentrations at the edges of slab due to curling and warping.

Four mechanisms have been put forward by Cordon to explain the deterioration of concrete aggregates and of concrete due to aggregates.

The first mechanism proposed by Cordon is 'elastic accommodation'. Most aggregates have higher tensile strength as compared to cement paste hence, on freezing, aggregates can expand elastically to a considerable extent without fracturing and can withstand considerable pressure. The surrounding cement paste may not be able to sustain so much strain and may crack. It does not explain how the paste might itself fail during freezing.

Cordon's second mechanism is the 'critical size of aggregate'. When saturated aggregates in concrete freeze, excess water is pushed out due to the formation of ice hence exerting hydraulic pressure. In the case where the water is forced to move short distances through the pores the hydraulic pressure may be small, but, if water has to move longer distances through the pores before coming out, hydraulic pressure may increase critically hence resulting in damage in aggregates. The size of aggregate hence becomes critical if the length of pores through which the water has to travel before coming out generate critical hydraulic pressures for the aggregate to fail(51). However since aggregates are embedded in cement paste, the movement of water out of the aggregates may be restricted by the membrane of cement paste, hence the aggregates can be damaged due to internal fracturing without being of 'critical size'. Anyway, the aggregates will be damaged whether they are of critical size or not. Also, if the aggregates are large and porous, simultaneous freezing of water in all pores is more likely at greater depths, thereby reducing the possibility of any redistribution of water(13). A few lightweight aggregates have a number of pores which are closed initially but which open up later due to cyclic freezing and thawing(47). Concrete with such aggregates could be frost resistant in cases where it is not saturated during the freezing and thawing process by further ingress of moisture.

Cordon's third mechanism is 'accretion of water from surrounding paste'. A few rock aggregates may draw water from the surrounding paste as soon as ice crystals start forming in the aggregates. However, only very small quantities of water can be drawn by aggregates from the surrounding cement paste.

The fourth mechanism is 'expulsion of water from aggregates to cement paste'. On the freezing of saturated concrete aggregates and the formation of ice, excess water is pushed out of the aggregates into the cement paste. If this expelled water develops excessive hydraulic pressure, it damages the cement paste and the cement-aggregate interface. This mechanism could be significant in concrete with highly porous aggregates and ones with large sized pores.

The differences in thermal coefficients of expansion of aggregates and cement paste may also lead to deterioration of concrete. Formation of calcium carbonate hexahydrate in the pores of limestone coarse aggregates can produce expansive forces sufficient to cause D-cracking[50]. Litvan explained that mechanical failure of aggregates occurs if expulsion of water from the aggregates during cooling is lower than desired. It occurs where the permeability is low and porosity, degree of saturation and cooling rate are high[50].

Cady[52] described three mechanisms of frost damage in aggregates. The first is the hydraulic pressure generated by the advancing ice front in critically saturated pores.
The second mechanism is the 'ordered water theory' which proposes a temperature dependent volume change in adsorbed or ordered water. Adsorbed water is held firmly with the pore walls due to physical forces and increases with decrease in temperature, thereby creating destructive pressures on pore walls. The third mechanism proposed by Cady is the 'dual mechanism theory' which states that hydraulic pressure along with the adsorbed water mechanism are responsible for damage to freezing aggregates in concrete. The adsorption mechanism is favourable in clay bearing limestones whereas stones with less clay and large pores are likely to be damaged by hydraulic pressure.
Damage due to frost action in stone and concrete is caused by a combination of factors like volumetric expansion of water whilst forming ice, degree of saturation of rock pores, pore system, pore size and continuity[50]. Adsorption of large amounts of water in aggregates having a very fine pore structure can disrupt them through shear due to differential volume changes upon both freezing and thawing[57]. Since there is no freezing in the fine pores, water migrates to the freezing mass outside the aggregate or to larger pores within the specimen, hence increasing the alkali concentrations of adsorbed water along with shrinkage of fine pores. On thawing, due to increased

concentrations of adsorbed water in fine pores, they take more water due to osmotic pressures thereby expanding[57]. Fine pored aggregates are therefore least durable to freezing and thawing especially when subjected to deicing chemicals which increase the osmotic pressures thereby increasing the saturation. Freezing in micro capillary pores is almost instantaneous when the temperature falls sufficiently, hence the durability of such rocks depends upon the degree of saturation and amount of freezable water. Rocks with macro capillary pores become saturated readily and they are drained easily, and hence they are easily damaged if frozen in critically saturated conditions and freezing pressures cannot be accommodated[57].

Some aggregates like granite, basalt, diabase, quartzite and marble have little quantities of freezable water due to very low absorption and very fine pore structure and hence no stresses are produced by freezing[15]. Freezing in highly porous aggregates under saturated conditions would develop excessive pressures thereby rupturing the particle[15]. If such a particle is nearer to the surface, a pop out may result. Entrained air does not alleviate the effect of freezing in rocks[15]. Specific gravity, porosity, size of pores, absorption, degree of weathering and degree of saturation of aggregates are factors affecting D-cracking of concrete along with the permeability and thickness of cover of mortar[50].

A study by Teodoru[56] on the effect of aggregate type on frost resistance of concrete revealed that a higher proportion of fine aggregates (d <0.1mm) results in a lower frost resistance of concrete since the concrete with higher fines content contracts more on drying, thus enlarging the internal microcracks system. Also, an increase in the total surface area of the aggregates reduces the ratio of cement to the total surface area hence making it weaker. An increase of fines content (d<0.1mm) from 1.7% to 5.2% reduced the frost resistance to one third. It also revealed that in the presence of harmful minerals like opal in the aggregates, frost resistance cannot be improved by air entrainment and/or increasing the quantity of cement[56]. Freezing of water in fines cannot be a cause of deterioration since pores in fines are too small to permit any freezing[57].

The frost resistance of aggregate can be improved by reducing the maximum size of the aggregate and reducing the quantity of non-durable aggregates to a maximum of 35%. Vacuum saturation of highly non-durable aggregates in ethylene glycol solution improves the frost resistance but is not economically feasible due to high costs. Polymer impregnating or coating aggregates prior to mixing improves durability. Polymer impregnated concrete has been observed to be about ten times more durable as compared to air entrained concrete[50].

Properties of brick aggregates affecting frost resistance are now considered.

Bricks undergo reversible expansion and contraction due to wetting and drying, respectively. In addition, there is larger irreversible expansion taking place over a long period of time. This is greater on the first day and reduces subsequently reaching a limiting value after approximately six months. The maximum moisture expansion for each day can be controlled by a firing temperature which is between 900°C to 1000°C. Typical values for linear moisture expansion strains for a 0.229m long brick, after four months, range from 0.02 to 0.07%. Dimensional changes in clay bricks may also occur due to thermal expansion/contraction. Average values for the coefficient of thermal expansion of clay bricks lies within the range of 3.6 to $5.8*10^{-6}$ per °C as compared to 11 to $16*10^{-6}$ per°C for Portland cement pastes and 5 to $13*10^{-6}$ per °C for various rocks forming aggregates. Bricks are characteristically brittle and their stress/strain relationship remains almost linear up to the point of fracture. Strain at fracture is always around 10^{-3} whereas stress at fracture can vary over a wide range i.e failure stress/Young's modulus is approximately 10^{-3}. This strain is considerably lower than expected theoretically, due to the presence of minute cracks and flaws present in almost all the bricks. Young's modulus of bricks ranges from $3.5kN/mm^2$ for low strength bricks to $34kN/mm^2$ for high strength bricks. Under static loads, bricks show little or no plastic deformation prior to failure but under small alternating stresses, well below those which would cause fracture, bricks show considerable plastic or irreversible strains. Underburnt bricks are lighter in colour and lower in strength. The weight of bricks can be reduced by the presence of more voids in bricks or due to inadequate compaction of the raw meal before burning to form brick. Thin layers scale off on exposure to weather due to air collection between clay or shale particles during grinding. Lime present in clays used for brick manufacture should be ground finely otherwise it expands on absorbing water and causes the bricks to crack or flake. Sandlime bricks are made from a mixture of lime and sand. Engineering bricks are very strong and durable and are used in engineering works like piers, bridges etc(75).

Durability of bricks is a function of their resistance to frost action and moisture penetration. Fracture in bricks occur if the elastic resilience of the brick cannot accommodate the expansion of freezing water. Repeated freezing and thawing cycles accelerate the disruptive effect on brick. The rules followed to avoid frost damage to bricks are(75):

a. The water absorption, expressed in terms of percentage increase by weight of dry specimen after five hours boiling or by vacuum, is not greater than seven percent.

b. The saturation coefficient (ratio of absorption after immersion for twenty four hours to absorption after five hours boiling) is not greater than 0.6, i.e 40% of the pore space is difficult to fill with water so as to provide space for freezing water to expand in brick.

The durability designation of bricks is given in Table 7.1.

DESIGNATION	FROST RESISTANCE	SOLUBLE SALT CONTENT
FL	Frost resistant (F)	Low (L)
FN	Frost resistant (F)	Normal (N)
ML	Moderately frost resistant (M)	Low (L)
MN	Moderately frost resistant (M)	Normal(N)
OL	Not frost resistant (O)	Low(L)
ON	Not frost resistant (O)	Normal(N)

Table 7.1. Durability Designation (BS 3921: 1985)

where soluble salt content is specified as

Low(L) with maximum %age by mass of

0.30 of calcium

0.03 of magnesium

0.03 of potassium

0.03 of sodium

0.50 of sulphate

Normal(N) No limit on soluble salt content.

c. Compressive strength of brick is more than $48N/mm^2$.

Hence the frost resistance of brick aggregates depends on their absorption and the compressive strength of bricks from which these are obtained. Highly absorptive bricks with lower crushing strength and large pores sizes may be damaged in few cycles of freezing and thawing. High strength bricks with low absorption, in conformity with the rules given above, can produce frost resistant aggregates on crushing.

7.2.3. Overall effects on concrete

Aggregates are normally not in a critical state of saturation at the end of the construction period because of self desiccation during the chemical reaction during hardening of cement paste and loss of moisture due to evaporation. Hence if the aggregates later become critically saturated, it will be due to water from surroundings or some other external source. Structures where all exposed surfaces are kept wet continously and yet subjected to periodic freezing are quite uncommon. Usually concrete sections with at least one surface exposed to atmosphere tend to dry out in the dry season[15]. Also, partial drying between the freeze thaw cycles would greatly reduce the damage[13].

When the cement paste becomes critically saturated, it may fail when subjected to freezing. Similarly if absorptive aggregates are used in concrete subjected to a consistently wet environment, it would fail on freezing if the coarse aggregates become saturated[15]. If saturated aggregates or aggregates obtained from underwater sources are used directly for concreting and the concrete has to go into service in wet season or shortly before wet season, it could be disadvantageous. Similarly, absorptive aggregates which are readily saturable may not be sufficiently dried due to self desiccation of cement paste and in the absence of a long dry period before wet season could be disastrous for such concrete[15]. The rate of absorption of aggregate in concrete depends upon the permeability of the cement paste which is determined by its cement content, water/cement ratio and period of wet curing. Hence the rate of absorption of aggregate can be lowered by reduced water/cement ratio and good curing. Limited length of wet and dry seasons is an important consideration in reducing the permeability of cement paste and increasing the time for the aggregate to become critically saturated(15). The extent of deterioration increases with repeated cycles of freezing and thawing and varies from surface scaling to complete disintegration. Drying of coarse aggregates before mixing or allowing concrete to dry before freezing increases the durability of concrete even if it was wetted before testing(50). Larger aggregate size decreases the resistance to freezing and thawing and critical degree of saturation for aggregates is between 80% and 90% rather than theoretical 91% probably due to non-uniform distribution of water in the pore system(50).

A study on the temperature and saturation differentials in slabs shows that as the surface of concrete absorbs sufficient radiant energy the surface temperature rises to above freezing point whereas the bottom and surrounding portion of pavement would still be frozen. Later, when the sun's energy is not available and the air temperatures are also below freezing point, freezing in pavement starts from top to bottom. If the pavement had not fully thawed through its depth at the end of thawing period, freezing would also start from frozen bottom to top due to thermal gradients. The resulting freezing from top and bottom converge at a saturated non-frozen zone which may be near the surface of concrete. The boundary between the frozen and unfrozen zone would be subjected to maximum stresses and would result in a region from which microcracking could be initiated[40]. Denial of surface or sub-surface moisture may decrease the development of D-cracking in concrete but it cannot be stopped[50].

Addition of deicing salts can introduce further gradients of subsurface saturation by lowering the vapour pressure and increasing the concentration of salts at the surface. Lower vapour pressure reduces the drying rate of the sub-surface of pavements. The concentration of salts at the top draws more moisture from the immediate surroundings of the pavement whereas the sub-surface is still saturated. Hence water from the top surface evaporates rapidly leaving a drier surface. On freezing, the drier upper surface is resistant whereas in the saturated sub-surface ice lenses start forming which exert pressure resulting in sub-surface failure and hence spalling of the drier top surface starts[40]. Further partial thawing and complete freezing cycles would totally damage the surface of pavement. Solar radiation can cause many more such cycles than changes in temperature alone[40]. NaCl solution causes significantly greater expansion by increasing the osmotic pressure differential as it becomes concentrated on pore surfaces due to adsorption hence resulting in breakdown[57]. Hence the pore size distribution, surface absorption characteristics and volume changes on wetting of aggregates greatly affects the concrete durability[57].

It is difficult to differentiate the deterioration due to freezing and thawing from deterioration due to aging of concrete which also results in delayed cracking. Delayed cracking occurs in structures exposed to ambient weathering changes like wetting and drying and cooling and heating[53]. This phenomenon occurs due to the presence of significantly larger amounts of uncombined lime intermittently present in cement clinker which expands slowly by penetrating moisture. A study on the effects of stress on deterioration of concrete due to freezing and thawing shows that stress does affect the frost resistance of concrete but its effect is not dominant. Surfaces subjected to static tensile stress deteriorated slightly faster than the unstressed surfaces whereas surfaces subject to static compression or biaxial stress due to torsion deteriorated at a reduced rate. Slabs with different flexibilities subjected to cyclic tensile forces of equal magnitude exhibited little difference in scaling or severity of cracking. Relatively low or high cyclic tensile stresses had little influence on the rate of scaling. Slabs subjected to cyclic compressive stresses scaled faster than the unstressed slabs[49]. Significant differences in the frost resistance have been observed for specimen made from different batches of concrete with same basic mix and similar air contents. A comparison of the measured properties of concrete and air void system could not explain this inconsistency of behaviour but a microscopic examination revealed significant differences in the composition of fine aggregates. This variation in composition of sand influences the thermal length change significantly hence resulting in variations in surface mortar damage as compared to inner concrete. Periodic wetting and drying during the early stages of freezing and thawing improved the durability of concrete slabs(49).

Keeping the thermal strain differentials low between the layers of concrete can produce concrete which is durable indefinitely. Concrete containing coarse and fine limestone aggregates has been observed to be highly resistant in laboratory frost resistance tests whereas concrete with coarse limestone aggregate and sand has shown low resistance.

Concretes with high range water reducing admixtures have no significant deleterious effect on the durability of concrete exposed to cyclic freezing and thawing environment or deicing salts. The behaviour is similar to concrete without admixtures. However, reduction of w/c ratio below 0.35 greatly reduces the permeability which reduces the amount of water imbibed hence reducing the amount of freezable water(14).

The age of concrete at the time of frost attack is also significant. Frost can cause great damage in young concrete especially within first 7 days, after initial setting of cement starts, when the concrete has not attained sufficient strength and the pore structure has not developed. Damage in this period due to frost is irreparable, although a slight amount may be recovered due to further hydration of cement in the later period. A highly porous and weaker concrete would hence result[12,13].

7.3. METHODS OF TESTING FROST RESISTANCE

A brief survey of all the existing test methods will be carried out in this section. The survey will be carried out in following parts:

1. Tests on aggregates including:

   i. Soundness tests.

   ii. Weathering tests as confined and unconfined freezing and thawing tests.

   iii. Measurement of a physical property associated with the performance of the aggregates like porosity, pore size and absorption.

2. Tests on concrete include:

a. ASTM C666 - Test for resistance of concrete to rapid freezing and thawing

b. ASTM C671 - Test for critical dilation of concrete specimen subjected to freezing

c. ASTM C682 - Evaluation of frost resistance of coarse aggregates in air entrained concrete by critical dilation procedures

d. ACI SP 100-40 - Rapid one cycle test for evaluating aggregate performance when exposed to freezing and thawing in concrete

e. BS 5075: Part 2: 1982: Appendix C - Test for resistance to freezing and thawing.

f. RILEM 4 CDC - Methods of carrying out and reporting freeze thaw tests on concrete with and without deicing chemicals.

g. RILEM 4 - CDC - The critical degree of saturation method of assessing the freeze thaw resistance of concrete.

7.3.1. Tests on aggregates

Soundness tests have been used to identify frost resistance in aggregates. The soundness test given in ASTM C688 and BS 812: Part 121: 1989 subjects aggregates to repeated cycles of immersion in sulphate solution and drying and deterioration of aggregates is observed in terms of fines (<10mm) generated. Although it takes a short time to test the aggregates, it does not accurately duplicate natural weathering mechanisms, results are generally not reproduceable and do not correlate well with the field performance of aggregates subjected to cyclic freezing and thawing[50].

Other tests to indicate frost resistance in aggregates are generally of two types:

a. Weathering tests as confined and unconfined freezing and thawing tests.

b. Measurement of a physical property associated with the performance of the aggregates like porosity, pore size and absorption.

In unconfined weathering tests linear and volumetric particle expansion have been observed to indicate frost susceptible aggregates. Volumetric expansion using saturated particles in a cooling bath with a mercury displacement dilatometer was observed to detect durable particles and those with low to moderate relative rating but estimate of field behaviour is difficult to be made by this test(50).

With unconfined tests on aggregates, it must be remembered that frost susceptibility is not a basic property of an aggregate. The prevailing environmental conditions and degree of saturation are also important considerations along with the physical characteristics of the aggregate(50).

Data on permeability, porosity and absorption on different aggregates was correlated with a test of average dilation per cycle in slow cooling revealing that vacuum saturated absorption values of less than 1% indicated highly durable aggregates whereas values of more than 5% revealed highly susceptible aggregates. Porosity in coarse aggregates can be measured by ASTM C127 - Test for specific gravity and absorption of coarse aggregates. Pore size distribution is measured by vapour adsorption or mercury porosimetry whereas absorptivity i.e. the rate at which water is imbibed is determined in order to calculate the equivalent pore size. Aggregates with good service records are generally coarse grained or extremely fine grained, whereas non-durable aggregates are generally fine grained[50].

Frost susceptible aggregates can also be identified by petrographic examination which is used to determine basic properties of aggregates related to mineralogical composition, texture and structure. Mineral constituents with poor performance records can hence be identified. Particle shape, pore structure and chemical and physical properties may also be identified. It is often used to verify other tests[50].

7.3.2. Tests on concrete

Freezing and thawing tests on aggregates confined in cement matrix are considered to be the most satisfactory method of predicting the field performance of concrete[50]. For rapid and economic laboratory evaluation of the specimens to assess their frost resistance the tests need to be somehow accelerated keeping in view the field conditions. Different types of tests to study the effects of cyclic freezing and thawing on concrete are:

a. ASTM C666 - Test for resistance of concrete to rapid freezing and thawing

b. ASTM C671 - Test for critical dilation of concrete specimen subjected to freezing

c. ASTM C682 - Evaluation of frost resistance of coarse aggregates in air entrained concrete by critical dilation procedures

d. ACI SP 100-40 - Rapid one cycle test for evaluating aggregate performance when exposed to freezing and thawing in concrete

e. BS 5075: Part 2: 1982: Appendix C - Test for resistance to freezing and thawing.

f. RILEM 4 CDC - Methods of carrying out and reporting freeze thaw tests on concrete with and without deicing chemicals.

g. RILEM 4 - CDC - The critical degree of saturation method of assessing the freeze thaw resistance of concrete.

ASTM C666 and BS 5075: Part 2 method of freezing and thawing involves high rates of freezing as against a maximum of about 3°C/hour occurring naturally. Higher freezing and thawing rates in laboratory testing may not be compatible with the deterioration mechanisms working in the field during freezing and thawing. Also, deterioration would result from differential shrinkage of aggregates and mortar because of differential coefficients of thermal expansion and contraction due to temperature reversals and due to the temperature shock caused by sudden temperature changes. Repeated cyclic freezing and thawing may also result in deterioration due to fatigue failure rather than freezing and thawing. Freezing of the specimen in water is several times more severe than freezing in air(14), since evaporation of water during freezing creates some extra space for expansion but due to provision of extra water by the surroundings makes the specimen critically saturated during freezing, thus increasing the damage. Also, confined freezing of specimen in a container may damage them due to pressures exerted by the increasing volume of freezing water. Some accelerated freezing and thawing tests result in deterioration of concretes which would otherwise be satisfactorily durable in practice[14]. Permanent saturation imposed in some laboratory tests may also saturate the air bubbles present in concrete hence resulting in failure. These test conditions are also unrepresentative of real conditions but concretes withstanding such large cyclic freezing and thawing regimes as 150 cycles indicate highly durable concrete under service conditions[14].

The ASTM C671 method involves more realistic temperature gradients during freezing and thawing and possibility of temperature shock does not exist but freezing and thawing in water makes conditions extreme.

All the existing frost resistance tests assume complete freezing and thawing during the testing process, which may reflect the field conditions in the case of thin sections or at the corners and edges only of thicker specimen and with aggregates like stone and gravel, which could fully thaw throughout the depth of the section in the available thawing period. This mechanism of thawing may not work at all with deeper sections which are only partially thawed due to limited thawing times in nature as compared to longer freezing times, or due to the presence of aggregates like crushed brick where the resistivity to thermal transmission is higher then normal aggregates. Such concretes, on freezing, would have an ice front advancing from top to bottom due to lowering external temperatures and, in addition, there would be a second ice front advancing from the frozen bottom upwards, since the bottom would be still frozen due to incomplete thawing. The maximum stresses in this case would be concentrated in the region between the two advancing ice fronts and the maximum deterioration would occur at the surface where the two ice fronts meet(40).

Methods of assessing frost damage are measurement of length changes, weight changes, dynamic modulus of elasticity, flexural and indirect compressive strengths and ultrasonic pulse velocity. Length change is the most effective method since frost-prone concretes exhibit large changes in length. Flexural resonant frequency measurements are most effective in measurement of dynamic modulus since the whole specimen is flexed during these measurements. Ultrasonic pulse velocity measurements could result in large errors in the event of surface damage since the accuracy of this method depends upon the evenness of the contact surface between the transducers and the concrete specimen(55). Weight change is effective where frost damage is in the form of surface scaling. ASTM and BS tests on freezing and thawing continue until a 40% reduction in the dynamic modulus of elasticity is achieved whereas the German standard STAS 3518-68 allows a loss of 15% in dynamic modulus or 25% in compressive strength(56).

7.4. TEST METHOD SELECTED FOR TESTING THE FROST RESISTANCE

Frost susceptibility is not a basic property of an aggregate. The prevailing environmental conditions and degree of saturation are also important considerations along with the physical characteristics of the aggregate and mortar in concrete. Hence frost resistance testing of actual concrete specimen is more helpful in assessing the interaction of aggregates and mortar in the redistribution of water during freezing and their actual performance in the field.

In order to facilitate understanding of freezing and thawing behaviour of concrete with brick aggregates, following tests were also carried out to investigate the behaviour of different types of bricks to saturation, drying, freezing and thawing.

To investigate the expansion and contraction on saturation and drying, respectively, of different types of bricks, used in this investigation, measurements were taken on three bricks of each type by saturating them in water for twenty four hours and then oven-drying them for twenty four hours at 100±5°C.

Behaviour of the selected bricks on freezing and thawing was investigated by freezing three bricks of each type and then thawing. The bricks were saturated in water for twenty four hours, wrapped in heavy duty polyethylene, sealed and then frozen to -10°C in sixteen hours. Thawing was then carried out for eight hours at 20°C. Length measurements were taken after saturation, freezing and thawing.

The RILEM 4 CDC method of testing frost resistance of concrete was selected for carrying out testing on brick aggregate concrete. Although sensitive to initial moisture content of the specimen, it has the advantage of more realistic freezing and thawing rates and surrounding conditions as compared to other methods along with requiring simple freezing equipment for testing.

The specimens were wrapped in heavy duty polyethylene and sealed before they were subjected to cyclic freezing and thawing. Samples were frozen to -10°C at a rate of 3.5°C/hour for 16 hours. Thawing was carried out by raising the temperature of the cooling cabinet to 20°C with the help of a small fan heater, for 8 hours. Samples were only removed from the cabinet for taking the readings. The centre of samples cooled down to -10°C at the end of freezing and reached a minimum of 5°C at the end of thawing period. One cycle per day of freezing and thawing was used. Figure 7.1 shows a specimen of frost resistance test wrapped up and placed inside the freezing chamber.

Length, weight and resonant frequencies were monitored to assess the frost damage after every ten cycles for a total of 50 cycles.

7.5. PERFORMANCE OF BRICKS

It was observed that normal construction bricks show an average expansion on saturation and contraction on drying of 0.035% whereas sandlime bricks show average

Figure 7.1. Specimens of frost resistance test in the refrigerating cabinet.

expansion/contraction of 0.015% and engineering 'B' bricks show an average of 0.02%.

In freezing and thawing of bricks, average shrinkage of 0.0058% was observed for normal construction bricks and 0.026% for sandlime bricks. All normal construction bricks cracked at the center on freezing. Engineering bricks were observed to expand by an average value of 0.006%.

7.6. PERFORMANCE OF CONCRETE WITH CRUSHED BRICK COARSE AGGREGATE

Table 7.2 gives a summary of the results of frost resistance test whereas Tables 7.3 to 7.6 give the detailed performance of different concretes when subjected to frost resistance test. Figures 7.2 and 7.3 show the variation of dynamic modulus and length, respectively, with the number of freezing and thawing cycles.

Concrete with normal construction brick aggregate started expanding continously and large expansions resulted in

MIX	LENGTH CHANGE	REDUCTION IN DYNAMIC MODULUS
LBC/63	+0.2177%	29%
SBC/63	+0.045%	0.75%
EBC/63	-0.05%	8.3%
GC/63	+0.0095%	10.95%
LBC/50	-0.01%	6.96%
SBC/50	-0.07%	1.14%
EBC/50	-0.04%	11.5%
GC/50	-0.048%	7.33%
EBC/385	+0.05%	9.10%
GC/385	+0.07%	14.4%
EBC/296	+0.046%	6%
GC/296	+0.035%	0%

Table 7.2. Summary - Frost resistance test (50 cycles).

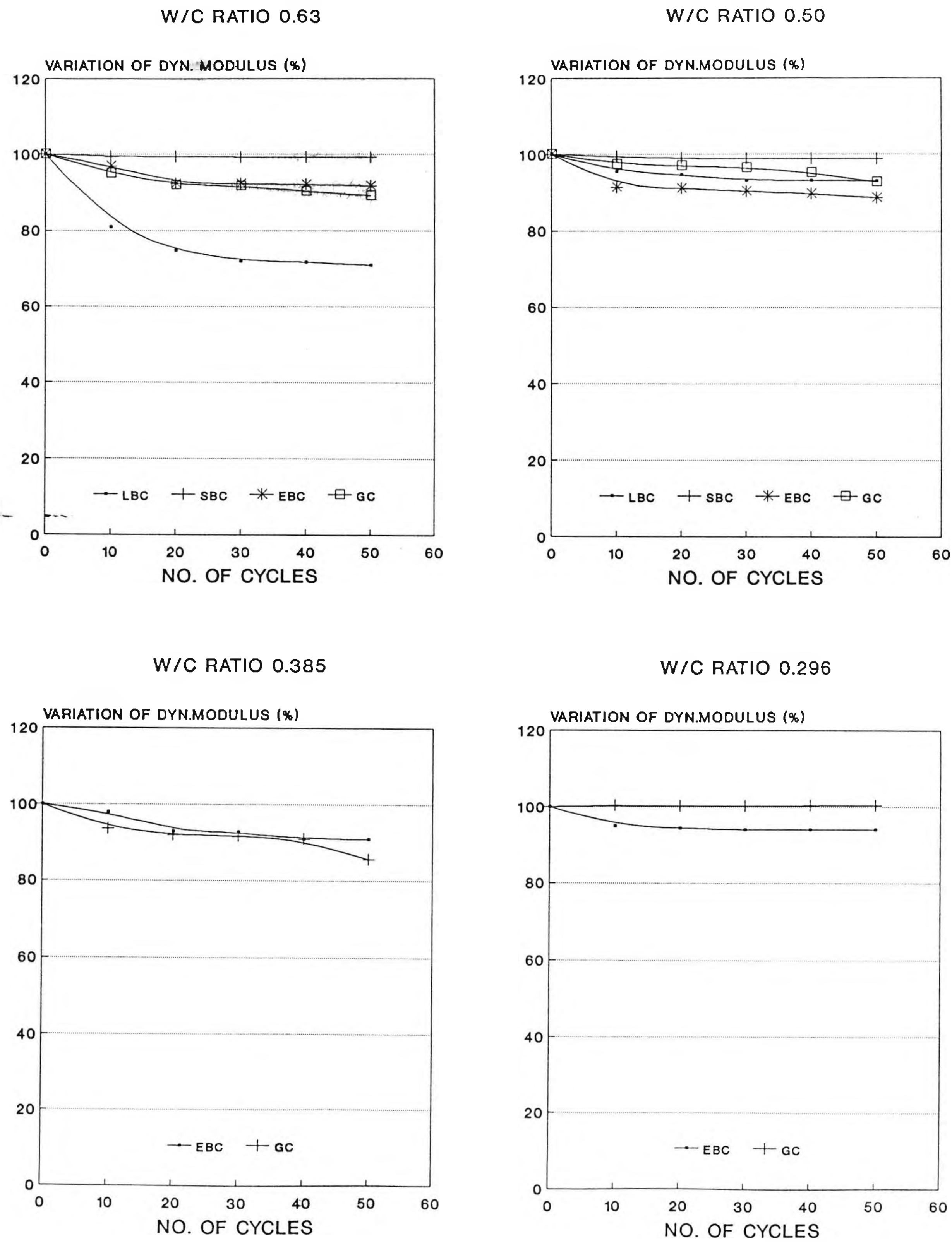


Fig. 7.2. Variation of dynamic modulus vs Number of cycles

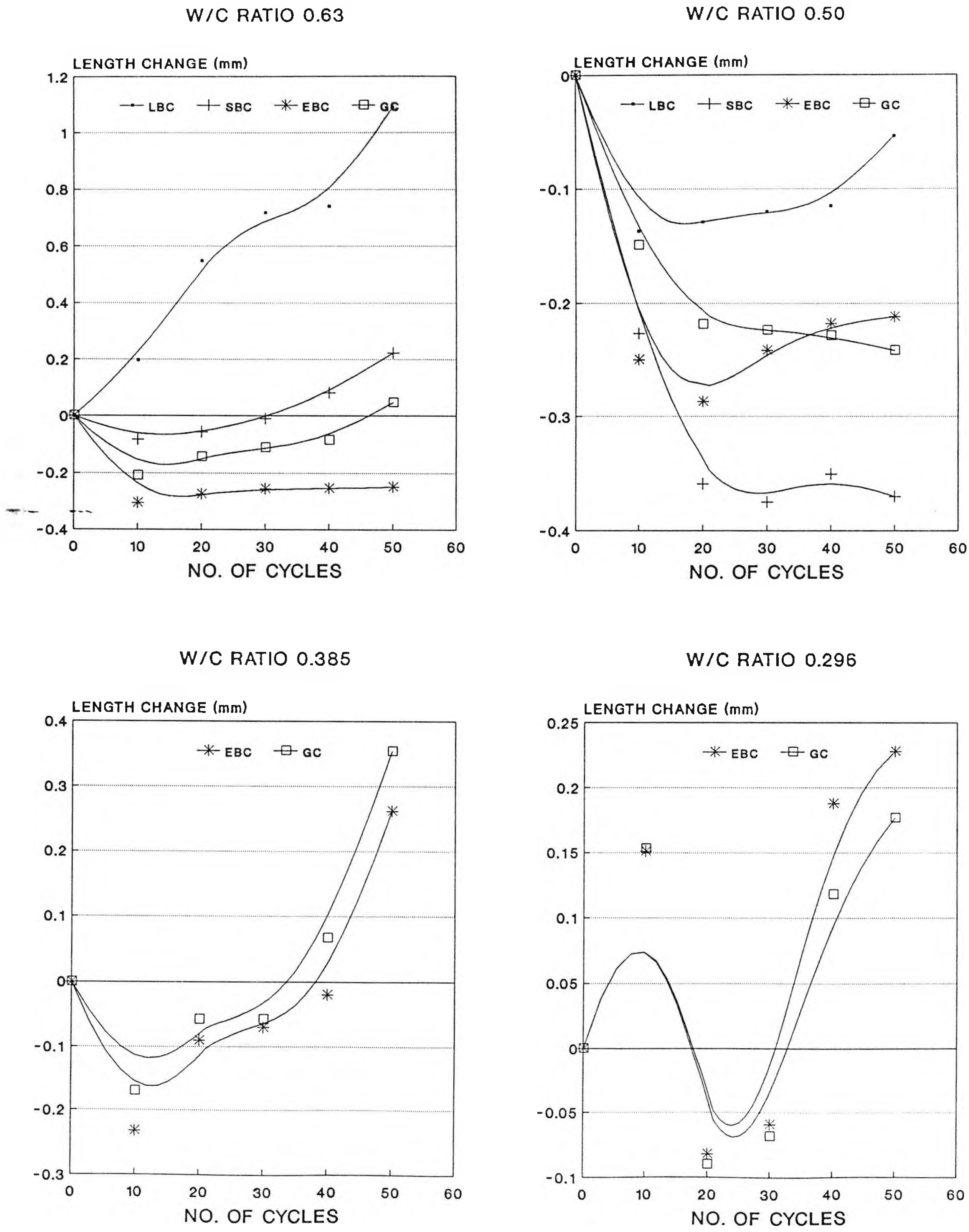


Fig. 7.3. Variation in length vs Number of cycles

rapid decrease in dynamic modulus as shown in Figure 7.2. and 7.3. For w/c ratio of 0.63, increase in length after 50 cycles was observed to be 0.2177% and the corresponding reduction in dynamic modulus was 29% as shown in Table 7.3. For w/c ratio of 0.50, increase in length at the end of 50 cycles was 0.01% and corresponding reduction in dynamic modulus was 7%. There was slight decrease in length in first thirty cycles after which the length again started

Sample No.1. Normal construction brick aggregate concrete
W/C Ratio - 0.63
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	276.8	296.5	331.67	348.5	350.67	385.67
Weight(g):	10691	10683.7	10653	10651.3	10652.3	10648
R frequency(Hz):	3255.7	2928	2818.5	2762.67	2757.3	2741.3
Dyn.Mod.(N/mm^2):	22663	18331.9	16956	16305.2	16245.1	16073

Reduction in dyn mod = 29%, Increase in length = 0.2177%

Sample No.1. Normal construction brick aggregate concrete
W/C Ratio - 0.50
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	313.6	300	300.8	301.6	302.17	308.3
Weight(g):	11026	11041	11041	11043	11046.3	11059.7
R frequency(Hz):	3515	3433	3420	3390	3389	3386
Dyn.Mod.(N/mm^2):	27251	26011	25815	25369	25362.4	25354.4

Reduction in dyn.mod.= 6.96%, Decrease in length = 0.01%

Table 7.3. Frost resistance test on concretes with normal construction brick aggregate.

increasing as shown in Figure 7.3 showing the frost proneness of concrete. The large increase in length and rapid reduction in dynamic modulus of normal construction brick aggregate concrete is due to the high absorption of about 20% of these aggregates. When the bricks from which these aggregates are obtained were subjected to freezing and thawing all the bricks cracked on first freezing only. As mentioned in Chapter 6, capillary rise test on normal construction bricks revealed that these bricks had large pore sizes in the range of 100 to 1,000nm, hence large pores have a larger amount of freezable water. Since the specimen were fully saturated on start of testing, expansion of water in the aggregates on freezing pressurises excess water out of the aggregate into the surrounding mortar. On further cooling, this water expands and exerts dilative pressures on the mortar resulting in microcracking within the mortar, along the bond surface between mortar and aggregate particles and also within the aggregate particles. Cyclic freezing and thawing tends to increase the microcracking thereby resulting in loss of strength along with length increases. The increase in length as well as reduction in dynamic modulus of concrete with normal construction brick as aggregate are much higher as compared to concrete with Thames Valley gravel rendering this type of concrete highly susceptible to frost damage. Due to the presence of 2375ppm of chlorides and similar quantity of sulphates in normal construction brick aggregates, on freezing of water in pores of the aggregate, increased concentration of salts in the unfrozen solution attracts more water thereby increasing the disruptive action of cyclic freezing and thawing.

Concrete with sandlime brick aggregate shows some contraction before expanding as shown in Figure 7.3. For w/c ratio of 0.63, increase in length after 50 cycles was observed to be 0.045% and the corresponding reduction in dynamic modulus was 0.75% as shown in Table 7.4.

Sample No.2. Sandlime brick aggregate concrete
W/C Ratio - 0.63
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	241.5	249	235.75	240.5	249.75	263.7
Weight(g):	11030.5	11034	11034.5	11034	11034	11034
R frequency(Hz):	3458.5	3447	3447.5	3445	3445	3443.5
Dyn.Mod.(N/mm^2):	26387.5	26229	26223.5	26189	26199.5	26191

Reduction in dyn. mod.= 0.75%, Increase in length = 0.045%

Sample No.2. Sandlime brick aggregate concrete
W/C Ratio - 0.50
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	293.6	271	257.83	256.17	258.6	256.67
Weight(g):	11162	11161	11164.7	11164.7	11166	11167
R frequency(Hz):	3543	3533	3526	3524.67	3525.6	3525
Dyn.Mod.(N/mm^2):	28028	27838	27721.6	27698.9	27710	27710.3

Reduction in dyn.mod.= 1.14%, Decrease in length = 0.07%

Table 7.4. Frost resistance test on concretes with sandlime brick aggregate.

For w/c ratio of 0.50, increase in length at the end of 50 cycles was 0.07% and corresponding reduction in dynamic modulus was 1.14%. There was slight contraction in first twenty cycles after which slight expansions took place as shown in Figure 7.3. The small increase in length and negligible reduction in dynamic modulus of sandlime brick aggregate concrete is due to the presence of fine capillaries varying from 10 to 100nm in diameter thereby leaving little amounts of freezable water in the pores. When the bricks from which these aggregates are obtained were subjected to freezing and thawing an average value of

0.0048% of shrinkage was observed. Capillary rise test carried out in the permeability testing on sandlime bricks revealed that these bricks had pore sizes in the range of 100 to 1,000nm, hence finer pores carry a smaller amount of freezable water. Concrete with sandlime brick aggregates showed negligible loss of dynamic modulus as compared to concrete with Thames Valley gravel although expansions were higher. The very low loss in dynamic modulus is possibly due to similar amounts of expansions/contractions in aggregates as well as mortar, thereby preventing microcracking within the aggregates as well as in the mortar and the interface between mortar and aggregate.

Concrete with engineering brick aggregate also shows slight contraction before expanding as shown in Figure 7.3.

For w/c ratio of 0.63, increase in length after 50 cycles was observed to be 0.05% and the corresponding reduction in dynamic modulus was 8.3% as shown in Table 7.5. For w/c ratio of 0.50, increase in length at the end of 50 cycles was 0.04% and corresponding reduction in dynamic modulus was 11.5%. For w/c ratio of 0.385, increase in length at the end of 50 cycles was 0.05% and corresponding reduction in dynamic modulus was 9.11%. For w/c ratio of 0.296, increase in length at the end of 50 cycles was 0.046% and corresponding reduction in dynamic modulus was 6%. The small increase in length and reduction in dynamic modulus of engineering brick aggregate concrete is due to the presence of fine capillaries varying from 10 to 100nm in

Sample No.3. Engineering brick aggregate concrete
W/C Ratio - 0.63
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	290.67	259	263.17	265	265.2	265.8
Weight(g):	11980	11981	11972	11983	11985	11989
R frequency(Hz):	3660.3	3606.3	3521.6	3518	3513	3505
Dyn.Mod.(N/mm^2):	32101	31120	29649	29630	29552	29433

Reduction in dyn.mod.= 8.3%, Decrease in length = 0.05%

Sample No.3. Engineering brick aggregate concrete
W/C Ratio - 0.50
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	314.5	289.5	285.8	290.33	292.67	293.33
Weight(g):	11383	11388	11396	11397	11398	11398
R frequency(Hz):	3570	3412	3407	3390	3379	3357.6
Dyn.Mod.(N/mm^2):	29015	26488	26426	26169.7	26004.9	25678

Reduction in dyn.mod.= 11.49%, Decrease in length = 0.042%

Sample No.3. Engineering brick aggregate concrete
W/C Ratio - 0.385
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	271.17	248	262.17	264.17	269.2	297.2
Weight(g):	11951.2	11947	11946.3	11949.7	11955	11994
R frequency(Hz):	3385.3	3325.6	3263.3	3261.17	3227	3220
Dyn.Mod.(N/mm^2):	27392.7	26832	25434.4	25410.4	24901	24897

Reduction in dyn.mod.= 9.11%, Increase in length = 0.052%

Sample No.3. Engineering brick aggregate concrete
W/C Ratio - 0.296
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	251.67	266.83	243.5	245.83	270.5	274.5
Weight(g):	11332	11333	11335	11335.7	11338.3	11367
R frequency(Hz):	3392	3305	3296	3288	3286	3282.7
Dyn.Mod.(N/mm^2):	26077	24773	24620	24504.2	24504.2	24512

Reduction in dyn.mod.= 6%, Increase in length = 0.046%

Table 7.5. Frost resistance test on concrete with engineering brick aggregate.

diameter reducing the amounts of freezable water in the pores. When the bricks from which these aggregates are obtained were subjected to freezing and thawing, an average value of 0.006% of expansion was observed. Capillary rise test on engineering bricks revealed that these bricks had pore sizes in the range of 10 to 100nm. The reduction in dynamic modulus along with expansion and contraction on cyclic freezing is somewhat similar to concrete with Thames Valley gravel, with slight variations.

Concrete with Thames Valley gravel as aggregate also shows slight contraction before expanding. Table 7.6 gives the performance of gravel concrete in the frost resistance test.For w/c ratio of 0.63, increase in length after 50 cycles was observed to be 0.0095% and the corresponding reduction in dynamic modulus was 10.95%. For w/c ratio of 0.50, increase in length at the end of 50 cycles was 0.048% and corresponding reduction in dynamic modulus was 7.33%. For w/c ratio of 0.385, increase in length at the end of 50 cycles was 0.071% and corresponding reduction in dynamic modulus was 14.39%. For w/c ratio of 0.296, increase in length at the end of 50 cycles was 0.035% and corresponding reduction in dynamic modulus was 0%.

7.7. CONCLUSION

Concrete with normal construction brick aggregates is highly frost susceptible and shows significant expansions along with large reductions in dynamic modulus when subjected to cyclic freezing and thawing.

Concrete with sandlime brick aggregates has better frost resistance as compared to concrete with gravel with similar w/c ratio, since there is negligible loss in dynamic modulus in spite of some expansion on cyclic freezing.

Sample No. 4 Gravel Concrete
W/C Ratio - 0.63
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	273.9	252.92	259.5	262.83	265.5	278.67
Weight(g):	12424	12425.7	12426	12426.5	12428	12428.7
R frequency(Hz):	4546	4432.67	4360	4351	4319	4288.67
Dyn.Mod.(N/mm^2):	51352	48788.4	47215	47088.8	46349	45728

Reduction in dyn.mod.= 10.95%, Increase in length=0.0095%

Sample No. 4 Gravel Concrete
W/C Ratio - 0.50
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	272.67	257.8	250.8	250.3	249.8	248.5
Weight(g):	12634.3	12642	12643	12646.3	12646	12654.3
R frequency(Hz):	4612.3	4553	4542.67	4530.67	4501	4438.67
Dyn.Mod.(N/mm^2):	53754.7	52382	52134.2	51855	51192	49814.3

Reduction in dyn.mod.= 7.33%, Decrease in length = 0.048%

Sample No. 4 Gravel Concrete
W/C Ratio - 0.385
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	245.83	228.83	240	240	252.5	281.3
Weight(g):	12218	12178.7	12213	12212.3	12214.7	12220
R frequency(Hz):	4377.3	4243.67	4198	4193.7	4173.3	4047
Dyn.Mod.(N/mm^2):	46821	43820.9	43035	42945.8	42558.7	40085

Reduction in dyn.mod.= 14.39%, Increase in length = 0.071%

Sample No. 4 Gravel Concrete
W/C Ratio - 0.296
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	233	248.3	224	226.17	244.8	250.7
Weight(g):	12131.2	12133.3	12133	12134.3	12136	12138
R frequency(Hz):	4352.3	4358.67	4358	4357	4358	4358
Dyn.Mod.(N/mm^2):	45959.1	46129.9	46070	46057.6	46116	46137

Reduction in dyn.mod.= 0%, Increase in length = 0.035%

Table 7.6. Frost resistance test on concrete with gravel aggregate.

Concrete with engineering brick aggregates behave somewhat similar to concrete with Thames Valley gravel when subjected to cyclic freezing and thawing.

On comparing frost resistance on the basis of similar compressive strength, concrete with engineering brick aggregate with w/c ratio of 0.50 showed slight contraction with about 11% reduction in dynamic modulus as compared to gravel concrete with w/c ratio of 0.296 showed slight expansion without any loss in dynamic modulus.

CHAPTER 8

SULPHATE RESISTANCE

Investigations on sulphate resistance of concrete with different types of crushed brick aggregates are covered in this chapter.
A general discussion on sulphates, their occurrence and effects is given in section 8.1, followed by a study of the mechanism of sulphate attack in section 8.2. The mechanism of attack by various types of sulphates is considered along with their effects on various compounds present in cement hydrates. Methods of protection from sulphate attack are also studied.
The available methods of testing sulphate resistance of concrete are surveyed in section 8.3 along with methods of measuring damage due to sulphate attack. Section 8.4 gives the details of the method selected for sulphate resistance testing of concrete with crushed brick aggregates and the methods selected for measuring the damage due to sulphate attack. The performance of concrete with different types of crushed brick aggregates is discussed in section 8.5 followed by conclusions in section 8.6.

8.1. GENERAL

Sulphates are widely distributed in nature and are present in virtually all soils, particularly those with high proportions of clay are present. Sulphate attack on concrete is due to the presence of sulphates in groundwater or water surrounding the structure. A typical sulphate solution is groundwater of some clays which contain sulphates of calcium, sodium and magnesium. BS 8110: Part 1: 1985 classifies sulphate attack in terms of the concentrations of sulphates present (Table 1). Sulphates are also found in sea waters and in imported fill containing blast furnace slag or cinders[15]. The severity of sulphate attack on concrete depends upon:

a. the concentration and nature of sulphate present in the solution;

CLASS	CONCENTRATION OF SULPHATES - SO3			TYPE OF CEMENT	CEMENT CONTENT MINIMUM	FREE W/C RATIO MAXIMUM
	IN SOIL 1.	IN SOIL 2	GROUND WATER			
	%	g/L	g/L		kg/m3	(BRE DIGEST 250)
1	<0.2	<1.0	<0.3	All cements BS12 cements + pfa BS12 cements + ggbs	300	0.60
2	0.2 to 0.5	1.0 to 1.9	0.3 to 1.2	All cements BS12 cements + pfa BS12 cements + ggbs	330	0.50
				BS12 Cement + 25 to 40% pfa BS12 Cement + 70 to 90% ggbs	310	0.55
				BS4027 cements(SRPC) BS4248 cements(SSC)	280	0.55
3	0.5 to 1.0	1.9 to 3.1	1.2 to 2.5	BS12 Cement + 25 to 40% pfa BS12 Cement + 70 to 90% ggbs	380	0.45
				BS4027 cements(SRPC) BS4248 cements(SSC)	330	0.50
4	1.0 to 2.0	3.1 to 5.6	2.5 to 5.0	BS4027 cements(SRPC) BS4248 cements(SSC)	370	0.45
5	>2	>5.6	>5	BS4027 cements(SRPC) and BS4248 cements(SSC) with adequate protective coating.	370	0.45

1 - Total SO_3 2 - SO_3 in 2:1 soil extract

Table 8.1. Concrete exposed to sulphate attack - BS8110: Part 1: 1985

b. the level of water table and its seasonal variation;

c. the flow of groundwater and soil porosity;

d. the form of construction;

e. the quality of concrete

The most common sulphates are calcium sulphate (gypsum or selenite), magnesium sulphate (Epsom salt) and sodium sulphate (Glauber's salt)[63]. The low solubility calcium salt is potentially less dangerous as compared to the high solubility magnesium and sodium sulphates. All these salts dissolve in water to produce neutral solutions with pH values around 7[64]. 2g/l of calcium sulphate produces saturation as compared to 150 or 200 times for magnesium and sodium sulphates, respectively[63].

Acidified sulphates may be found in certain groundwaters due to oxidation of sulphides to form sulphuric acid. Basic compounds such as calcium carbonate react with this acid to form neutral sulphates, but, in the absence of such basic compounds in insufficient quantity, a portion of free acid remains in groundwater which attacks Portland cement and protection by an impermeable membrane is necessary[63,64].

Sulphates may be present in colliery shale used as fill material beneath concrete floors which could attack concrete from the underside due to moisture from groundwater. Movement of sulphate ions, with the water or by diffusion, in undisturbed clay soils is likely to be negligibly slow[64]. Vertical or horizontal movements of water due to seasonal variations may alter the concentration of sulphates[63].

Thinner sections are likely to be damaged more quickly by sulphates as compared to thicker sections for the same concrete quality and aggressive conditions[63]. Structures with one or more surfaces exposed for evaporation or where the possibility of wetting/drying exist due to temperature changes or variation in water levels, are likely to be damaged more quickly as compared to concrete structures embedded in soils with no exposed surface available for evaporation[63,68]. Thus basements, culverts, retaining walls and ground floor slabs are the most troublesome situations. The head of water developing behind retaining walls, basements, etc aids penetration considerably[64]. Adequate drainage minimises sulphate attack[64]. Higher temperatures increase the ionic activities as do higher concentrations, thus accelerating sulphate attack[13,68]. Occasionally sulphate attack has been observed to start in small surface pockets and then to penetrate radially to weaken a thin surface film of surrounding concrete[65].

Sulphates may reveal their presence by[64]:

Translucent colourless crystals visible in the walls of fresh excavations.

A white, frost like rime forming as newly exposed soil dries.

A milky white tinge to groundwater seeping into pits or trenches.

Concrete with low permeability and with the appropriate type of sulphate resisting cement will resist sulphate attack. Partial replacement of cement by pozzolans or pfa/slag should be considered depending upon the severity of attack. However a reduced rate of hardening and strength development must be considered when using pfa or slag in cold environments[63]. Sulphate resisting cement is designed to resist sulphate attack hence it should not be mixed with ordinary or rapid hardening cement since this would affect its sulphate resisting qualities[64].The mix design should permit full compaction by employing sufficient workability. Low w/c ratios are desirable along with correct dosages of workability aids. Admixtures containing calcium chloride should be avoided since on absorption of moisture, expansions due to chloride add to the expansions due to sulphate attack thereby accelerating the deterioration process[63].

8.2. MECHANISM OF DAMAGE DUE TO SULPHATE ATTACK

The main compounds in Portland cement are C_3S (Tricalcium silicate), C_2S (Dicalcium silicate), C_3A (Tricalcium aluminate) and C_4AF (Tetracalcium aluminoferrite). C_3S and C_2S are responsible for the hydrated strength of cement. Hydration of C_3S produces twice as much lime[$Ca(OH)_2$] as compared to hydration of C_2S, in addition to the C-S-H hydrate. The presence of C_3A is undesirable and contributes little to strength of cement at early age however it facilitates combination of lime and silica in the manufacturing stage of cement. Gypsum (Calcium sulphate) is added to cement to stabilise C_3A and thereby avoid flash set. Ettringite (calcium sulphoaluminate) is produced but, due to plastic/semi-plastic state of concrete, expansion can be accommodated. C_4AF is present in small quantities and reacts with gypsum to form calcium sulphoferrite which may accelerate hydration of silicates[12].

Diffusion of sulphates into concrete is not simple. Hydroxyl anions diffuse rapidly compared to sulphate ions and the associated cations, hence diffusion of sulphate ions is by replacement of hydroxyl ions with sulphate ions within the concrete. Hydroxyl ions would simply leach out, particularly in smaller specimens, and, where the pH of the environment is at a value less than that of saturated $Ca(OH)_2$, hydroxyl ions will diffuse through the concentration gradient to the outer surface of concrete[65].

On attack by sulphate solution from an external source, C_3A reacts with sulphates to produce ettringite or calcium sulphoaluminate ($3CaO.Al_2O_3.3CaSO_4.31H_2O$) and lime [$Ca(OH)_2$] reacts with sulphates to form gypsum (calcium sulphate)[12,64]. On absorbing water, ettringite and gypsum produce expansive forces which can increase sufficiently to cause deformation, cracking and eventually complete disintegration[64]. Formation of ettringite is generally blamed for most of the expansion and disruption of concrete by sulphates[15]. Up till now, there has been no single explanation as to why combinations of sulphate and C_3A lead to expansion[13]. However the quantity of ettringite produced were found not to correlate with the resulting expansions and similar amounts of ettringite were produced by Sulphate Resisting Portland Cement and Ordinary Portland Cement in sulphate environments[65]. The ettringite nucleation and growth may provide better correlation with bulk expansion. An alternative view suggests that finely divided or colloidal ettringite is formed at early stages of sulphate attack which then attracts water from environments through osmotic forces resulting in expansion(65). Another view proposes the formation of thaumasite at reduced temperatures of around 5°C. Thaumasite has a similar crystal structure to ettringite and products containing both these materials have been identified. Thaumasite has also been identified in exposed brickwork. Reduced temperatures have been observed to aggravate the rate of disintegration. Late formation of ettringite in precast units made from high strength concrete and having been heat treated has been reported to reduce strength when subjected to open-air weathering for several years(72).

$Ca(OH)_2$ is required for the growth of ettringite crystals to result in expansion and also to reduce ettringite solubility hence avoiding any redistribution of the growing crystals into the available pore space. $Ca(OH)_2$ can be removed by pozzolanic action or by reaction with sulphates to form calcium sulphate to form non expansive ettringite.

In addition to the chemical reactions by sulphates on cement hydrates, physical action of crystallization of sulphate salts in concrete pores can also lead to considerable damage(15). This is a reason for considerable damage in heavy sections on the exposed outer surfaces adjacent to cracks and leaking joints when the other sides of such sections are subjected to strong sulphate solutions[15]. Distress has been commonly observed to occur at the water line in the case of disintegration of rock, brick and concrete in soils with high soluble salt content[65].

Magnesium sulphate has a more damaging effect than other sulphates since it decomposes hydrated calcium silicates in addition to lime and calcium aluminate hydrate. The hydrated magnesium silicate eventually formed has no binding properties[12,64]. Withdrawal of free and combined lime is rapid, especially at higher concentrations and diffusion of sulphate ions into the paste is accelerated. Ettringite will not be formed in the outermost layers which would crack due to internal expansion. $Mg(OH)_2$ deposits formed may partly seal the concrete surface. Crystal growth mechanism by gypsum may cause expansion in weaker pastes[65]. Surface flaking and spalling of the concrete specimens has been observed when the offensive sulphate solution comprised of a mixture of sodium and magnesium sulphates, hence deterioration of concrete can be detected by visual observation[65]. Concrete subjected to attack by magnesium sulphate solution shows greater expansions as compared to attack by other sulphates hence the deterioration is more rapid.

Attack by calcium sulphate is assumed to act only on calcium aluminate and ferrite hydrates forming ettringite and causing expansion. General weakening of the paste does not occur unless $Ca(OH)_2$ is removed by leaching/dissolution, hence general weakening of the structure is likely to be very slow unless the paste is highly porous(65).

Sodium sulphate solutions attack calcium aluminate and ferrite hydrates forming ettringite and causing expansion. Withdrawal of lime and deposition of gypsum increases the porosity and weakens and disintegrates the structure at higher sulphate concentrations. Expansion due to gypsum crystal growth is possible only when the structure is weakened after many years(65). Swelling and cracking of the main body of the concrete specimen was observed on attack by sodium sulphate solution, hence visual observation may not detect deterioration until it is significant, making sulphate attack by sodium sulphate the most severe(65).

The extent of sulphate attack depends upon the concentration of sulphates, permeability of concrete and rate of leaching out of lime from affected areas(12).

Protection against sulphate attack can be achieved by the use of dense, high quality concrete with low w/c ratios and cement with sulphate resisting properties. Air entrainment can be beneficial only in so far as it reduces the w/c ratio(15). For rich mixes with cement contents around 390kg/m^3, the attack is slow and little difference in behaviour has been observed between cements with high and low C_3A contents whereas for low to medium lean mixes with cement content of 223 and 307kg/m^3, the attack was observed to be rapid[65]. Slag cement mixes have been reported to suffer no damage in sodium sulphate solutions as compared to Portland cement mixes with varying C_3A content where the concentration of sulphates in the solution were raised to 5%. However damage began to show after 10.5 years in mixes with slag and sulphate resisting cements[65].

Sulphate resistance of cement is proportional to its C_3A content which is reduced to a maximum of 5% in sulphate resisting cement. High C_4AF content could also be detrimental to sulphate resistance. Pozzolans, like fly ash, combine with free lime resulting from the hydration of cement hence these are added to cement in the quantities of 15 to 20% of the Portland cement content in conditions of severe exposure to sulphates. Replacement of Portland cement by 20 to 40% of pfa increases the sulphate resistance of concrete. Pozzolans are also added to supersulphated or sulphate resisting cements in very severe sulphate exposure conditions[15]. The addition of calcium chloride to concrete reduces its sulphate resistance[15]. Portland blast-furnace cement with a minimum of 65% slag are taken to be highly sulphate resisting[13]. However, low C_3A Portland cement has very high permeability to chloride ions as compared to Portland blast furnace cement with high slag content, although both have similar sulphate resisting qualities. The behaviour of different cements/blends has been observed to be different with different sulphates. Substantial expansions were observed in Portland cement blended with silica fume when subjected to strong magnesium sulphate, whereas negligible expansions resulted with strong sodium sulphate solution. Sulphate resisting cement also expanded slightly more in magnesium sulphate as compared to sodium sulphate. Mass loss was also observed to be substantial with magnesium sulphate as compared to sodium sulphate. For OPC with slag or pfa blends and SRPC with pfa or slag blend, magnesium sulphate was more aggressive than sodium sulphate[65]. Hence care is needed to select the appropriate cement for different environments such as concrete subjected to seawater or deicing salts or where consideration of corrosion of reinforcement is at stake[13].

Addition of chloride or sea-water has been observed to increase the intensity of sulphate attack. When chlorides are present in addition to sulphates in the offensive solutions, calcium chloroaluminates are formed and greater expansions have been observed as compared to expansions by sulphate solutions only. Increased quantities of ettringite are formed. Greater expansions could be due to the expansion due to chloride adding up to the expansions due to sulphates hence resulting into a greater total. Chloride ions have been observed to penetrate the paste structure much more quickly as compared to sulphate ions[65]. Expansions in pure chloride solutions may also be due to reactions involving the sulphates already present in cement, since ground clinker pastes did not show any expansion under similar conditions(65). Blastfurnace slag cements with slag content of over 70% have proved to be highly resistant to sea-water.

Addition of OH^- ions in sulphate environments have been observed to reduce expansions drastically for Portland cement paste from 2% to 0.2% after one year in 10% sodium sulphate solution, with and without 5% NaOH in the sulphate solution, respectively.

Addition of $NaHCO_3$ to sulphate solution also reduced expansions in all mortars, except high C_3A cements in $MgSO_4$ solutions(65). The reduction in the rate of sulphate attack is due to deposition of the calcite ($CaCO_3$) formed which reduces the penetration of sulphates. Formation and deposition of brucite i.e. $Mg(OH)_2$ in $MgSO_4$ solutions further increases the sulphate resistance(65). Ettringite is not formed if the cement paste is carbonated before subjected to sulphate attack hence no expansion occurs. Gypsum may also fail to form in such systems hence fully carbonated systems should be immune to sulphate attack(65). Carbonate aggregates like limestone and dolomite have been observed to posess better sulphate resistance and this is due to the formation of carboaluminate ($C_3AC\bar{C}H_{12}$) which limits the formation of destructive ettringite. Hence the use of coarse and fine limestone aggregates may considerably increase the sulphate resistance of concrete[71].

8.3. METHODS OF TESTING SULPHATE RESISTANCE

A brief survey of the available test methods to investigate sulphate resistance of concrete is carried out in the following parts:

a. Concentration of sulphates

b. Size of test specimen

c. Rate of contact

d. Temperatures during testing

e. Methods of monitoring damage

8.3.1. Concentration of sulphates

Sulphate concentrations of 6000mg $SO_4^{=}$/l in groundwater are considered to be very severe and a protective coating or any other barrier is invariably required even for high sulphate resisting cements[65]. Sulphate concentrations of up to 10% of sodium sulphate and 10% of magnesium sulphate have been employed in accelerated tests with critical expansions resulting in about 200 days with Portland cement. The use of strong solutions has the advantage of increasing the rate of disruption, but there have been some doubts on the results of these accelerated tests since higher concentrations induce different physical and chemical effects. The rate of expansion increases with the concentration of sulphates. At very high concentrations sodium and magnesium sulphates give similar expansions whereas for reduced concentrations magnesium sulphate has been observed to result in greater expansion as compared to sodium sulphate[65]. Reduced temperatures also aggravate the rate of disintegration and tend to reduce differences between different binder types[65].

8.3.2. Size of test specimen

Use of a smaller sized test specimen tends to enhance the leaching of $Ca(OH)_2$ which is not typical of larger structures. Lime saturation in sulphate environments will prevent this enhanced leaching of lime but is unrepresentative of the practical situation. Where the pH value of the sulphate solution is controlled at around 7, i.e. neutral, loss of mass would be promoted by enhanced leaching of lime[65]. Larger size of specimen would create other practical problems in testing.

8.3.3. Rate of contact

Increased rate of contact can be achieved by increasing the exposure of concrete to sulphates. In the ASTM C452 test, excess gypsum is mixed with unhydrated cement and mortar bars formed are immersed in distilled water and expansion measurements are monitored. The test results may be suspect in case of binders which derive their sulphate resistance from reduced rate of ingress[65]. Also binders which require longer curing periods before becoming effective may be badly rated by this test.

Disruption in concrete specimens stored in sulphate solutions have been monitored but such tests in the laboratory are likely to run for very long periods before significant results are obtained.

Semi-immersion of specimens in sulphate solution for longer periods results in deterioration in the immersed half in the case of sodium sulphate solutions whereas the other half showed deterioration in case of magnesium sulphate solutions. Fully immersed specimen have been observed to suffer attack more rapidly than semi-immersed specimen. Daily cycles of immersion in sulphate solution and drying of concrete results in almost eight times greater rate of degradation as compared to lower frequency immersion/drying cycles[65]. Wetting in sulphate solution varied from sixteen to twenty four hours.

8.3.4. Temperatures during testing

Drying temperatures of 54°C and 70°C have been used for durations varying from eight hours to a number of days, without affecting the concrete properties[65,69].

It has been observed that lower temperatures increase the rate of expansion on attack by sulphate solutions. In sodium sulphate solution, expansions were observed to be a maximum at 10°C, slightly reduced at 20°C and negligible at 40°C. On the contrary, in magnesium sulphate solutions, expansions were moderate at 10°C, increased at 20°C and became negligible at 40°C. Expansions reduced with increase in temperature from 5 to 20 to 40°C[65]. It is suggested that, at reduced temperatures, ettringite is transformed into thaumasite, a complex sulphate salt $CaSiO_3.CaCO_3.CaSO_4.15H_2O$, which is responsible for deterioration. At increased temperatures thaumasite does not cause expansion. Thaumasite has been identified in tunnel linings showing advanced deterioration and in old buildings with exposed brickwork[65,69].

8.3.5. Methods of monitoring damage

The following methods are utilized for estimating the extent of sulphate attack or deterioration in concrete due to sulphate attack:

a. Visual observation

b. Measurement of strength

c. Measurement of expansion

d. Determination of elastic modulus

e. Estimation of volume or mass loss

Visual inspection is usually used in conjunction with other methods like strength, expansion or elastic modulus measurements. Visual inspection alone may not be a reliable method since a general weakening of the structure may result without much external evidence as in the case of offensive solutions with high sodium sulphate content.

Strength measurements of compressive and flexural strength have been used to monitor sulphate attack but the large number of test specimens required for such testing restrict this method to measurements of residual strengths only whilst the deterioration is monitored during the test by other methods.

Expansion measurements of test specimen show satisfactory results for specimens immersed in sodium sulphate solution where disintegration is less complex and the specimens show greater expansions at failure but on the contrary, specimens subjected to mixed offensive solution of sodium and magnesium sulphate tend to fail by surface scaling without much expansion[65]. Expansion measurements have been measured until an expansion of 0.1% is usually attained.

Periodic measurements of dynamic modulus of elasticity by monitoring the resonant flexural frequencies have been used to monitor deterioration in concrete due to sulphate attack. Falls in modulus have been observed to accompany more significant expansions. The change in modulus could be correlated with the expansion measurements[65]. Measurements of ultrasonic pulse velocity were observed not to be in accord with expansion nor the strength measurements.

Volume or mass loss has also been used to monitor deterioration of concrete by sulphate attack and gives an indication of the state of disruption.

8.4. METHOD SELECTED FOR TESTING SULPHATE RESISTANCE

The following factors must be considered in the selection of test method to assess the sulphate resistance of concrete with different types of crushed brick aggregates:

a. Type and concentration of sulphate solution

b. Size of test specimen

c. Rate of contact

d. Temperatures during the test

e. Methods of assessing damage

Sulphate solution selected for testing sulphate resistance of concrete with crushed brick aggregates comprised of 10% magnesium sulphate and 10% sodium sulphate.

Size of test specimen selected was 100*100*500mm prisms.

Rate of contact selected was twenty four hours of saturation in sulphate solution at 20°C followed by a similar period of drying at 70°C for 50 cycles of saturation and drying. The specimen were cooled to room temperatures after drying and were then placed in sulphate solution for saturation.

Methods employed for assessing sulphate damage were measurements on expansion and weight along with determination of dynamic modulus of elasticity after every ten cycles.

100*100*500mm prisms were selected for sulphate resistance tests to keep the ratio of size of test specimen and maximum size of aggregate to slightly over 2.5. Concentration of 10% of magnesium sulphate and similar amount of sodium sulphate was selected to sufficiently accelerate the tests. These concentrations have been used in the past in sulphate resistance tests. Rate of contact employed in this investigation was alternate saturation and drying for twenty four hours each. This contact regime was selected to accelerate the deterioration rate so as to keep the tests within manageable time span along with no other harmful effects, other than damage due to sulphates.

Similar rate of contact has been used in the past. Methods employed to assess sulphate damage were expansion and weight measurements along with determination of dynamic modulus at regular intervals. These methods have been successfully used in the past.

8.5. PERFORMANCE OF BRICK AGGREGATE CONCRETE

Table 8.2 gives a summary of the sulphate resistance test.

MIX	EXPANSION %	REDUCTION IN DYNAMIC MODULUS %
LBC/63	0.067	1.70
SBC/63	0.0026	23.44
EBC/63	0.045	28.00
GC/63	0.018	40.86
LBC/50	0.05	6.63
SBC/50	0.06	38.30
EBC/50	0.018	16.30
GC/50	0.03	70.65
EBC/385	0.106	24.50
GC/385	0.058	54.92
EBC/296	0.08	34.70
GC/296	0.096	60.60

Table 8.2. Summary - Sulphate resistance test.

Figures 8.1 and 8.2 show the variation of dynamic modulus and length with the number of cycles, respectively.

The performance of concrete with normal construction brick aggregate is given in Table 8.3.

For concrete with normal construction brick aggregates, it was observed that maximum expansion after 50 cycles was 0.067% and associated reduction in dynamic modulus was 1.7% for w/c ratio of 0.63 whereas maximum expansion was 0.05% and corresponding reduction in dynamic modulus was 6.63%

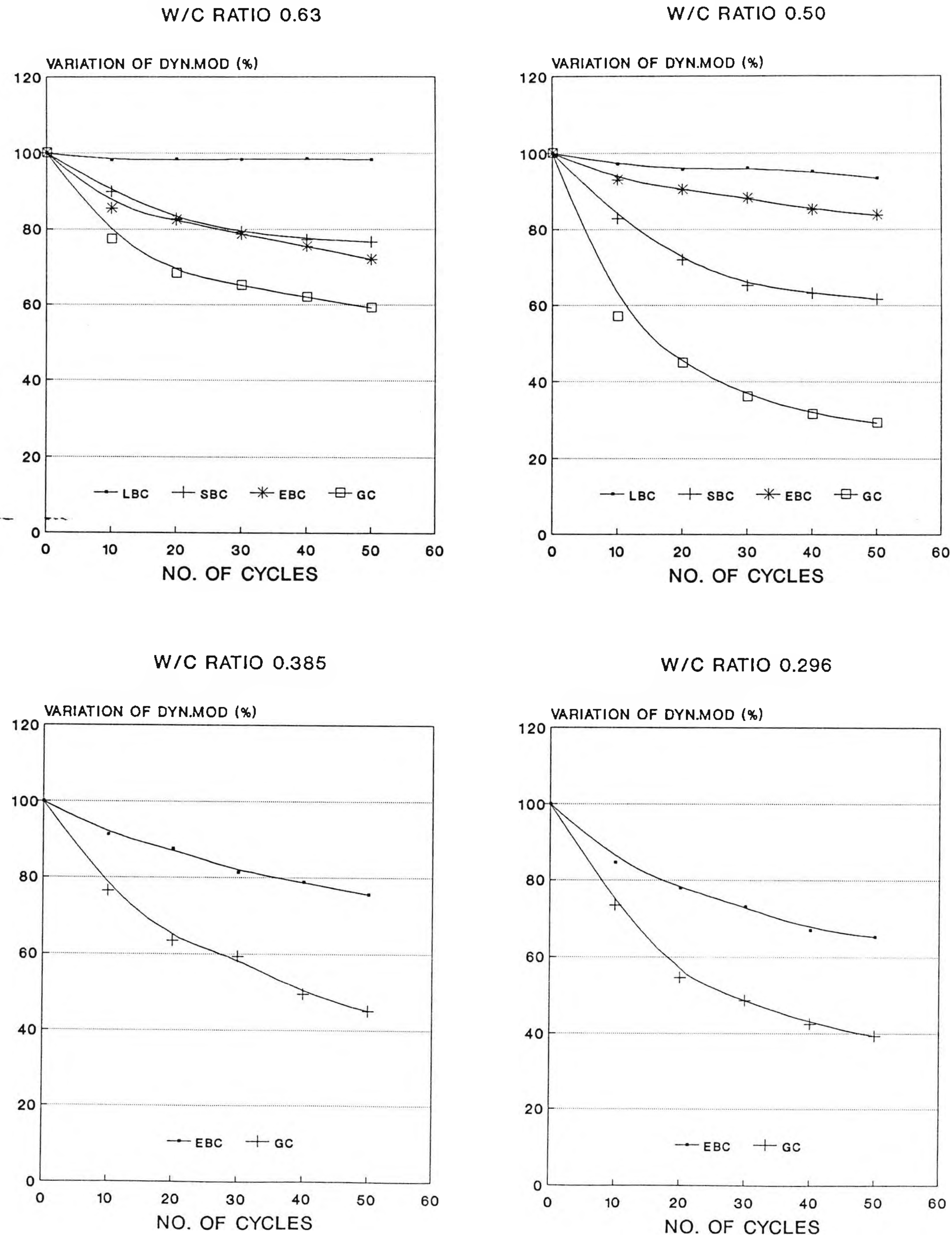


Figure 8.1. Variation in dynamic modulus vs Number of cycles.

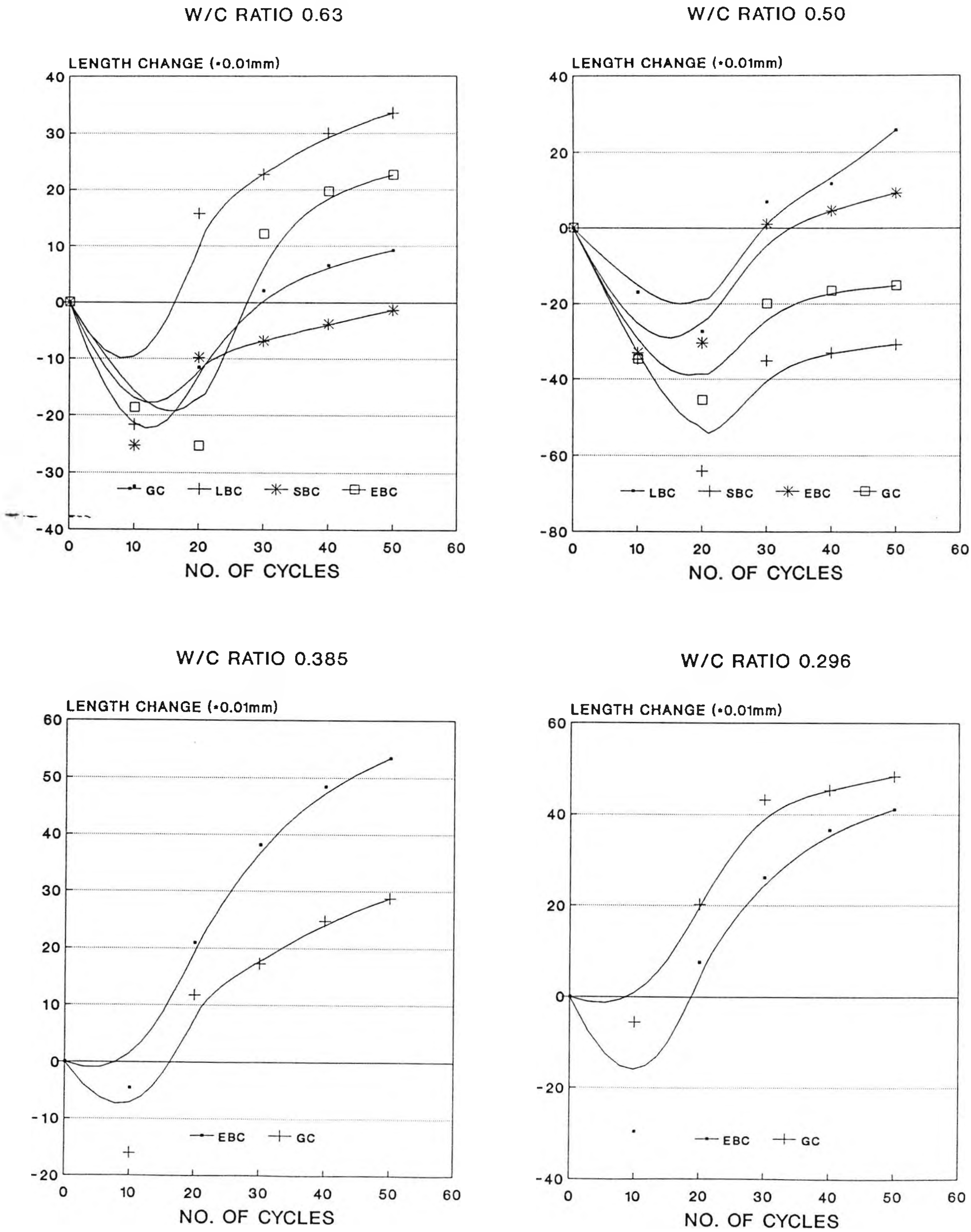


Figure 8.2. Length change vs Number of cycles.

Sample No.1 Normal construction brick aggregate concrete
W/C ratio 0.63
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	278.83	257.17	294.5	301.5	308.8	312.3
Weight(g):	10747.5	10531	10564	10584.3	10637	10653
R frequency(Hz):	3263	3267.7	3263.7	3259	3255	3247
Dyn.Mod.(N/mm^2):	22886	22459	22519.1	22503.7	22567	22494

Reduction in dyn mod = 1.7%, Increase in length = 0.067%

Sample No.1. Normal construction brick aggregate concrete
W/C ratio 0.50
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	283.83	266.67	256.3	290.67	295.5	309.5
Weight(g):	10935	10791.3	10724.7	10739	10790.7	10812
R frequency(Hz):	3478.3	3451.3	3438.7	3426.3	3415	3378
Dyn.Mod.(N/mm^2):	26460	25690.4	25335.3	25419	25180.5	24706

Reduction in dyn mod = 6.63%, Increase in length = 0.05%

Table 8.3. Performance of normal construction brick aggregate concrete in sulphate resistance test.

for w/c ratio of 0.50. Concrete with Thames Valley gravel showed expansion of 0.018% with reduction in dynamic modulus of 40.86% for w/c ratio of 0.63 and expansion was 0.03% with reduction in dynamic modulus of 70.65% for w/c ratio of 0.50. Hence the reduction in dynamic modulus for concrete with Thames Valley gravel is almost twenty times for w/c ratio of 0.63 and almost ten times for w/c ratio of 0.50 as compared to normal construction brick aggregate concrete. However the increase in length for concrete with normal construction brick aggregates was almost twice the value for concrete with Thames Valley gravel but was still significantly less than the critical value of 0.1%. Extensive pitting and scaling along with numerous minute cracks were observed on the surface of concrete after 30 cycles of saturation in sulphate solution and drying alternately. Figure 8.3 shows a specimen of concrete with normal construction brick aggregate after 50 cycles of sulphate test.

The reason for such a small reduction in dynamic modulus of concrete with normal construction brick aggregate is that normal construction brick aggregate is highly porous with absorption of around 20%. The possible formation of ettringite and its expansion by absorbing water can be accommodated in the large pores available in the brick aggregates, without having significant effects on the existing microstructure of concrete. The fact that brick aggregates expand on saturation is further helpful in this process along with lower stiffness of the brick aggregates as compared to mortar which also reduces the microcracking between the aggregate and mortar interface. A similar amount of expansion and contraction of brick aggregates and mortar on saturation and drying greatly reduces the development of microcracks within mortar, aggregates and along the bond surface thereby reducing the loss in strength. The lower coefficient of thermal expansion of concrete with normal construction brick aggregates as compared to concrete with Thames Valley gravel also reduces the effects of differential expansion/contraction. Crystallisation of salts on drying tend to increase the expansion. The presence of carbonates in normal

Figure 8.3. A specimen of concrete with normal construction brick aggregate after 50 cycles of sulphate resistance test.

construction brick aggregate needs to be investigated as it can reduce or totally arrest any expansion due to ettringite formation. The net expansions of concrete with normal construction brick aggregates did not reach anywhere near the critical value. The loss in weight of concrete with normal construction brick aggregates was observed to be around 1% as compared to an average loss in weight of 3.9% for concrete with Thames Valley gravel.

Table 8.4 shows the performance of concrete with sandlime brick aggregate in the sulphate resistance test.

Sample No. 2. Sandlime brick aggregate concrete
W/C ratio 0.63
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	238.3	213.3	228.5	231.5	234.5	237
Weight(g):	10851.3	10212	9984	9961.3	9911	9906
R frequency(Hz):	3484.3	3406	3304	3249	3205.3	3191
Dyn.Mod.(N/mm^2):	26347.7	23669.8	21789	21024.6	20362	20172

Reduction in dyn mod = 23.44%, Decrease in length = 0.0026%

Sample No. 2. Sandlime brick aggregate concrete
W/C ratio 0.50
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	295.5	260.8	231.5	260.3	262.5	264.7
Weight(g):	11468.3	10812	10617.3	10538	10524.3	10511
R frequency(Hz):	3513	3293.3	3098.67	2962.7	2915.67	2883
Dyn.Mod.(N/mm^2):	28290.5	23421	20336.9	18473	17868.5	17451

Reduction in dyn mod = 38.3%, Decrease in length = 0.06%

Table 8.4. Performance of sandlime brick aggregate concrete in sulphate resistance test.

For concrete with sandlime brick aggregates, it was observed that the maximum expansion after 50 cycles was 0.0026% and associated reduction in dynamic modulus was 23.44% for w/c ratio of 0.63 whereas maximum expansion was

0.06% and corresponding reduction in dynamic modulus was 38.3% for w/c ratio of 0.50. Hence the reduction in dynamic modulus and expansion for concrete with sandlime brick aggregates is nearly half the value for concrete with Thames Valley gravel. The loss in weight of concrete with sandlime brick aggregate was observed to be around 8.5% which is slightly over twice the value for concrete with Thames Valley gravel. The excessive loss in weight of concrete with sandlime brick aggregates is due to the leaching of large amounts of lime resulting in increased amounts of sulphates diffusing into concrete causing large reductions in dynamic modulus. The expansion of concrete with sandlime brick aggregates was small. Small cracks and pitting on surface started after 20 cycles of saturation in sulphate solution followed by drying. After 40 cycles large cracks up to 2mm width and 6 to 7mm deep could be seen on the surface along with excessive pitting and cracking. Figure 8.4 shows a specimen of concrete with sandlime brick aggregate after 50 cycles of sulphate resistance test.

Table 8.5 gives the performance of concrete with engineering brick aggregates in the sulphate resistance test.

Concrete with engineering brick aggregates displayed a maximum expansion of 0.045% after 50 cycles and the associated reduction in dynamic modulus was 28% for w/c ratio of 0.63 whereas maximum expansion was observed to be 0.018% and corresponding reduction in dynamic modulus of

Figure 8.4. A specimen of concrete with sandlime brick aggregate after 50 cycles of sulphate resistance test.

Sample No.3. Engineering brick aggregate concrete
W/C ratio 0.63
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	300.67	282	275.3	312.8	320.3	323.3
Weight(g):	11717	11189.7	11189	11172.3	11164.3	11175
R frequency(Hz):	3672.3	3474.3	3414	3334.67	3266.7	3188
Dyn.Mod.(N/mm^2):	31603	26993.5	26057	24849.3	23846.3	22735

Reduction in dyn mod = 28%, Increase in length = 0.045%

Sample No.3. Engineering brick aggregate concrete
W/C ratio 0.50
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	297.83	264.8	267.3	298.83	303.2	307
Weight(g):	12105.7	11826	11779.7	11706	11698.7	11711
R frequency(Hz):	3577.3	3494	3450.3	3415.3	3357	3327
Dyn.Mod.(N/mm^2):	30983.4	28831	28011.6	27309.5	26373.2	25945

Reduction in dyn mod = 16.3%, Increase in length = 0.018%

Sample No.3. Engineering brick aggregate concrete
W/C ratio 0.385
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	248.3	243.67	269.17	286.5	296.7	301.7
Weight(g):	11780.3	11540.7	11495	11490.7	11517	11526
R frequency(Hz):	3576.67	3443.3	3383.3	3263.3	3209	3138
Dyn.Mod.(N/mm^2):	30140	27456.4	26338	24510.6	23765	22752

Reduction in dyn mod = 24.5%, Increase in length = 0.106%

Sample No.3. Engineering brick aggregate concrete
W/C ratio 0.296
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	272.2	242.7	279.8	298.3	308.67	313.3
Weight(g):	11520.2	11243.3	11076.7	11152	11159.3	11162
R frequency(Hz):	3482.67	3242.67	3163.67	3023	2893	2855
Dyn.Mod.(N/mm^2):	27922.8	23616.6	21758.3	20404	18706.7	18227

Reduction in dyn mod = 34.7%, Increase in length = 0.08%

Table 8.5. Performance of engineering brick aggregate concrete in sulphate resistance test.

16.3% for w/c ratio of 0.50. For w/c ratio of 0.385, maximum expansion was observed to be 0.106% with reduction in dynamic modulus of 24.5% and for w/c ratio of 0.296

maximum expansion was 0.08% and reduction in dynamic modulus was observed to be 34.7%. The average loss in weight of concrete with engineering bricks was observed to be 3.28%. The average reduction in the dynamic modulus for concrete with engineering brick aggregates was observed to be about 46% of the value for concrete with Thames Valley gravel. Average values for expansion of concrete with engineering brick aggregate were observed to be similar to concrete with Thames Valley gravel. Expansions in the case of concrete with engineering brick aggregate and with Thames Valley gravel, both reached the critical value of 0.1% with a loss in dynamic modulus of 24.5% and 54.9% respectively. Figure 8.5 shows a specimen of concrete with engineering brick aggregate after 50 cycles of sulphate resistance test.

Concrete with engineering brick aggregate displayed expansions similar to concrete with Thames Valley gravel yet the reduction in dynamic modulus was observed to be about 46% of the value of concrete with Thames Valley gravel because of difference in differential expansion/contraction of engineering brick aggregate and mortar and gravel and mortar due to their different stiffnesses. The stiffness of engineering brick aggregate is less than that of Thames Valley gravel and hence it is more compatible with the stiffness of mortar, due to which there is reduced microcracking within aggregates, aggregate and mortar interface and in mortar.

Figure 8.5. A specimen of concrete with engineering brick aggregate after 50 cycles of sulphate resistance test.

Table 8.6 gives the performance of concrete with gravel.

Sample No.4. Gravel concrete
W/C ratio 0.63
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	259.75	227.17	248.17	261.8	266.3	269
Weight(g):	12383.8	12015.7	11943	11929.3	11929	11938
R frequency(Hz):	4553.3	4068	3851	3746	3652.3	3566
Dyn.Mod.(N/mm^2):	51349.6	39716.8	35073	33482.4	31834	30368

Reduction in dyn mod = 40.86%, Increase in length = 0.018%

Sample No.4. Gravel concrete
W/C ratio 0.50
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	303.3	268.5	257.7	283.3	286.3	288
Weight(g):	12686.7	12390.7	12309	12281	12278	12274.7
R frequency(Hz):	4597	3537.3	3152	2831	2646.7	2550.7
Dyn.Mod.(N/mm^2):	54389.2	30964.6	24413	19670	17190	15961.9

Reduction in dyn mod = 70.65%, Decrease in length = 0.03%

Sample No.4 Gravel concrete
W/C ratio 0.385
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	228.5	211.67	240.2	245.8	253.3	257.3
Weight(g):	12257.5	11902.7	11780	11766.7	11752	11743.7
R frequency(Hz):	4493.67	3977.3	3652	3510.3	3211	3063.3
Dyn.Mod.(N/mm^2):	48945.4	37454.4	31081	29018.4	24258	22065.5

Reduction in dyn mod = 54.92%, Increase in length = 0.058%

Sample No.4 Gravel concrete
W/C ratio 0.296
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	225	219.5	245.17	268.17	270.3	273.3
Weight(g):	12114	11720	11608.7	11582.7	11558.7	11553
R frequency(Hz):	4395	3830.7	3315.67	3133	2933	2822
Dyn.Mod.(N/mm^2):	46795	34388.4	25544.8	22777.7	19922.8	18436

Reduction in dyn mod = 60.6%, Increase in length = 0.096%

Table 8.6. Performance of gravel concrete in sulphate resistance test.

Concrete with Thames Valley gravel showed expansion of 0.018% with a reduction in dynamic modulus of 40.86% for w/c ratio of 0.63, expansion of 0.03% with reduction in dynamic modulus of 70.65% for w/c ratio of 0.50, expansion of 0.058% with reduction in dynamic modulus of 54.9% for w/c ratio of 0.385, and expansion of 0.096% with 60.6% reduction in dynamic modulus for w/c ratio of 0.296. Average loss in weight of concrete with Thames Valley gravel was observed to be 3.9%. The large reduction in dynamic modulus of concrete with Thames Valley gravel is due to the difference in absorption of mortar and gravel particles leading to differential expansions. Due to the very low absorption of gravel particles, most of the sulphate solution is absorbed in the mortar only, resulting in expansion of the mortar due to the formation of ettringite and resulting expansion due to it. On drying, the formation of salt crystals also causes dilative pressures on the mortar since more sulphates are absorbed by it as compared to a negligible quantity absorbed by gravel particles. The differential expansion/contraction therefore results in developing of large number of microcracks in mortar and mortar-aggregate interface thereby greatly reducing the dynamic modulus and strength of concrete. Figure 8.6 shows a specimen of gravel concrete after 50 cycles of sulphate resistance test.

8.6. CONCLUSIONS

When subjected to sulphate attack, performance of concrete with different types of crushed brick aggregates perform as follows:

Concrete with normal construction brick aggregates show

Figure 8.6. A specimen of gravel concrete after 50 cycles of sulphate resistance test.

twice as much expansions as compared to concrete with gravel aggregate but the loss in weight is about one fourth and the reduction in dynamic modulus is negligible.

Concrete with sandlime brick aggregate shows almost half the value of expansion and reduction of dynamic modulus as compared to gravel concrete but loss of weight was slightly over twice the value for gravel concrete.

Concrete with engineering brick aggregate shows almost similar expansions as compared to concrete with gravel. The average reduction in dynamic modulus for concrete with engineering brick aggregate was 30 to 50% lower and the weight loss was 15% lower than concrete with gravel aggregate.

PART 4

HIGH STRENGTH CONCRETE WITH CRUSHED

BRICK COARSE AGGREGATES

Crushed brick has not previously been studied for use in high strength concrete, hence the aim of this investigation was to explore the possibility for the use of crushed brick aggregate obtained from high quality bricks with high crushing strength and low absorption in the manufacture of high strength concrete and also to investigate the performance of high strength concrete with crushed brick aggregate.
Three specimens from three different batches were tested to assess each property hence the values given for each property represent an average of a total of nine specimens.

CHAPTER 9

HIGH-STRENGTH CONCRETE WITH CRUSHED BRICK COARSE AGGREGATES.

Investigations carried out on high strength concrete with crushed brick aggregates are given in this chapter. A general discussion on high strength concrete, its advantages and factors affecting high strength concrete is given in section 9.1. Section 9.2 discusses the mechanism of superplasticising admixtures used in the manufacture of high strength concrete followed by a brief discussion on production of high strength concrete in section 9.3. Section 9.4 gives the design of high strength concrete. Section 9.5 covers the performance of high strength concrete with crushed brick aggregates including compressive strength of cubes and cylinders, flexural strength, stress/strain behaviour, ISAT,static and dynamic moduli of elasticity, ultrasonic pulse velocity and density measurements. Conclusions are given in section 9.6 followed by recommendations in section 9.7 which also suggests a design procedure for design of high strength concrete mixes with crushed brick aggregates.

9.1. GENERAL

High-strength concrete is concrete with compressive strength over 60N/mm^2 and is relatively new material. The high strengths are achieved by the use of good quality and well graded aggregates and w/c ratios reduced below 0.35 with the help of superplasticising admixtures. The use of crushed brick aggregate for the production of high strength concrete and its performance have not at all been investigated yet.

Hence the aim of this investigation is to explore the possible use of high strength, good quality bricks with low absorption values for use in high strength concrete, after crushing. The shape and texture of aggregates obtained by crushing good quality bricks improve the aggregate-mortar bond and increased strength of aggregate along with lower w/c ratio may result in high strength concrete.

The fundamental parameter of high strength concrete is the low porosity achieved by high cement contents i.e. in excess of 500kg/m^3, and high density. Greater compactness of high strength concrete results in improved durability. Strength gain with time is normal and consistent with reduction in w/c ratio(76). The increase in modulus of elasticity is not proportional with the rate of increase in strength.

With carefully selected aggegates, cement, a small percentage of cement replaced with cementitious material like silica fume, microsilica, pfa and with efficient superplasticiser, strengths of up to 150N/mm^2 are possible along with very low porosities due to the much smaller size of the particles of cementitious material helping in more efficient packing. Use of ultrafine portland cement, high early strength cement and high alumina cements have found to achieve very high strengths, when used with well graded crushed granite and natural sand(83). The shape of aggregates such as crushed granite and the fine grading of aggregates helps in achieving a stronger bond between the mortar and aggregates thereby increasing the ultimate compressive strengths of concrete. Use of pozzolans, workability aids and increased quantities of fines helps in achieving greater densities of concrete.

Efficient curing is essential since water is required from external sources for hydration of cement due to the very low w/c ratio. The small amount of water available in the mix is insufficient for hydration of the large amounts of cement required for high strength concrete. Longer curing time may also be needed for full development of strength due to the reduced rate of hydration which is due to reduced rate of penetration of moisture deep into hydrated cement, after initial hydration has taken place.

Additional advantages of high-strength concrete are that creep and shrinkage are reduced, hence loss of prestress is reduced[80]. Column sections can be reduced in size or, for the same cross section, the amount of reinforcing steel can be reduced. Hence floor areas increase in tall buildings, due to reduction in column sections. The reduction in reinforcing steel is about 1% for every 7N/mm^2 increase in concrete strength[83]. Increasing the strength of concrete from 40 to 80N/mm^2 results in a 42% reduction in column area and 33% in cost[77]. For bridges, the number of beams can be reduced, longer spans are possible without appreciable increase in dead weights. High strength is also advantageous for offshore structures where platform columns subjected to high stresses need to weigh as little as possible for floating stability.

Higher early strengths of high-strength concrete are also advantageous. Formwork stripping timings can be reduced along with a reduction in the amount of formwork due to smaller sections. High early strength is used in prestressed units to allow early detensioning i.e. in 6 to 7 hours as compared to normal 22 to 24 hours. Early stripping of moulds in production of precast units like tunnel segments, sleepers and piles etc. is possible[76]. Disadvantages appear to be relatively low shear strength[12]. Reduction of section modulus may result in increased deflections and cracking. Drastic reductions in steel percentage in columns may enhance shrinkage and creep, and load transfer from steel to concrete. Use of higher allowable stresses in prestressed structures may lead to higher creep losses. If high strength of concrete is derived from increased cement contents, increased shrinkage and creep strains will result.

The availability of high tensile reinforcing and prestressing steel with yield strengths of 600 to 700 N/mm^2, along with high strength concrete, has widened the field of use [83]. Congestion of reinforcement may be relieved by use of high strength steel. There is, however, the possibility of brittle and explosive failure which may result in high strength concrete due to fast propagation of ultimate cracks under very high stresses[83].

However these problems can be overcome by good design and selection of appropriate materials.

9.2. MECHANISM OF SUPERPLASTICISING ADMIXTURES

Superplasticisers are anionic surface active agents. They are chemically absorbed onto the cement agglomerates which also become negatively charged, hence the resultant repulsion results in more efficient dispersion of cement particles allowing high workability with reduced water/cement ratio or flowing concrete without increase in water content. Efficient dispersion of cement particles results in a more uniform hydration hence improved performance of concrete[76]. Superplasticisers permit water reductions from 20 to 33% and can be used at high dosage levels since they do not markedly lower surface tension of water. The actual reduction depends upon the performance of admixture, dosage, cement type, aggregate quality and ambient temperature[76]. Although the dosage of most superplasticisers is around 0.5 to 0.7% by weight of cement this can be increased to 1.2% before their water reducing capability peaks, as compared to 0.3% of cement for normal plasticisers[76]. The dosage of superplasticisers has to monitored very carefully since overdosage may result in segregation, as with overmixing.

Superplasticisers are of two main categories:

a. Sulphonated melamine-formaldehyde condensate

b. Sulphonated naphthalene-formaldehyde condensates

Additionally, certain modified lignosulphonates exist which are blended with plasticisers and superplasticisers. Lignosulphonate based superplasticisers have some retardation quality. Superplasticisers and plasticisers are based on chemicals referred to as non-hazardous in terms of corrosion, toxicity or flammability[76]. No known adverse effects of superplasticisers on concrete or steel reinforcement exist. BS 5075: Part 1: 1982 contains specification for plasticisers and BS 5075: Part 3: 1985 contains specifications for superplasticising admixtures. Creep and shrinkage are not adversely affected nor is durability[76]. Some reduction in cement content can offset the extra expense of superplasticiser, within the same mix design, especially for richer mixes, thereby greatly improving the strength and durability[76]. Increased cost of superplasticiser ranging fron £1.50 to £4.00/m^3 can be offset by[76]:

a. Reduced time for steam or high temperature curing.

b. Improved strength for precast items thereby reducing wastage and breakage.

c. Increased rate of construction.

d. Reduced need to vibrate due to high workability.

e. Increased rate of placing.

9.3. PRODUCTION OF HIGH STRENGTH CONCRETE

The batching, mixing and transportation of high strength concrete require more care. All materials should be weighed with automatic equipment for speed and accuracy. To maintain accurate w/c ratios, accurate moisture measurements of fine aggregate should be taken. Wet batching with 50% of water added before cement enhances efficiency. Workability checks should be made in advance to check the loss of workability due to journey of the truck mixer to the site and time taken to discharge concrete. Loss of workability can be dramatic once the effect of superplasticiser wears off[77].

9.4. DESIGN OF HIGH STRENGTH CONCRETE

The 'Design of normal concrete mixes'[1] method covers design up to strengths of 50N/mm^2. Although some individual high strength mixes are described in various papers, no general design methods or procedures exist for the design of high-strength concrete nor are there any guidelines on design/testing/use of high strength concrete. Little use of high strength concrete in U.K. has been reported whereas there is more published evidence of its use in U.S.A. The few construction companies which are using high strength concrete have designed the specific strength required by method of trial. One such design for 80N/mm^2 concrete specifies cement content of 540kg/m^3 and w/c ratio of 0.25[77]. Another development on 90N/mm^2 concrete used 30kg/m^3 of silica fume with 500kg/m^3 of cement and w/c ratio of 0.25[78]. Superplasticiser dosage of 14 l/m^3 was used along with a set retarding agent of 1.8 l/m^3 to produce flowing concrete. Air content of 4.4% was found. A strength of 72N/mm^2 developed in 7 days, 87N/mm^2 in 28 days and 100N/mm^2 in 91 days. Shrinkage was found to be the same as for normal concrete with w/c ratio of 0.4. Maximum shrinkage in high strength concrete developed much earlier due to high cement content. Only micropores were observed in the microstructure. An elastic modulus of 42.9MPa and a Modulus of rupture of 11MPa were found at 28 days[78]. Reduction in creep and shrinkage was observed in all the cases[80].

In order to establish a mix design for investigating properties of high strength concrete with crushed coarse brick aggregates, initially three mixes for characteristic strengths of 60, 80 and 100N/mm^2 were designed using OPC, Thames Valley well graded gravel (maximum 37.5mm diameter) and medium grading sand. A linear projection of compressive strength versus w/c ratio (Figure 4) from Design of normal concrete mixes method was considered initially beyond the limiting w/c ratio of 0.3 along with free water content. An estimate of density was made initially and later corrected after mixing. The entire mix design was reviewed after first testing and revised mixes were again investigated. Final mix design was then used to investigate properties of high strength concrete with crushed coarse brick aggregates. Table 9.1 gives the details of constituents.

CHARACTERISTIC STRENGTH N/mm^2	**W/C RATIO**	**CEMENT** kg	**SAND** kg	**WATER** kg	**AGGREGATE** kg
60	0.29	465	515	135	1335
80	0.24	565	490	135	1260
100	0.19	710	450	135	1155

Table 9.1: Design of high strength concrete mixes.

The mixes were tested for cube and cylinder compressive strengths, flexural strength, static and dynamic moduli and ultrasonic pulse velocity. Compressive strengths for cubes as well as cylinders were tested.

The control mix with Thames Valley gravel could achieve an absolute maximum compressive strength of 80N/mm^2. Further lowering of w/c ratio could not increase the compressive strength. The bond strength between the rounded gravel aggregate and the mortar is the limiting factor which limits the use of gravel as aggregate for concrete strengths upto a maximum compressive strength of 80N/mm^2. For a compressive strength of 100N/mm^2 crushed granite was used as control.

9.5. PERFORMANCE OF HIGH STRENGTH BRICK AGGREGATE CONCRETE

Tables 9.2 and 9.3 give the properties of high strength concrete.

TYPE OF AGGREGATE	W/C RATIO	CUBE STRENGTH 7DAYS N/mm^2	CUBE STRENGTH 28DAYS N/mm^2	CUBE STRENGTH 42DAYS N/mm^2	CYLINDER STRENGTH N/mm^2	FLEXURAL STRENGTH N/mm^2
Gravel	0.29	49.30	57.91	62.22	43.74	6.42
	0.24	68.47	76.24	80.70	59.95	7.29
	0.19	73.97	79.13	83.72	61.42	7.09
Granite	0.19	82.32	91.98	100.21	63.56	7.18
Engineering Brick	0.29	51.87	58.31	62.77	37.68	7.04
	0.24	66.61	71.89	79.82	49.23	6.47
	0.19	67.93	73.44	81.09	51.10	6.82

Table 9.2. Properties of high strength concrete.

9.5.1. Compressive strength

Compressive strength tests on cubes at 7 days and 28 days showed that the rate of development of strength of brick aggregate concrete was similar to that for normal aggregate concrete. However, it was observed that satisfactory strengths could be achieved in 42 days since water is required from external source for hydration of cement due

TYPE OF AGGREGATE	W/C RATIO	ISAT	ELASTIC STATIC N/mm^2	MODULUS DYNAMIC N/mm^2	PULSE VELOCITY km/s
Gravel	0.29	Very Low	24763.4	51378.2	4.79
	0.24	Very Low	25190.7	54563.1	4.82
	0.19	Very Low	25079.6	53684.7	4.84
Granite	0.19	Very Low	24967.7	48376.9	4.71
Engineering Brick	0.29	Very Low	15793.1	32758.7	4.2
	0.24	Very Low	15686.5	32095.4	4.2
	0.19	Very Low	15981.6	32754.8	4.3

Table 9.3. Properties of high strength concrete.

to very low w/c ratios. Hence longer curing time is needed for the development of characteristic strength due to reduced rate of penetration of moisture deep into hydrated cement, after initial hydration has taken place. Figure 9.1 shows the compressive strength achieved versus w/c ratio.

Brick aggregate concrete developed 80 to 85% of its characteristic strength in 7 days and 90 to 95% in 28 days. Average characteristic strength was achieved in 42 days. Brick aggregate concrete developed a maximum compressive strength of $80N/mm^2$ and a further reduction in w/c ratio did not result in an increase in compressive strength. The limiting factor is the strength of bricks from which the aggregate is obtained.

Cylinder strengths of brick aggregate concrete were observed to vary from 60 to 63% of the cube strength.

Since high strength concrete tends to be more homogeneous as compared to normal strength concrete, failure of cubes and cylinders of high strength concrete tends to be sudden and explosive due to the complete section reaching the

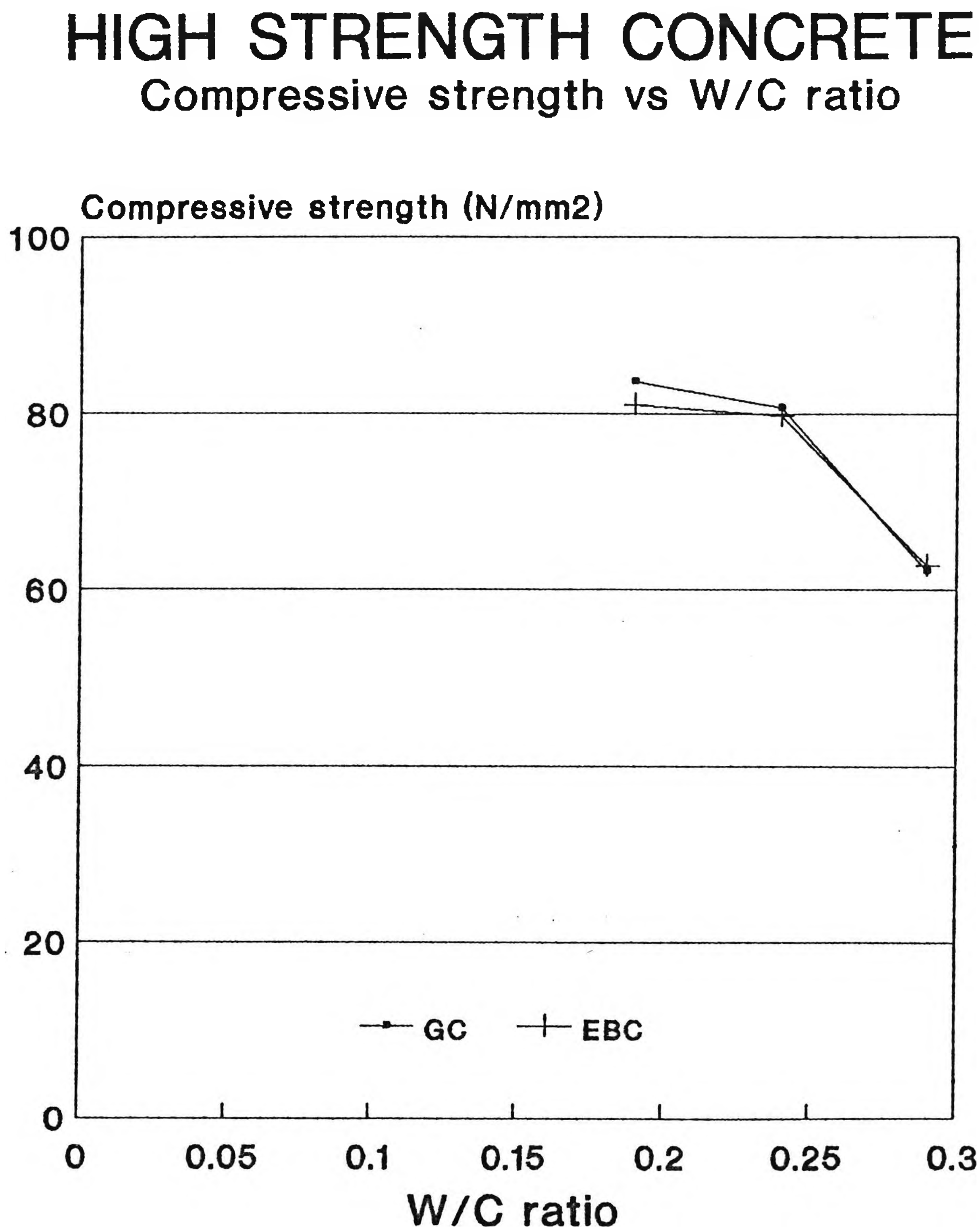


Fig 9.1. Compressive strength vs w/c ratio.

failure limit simultaneously. Sudden failure is likely to damage the compression testing machine and also the debris released from the specimen in such type of failure may injure the individual testing the concrete or anyone in the near vicinity unless protection is provided. A loading rate of 0.15 to 0.2N/mm^2/s was observed to be safe enough to observe failure, as compared to 0.2 to 0.4N/mm^2 specified by BS 1881: Part 116: 1983.

9.5.2. Flexural strength

150*150*750mm beams were cast for determining the flexural strength of concrete with brick aggregates and tested with third point loading. It was observed that the flexural strength of concrete with brick aggregate varied from 6.47 to 7.04N/mm^2 i.e. 8 to 11% of the 42 day compressive strength, for average compressive strengths of 60 to 80N/mm^2. Flexural strength of concrete with gravel aggregate varied from 6.4 to 7.29N/mm^2 i.e. 9 to 11% of the 42 day compressive strength. Hence flexural strength values for concrete with brick aggregates are similar to concrete with Thames valley gravel.

It was observed that failure in flexure across the section of test beams occurred by a crack both through the mortar and through the aggregate particles in the case of concrete with brick aggregates. In the control mix, with gravel aggregate, the failure crack propagated through the mortar and around the gravel particles. No gravel particles were observed to fail but failure occurred along the bond surface between the mortar and rounded gravel particles.

9.5.3. Stress/strain behaviour

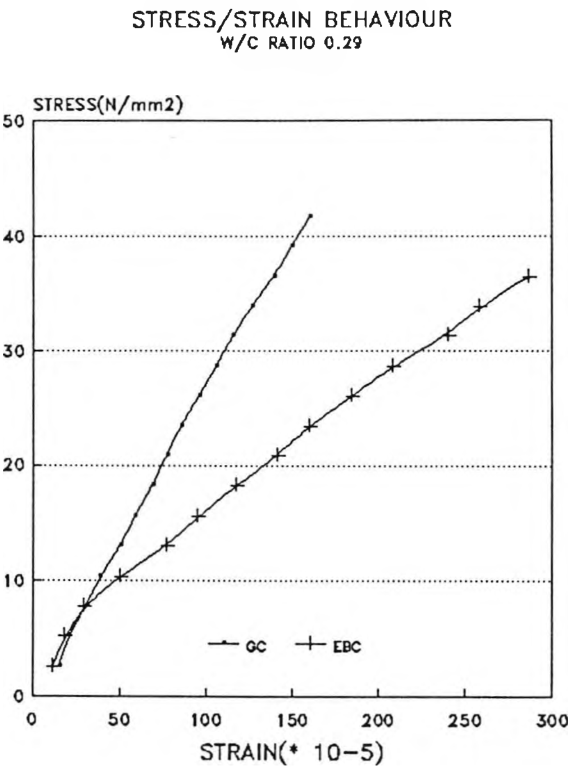
Stress/strain behaviour of brick aggregate concretes and concrete with Thames Valley gravel were studied on 150mm diameter, 300mm long cylinders. Increments of load were applied and strains measured for each increment. Figure 9.2 gives the stress/strain relationship of engineering brick aggregate concrete and the control mix for w/c ratios of 0.29 and 0.24. It was observed that the stress/strain behaviour of concrete with crushed brick as coarse aggregates was similar to that for concrete with Thames Valley gravel as coarse aggregates. Both the curves were observed to be almost linear up to the point of failure, except for the initial small portion. Higher values of strain were observed in the case of concrete with engineering brick aggregates.

9.5.4. Modulus of elasticity

9.5.4.1. Static modulus of elasticity

150mm diameter, 300mm long cylinders were prepared for determining the static modulus of elasticity in compression.

The static modulus of elasticity in the case of concrete with engineering brick aggregates was observed to vary from 15686.5 to 15981.6N/mm^2 whereas the static modulus of elasticity for concrete with Thames Valley gravel was observed to vary from 24763.4 to 25190.7N/mm^2. Hence the average static modulus of elasticity for concrete with



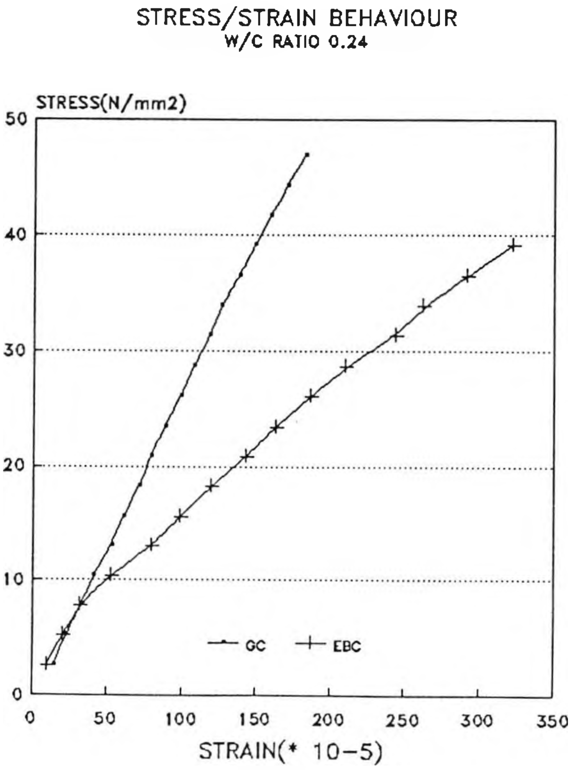


Figure 9.2: Stress/strain behaviour - W/C ratio 0.29
Stress/strain behaviour - W/C ratio 0.24

engineering brick aggregate is 36% lower than concrete with Thames Valley gravel.

9.5.4.2. Dynamic modulus of elasticity

Test beams, 150*150*750mm, were cast for carrying out the dynamic modulus of elasticity tests. The specimen were cured in water at 20^{0}C for 28 days before testing. The dynamic modulus of elasticity for concrete with engineering brick varied from 32095 to 32758N/mm^2 whereas for concrete with Thames Valley gravel it ranged from 51378 to 54563N/mm^2. Hence average dynamic modulus for concrete with engineering brick aggregate is 38% lower as compared to the value for concrete with Thames Valley gravel aggregate.

9.5.5. Ultrasonic pulse velocity

Ultrasonic pulse velocity tests for observing the velocity of pulses across the brick aggregate concrete specimen were carried out as per BS 1881: Part 203: 1986. 150mm cubes were water-cured for 28 days before testing for pulse velocity. The pulse velocities observed for different concretes are given in Table 9.3. Average pulse velocity across concrete with engineering brick aggregate was observed to be 4.2km/s for average values of static modulus of elasticity of 15833N/mm^2 and dynamic modulus of elasticity of 32426N/mm^2. For concrete with Thames Valley gravel as coarse aggregate the average pulse velocity was observed to be 4.8 km/s for average values of static modulus of elasticity of 24976N/mm^2 and dynamic modulus of elasticity of 52970N/mm^2. Hence the variation of pulse velocity in the case of concrete with engineering brick aggregate was observed to be 12.5% as compared to that in concrete with Thames Valley gravel aggregate. It was observed that pulse velocities, static moduli and dynamic moduli of elasticity obtained from experimental investigations did not correlate with the values given in BS 1881: Part 203: 1986.

9.5.6. Density of hardened concrete

Densities of hardened concrete were obtained by weighing the specimens (cubes) accurately at the end of the 28 days curing period, to obtain the saturated weight and measuring the dimensions accurately to obtain the volume of test cubes as per BS 1881: Part 114: 1983. The average saturated and dry densities for concrete with engineering brick aggregates were 2335 and 2314kg/m^3, whereas the average saturated and dry densities for concrete with Thames Valley gravel were observed to be 2480 and 2461kg/m^3. Hence the saturated and dry densities of concrete with engineering brick aggregate are about 6% lower than concrete with Thames Valley gravel.

9.5.7. Initial surface absorption

Initial surface absorption tests were carried out in accordance with BS 1881: Part 5: 1970. Results of ISAT are given in Table 9.3. Initial surface absorption for high strength concrete with crushed brick aggregates was observed to be similar to high strength concrete with gravel.

9.6. CONCLUSIONS

Brick aggregate obtained by crushing engineering 'B' bricks with crushing strength of $40N/mm^2$ can be used for high strength concrete up to a maximum characteristic strength of $80N/mm^2$. Higher compressive strengths are likely to be achieved by further improving the quality of crushed brick aggregates i.e. by crushing higher strength bricks.

Concrete with crushed engineering brick aggregates achieved a maximum compressive strength of $80N/mm^2$ beyond which the limiting factor is the crushing strength of bricks from which the aggregate have been obtained.

Thames Valley gravel concrete also could not exceed the ultimate maximum compressive strength of $80N/mm^2$ where the bond strength between the aggregate and mortar peaked.

It has been observed in this investigation that brick aggregates can be conveniently used for characteristic strengths of high strength concrete upto a maximum of twice the crushing strength of bricks from which they are obtained.

Compressive strengths of 60 and $80N/mm^2$ were successfully achieved. Flexural strength of brick aggregate concrete in the high strength range was observed to be between 8 to 11% of the compressive strength, similar to high strength concrete with round gravel as aggregate. The average static modulus of elasticity for concrete with engineering brick aggregate was observed to be 36% lower than concrete with Thames Valley gravel and average dynamic modulus of elasticity for concrete with engineering brick aggregate was 38% lower. About 6% lower densities were observed for high strength brick aggregate concrete as compared to high strength concrete with Thames Valley gravel. Surface absorption for high strength concrete with brick aggregates was observed to be similar to high strength concrete with gravel.

9.7. RECOMMENDATIONS

Coarse aggregates obtained by crushing engineering bricks can be used for the manufacture of high strength concrete. The following design procedure is recommended for design of high strength concrete with brick aggregates:

Step 1. Select w/c ratio against the desired strength from Figure 9.3. (Design Chart)

Step 2. Determine free water content from Table 9.4. Ensure the aggregates are in saturated surface dry condition.

Maximum Aggregate Size	Water
40mm	135kg/m^3
20mm	150kg/m^3

Table 9.4. Free water content

Step 3. Determine cement content from w/c ratio and free water content.

$$\text{Cement content} = \frac{\text{Free water content}}{\text{w/c ratio}}$$

Step 4. Determine total aggregate content.

To determine the total aggregate content, an estimate of the wet, compacted density is made from following:

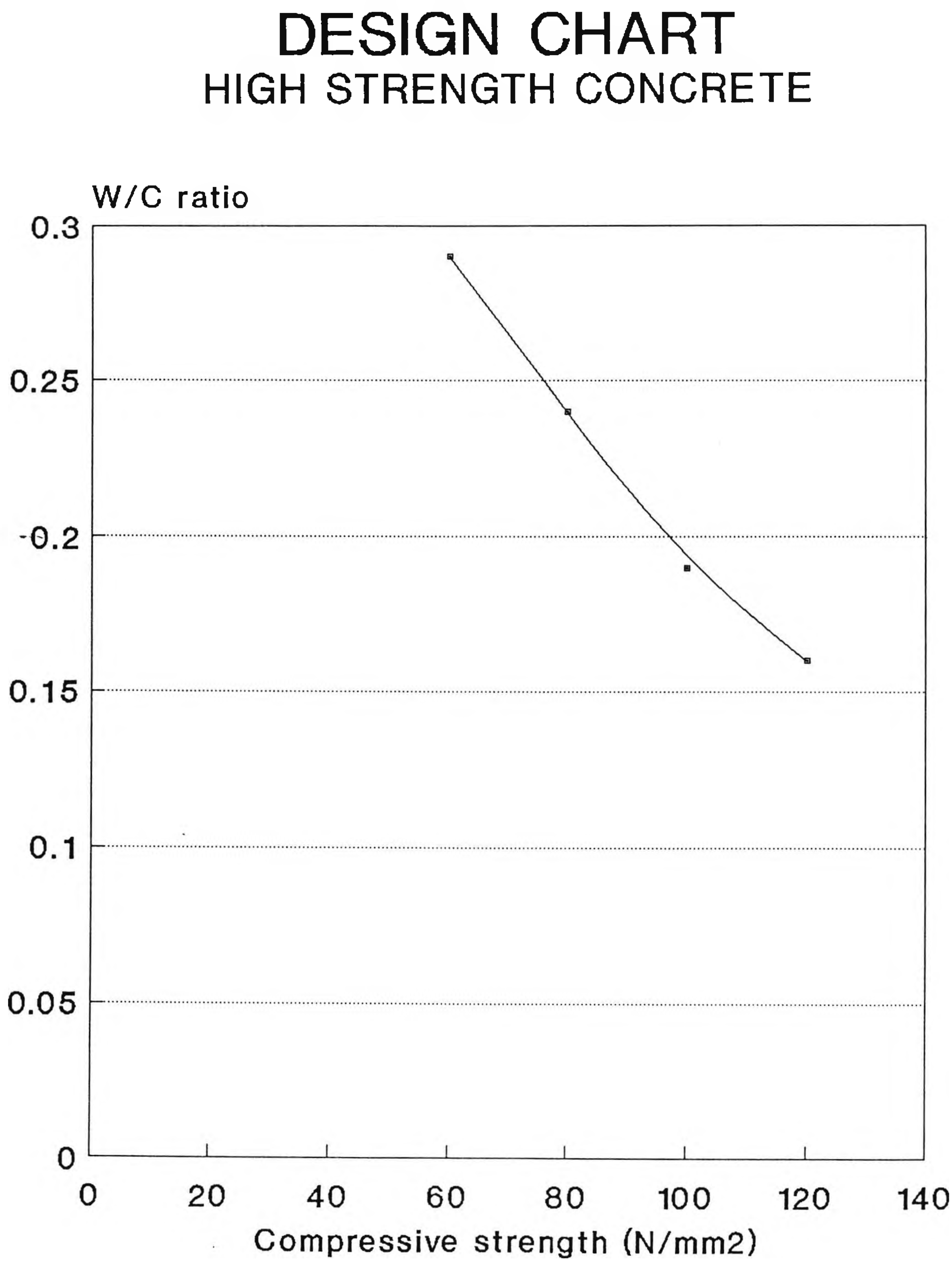


Figure 9.3: Design Chart - Compressive strength vs w/c ratio.

Fresh compacted density = 1025 * R.D.

where R.D is relative density of aggregate with a minimum value of 2.2.

Note:

a. Minimum crushing strength of bricks crushed to obtain aggregates for high strength concrete should not be less than $40N/mm^2$.

b. Crushed brick aggregates obtained from bricks with average crushing strength of $40N/mm^2$ will not be used for characteristic strength exceeding $80N/mm^2$.

Calculate total aggregate content from:

Total aggregate = wet compacted density - cement - water

Step 5. Determine fine and coarse aggregate contents.

Fine aggregates = %fines * Total aggregate content

Coarse aggregates = Total aggregate content - fine aggregates

Use 30 to 28% fines (medium grading), the higher value for higher w/c ratio and the lower one for lower w/c ratio varying from 0.29 to 0.16 respectively. Use of fine sand tends to increase the free water content whereas coarse sand tends to further reduce workability.

PART 5

CONCRETE WITH MIXED GRAVEL AND CRUSHED BRICK COARSE AGGREGATES

Investigations on concrete with mixed aggregates i.e various types of crushed brick aggregates plus gravel are covered in this part. Occasionally brick aggregates have been mixed with gravel and used in concrete but the effect of adding crushed brick aggregate to gravel and performance of concrete with mixed aggregates has not been investigated yet. Brick aggregates are added to gravel in selected percentages and the resulting concrete is investigated for its properties in this part.
Three specimens from three different batches were tested to assess each property hence the values given for each property represent an average of a total of nine specimens.

CHAPTER 10

CONCRETE WITH MIXED GRAVEL AND CRUSHED BRICK COARSE AGGREGATES

This chapter covers the investigations carried out on concrete with mixed aggregates. Two types of crushed brick aggregates were mixed with gravel in the ratios of 30:70 and 40:60 by weight and specimens were cast from the resulting concrete for investigations. Two w/c ratios were investigated. Tests were carried out to assess the compressive strength of cubes and cylinders of mixed aggregate concrete along with flexural strength, stress/strain behaviour, moduli of elasticity, ultrasonic pulse velocity determination, densities, surface absorption, shrinkage and frost resistance. The values obtained from these tests were compared with the values of concrete with gravel with similar w/c ratios.

10.1. GENERAL

Occasionally crushed brick aggregates from damaged/left over/wasted bricks are added in normal aggregates and used for concreting. There has been no information at all on the performance of concrete in which normal aggregates have been partly replaced with crushed brick aggregates. To investigate the performance of concrete with normal aggregates plus a percentage of crushed brick aggregates, two sets of specimen were prepared for experimental investigation by replacing 30% and 40% by weight of gravel aggregate by crushed brick coarse aggregates. The w/c ratios of two characteristic strengths of 35 and 50N/mm^2 of concrete with gravel were investigated for concrete with mixed gravel and crushed brick aggregates. The concrete specimen used as standard to carry out comparative study were prepared by using Thames Valley gravel. Water/cement ratio, quality of water, curing conditions and test methods were kept constant. Table 10.1 gives the quantities per cubic metre of concrete. Table 10.2 and 10.3 give the properties of concrete with mixed aggregates.

10.2. COMPRESSIVE STRENGTH

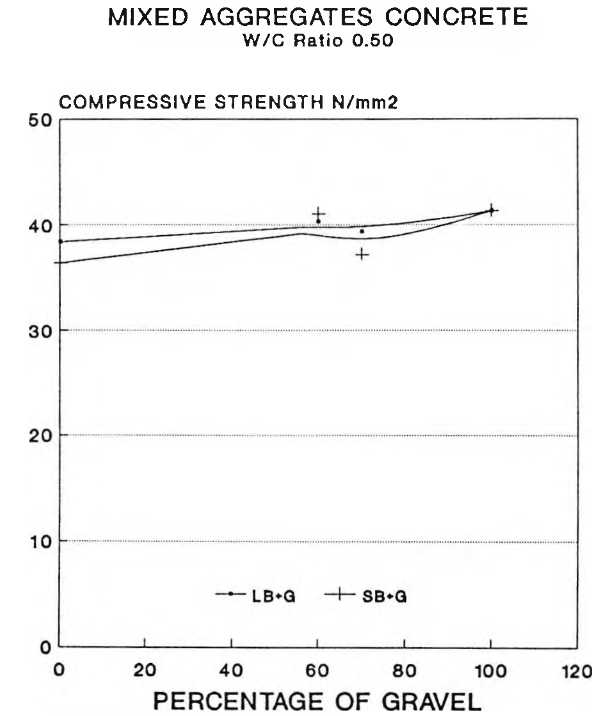
Compressive strength tests on cubes at 7 days and 28 days showed that the rate of development of strength of mixed

MIX	**11**	**12**	**21**	**22**
W/C RATIO	**0.5**	**0.385**	**0.5**	**0.385**
Density (average) kg/m^3	2330	2355	2345	2360
Cement kg/m^3	320	415	320	415
Water kg/m^3	160	160	160	160
Fine aggregate kg/m^3	575	535	595	535
Coarse aggregate kg/m^3	1275	1245	1270	1250
w/c ratio	0.5	0.385	0.5	0.385

MIX	**31**	**32**	**41**	**42**
W/C RATIO	**0.5**	**0.385**	**0.5**	**0.385**
Density (average) kg/m^3	2305	2325	2315	2330
Cement kg/m^3	320	415	320	415
Water kg/m^3	160	160	160	160
Fine aggregate kg/m^3	570	525	585	525
Coarse aggregate kg/m^3	1255	1225	1250	1230
w/c ratio	0.5	0.385	0.5	0.385

Table 10.1. Quantities per cubic meter of concrete.

aggregate concrete was similar to normal aggregate concrete. Specimen with 30% and 40% of gravel replaced by coarse crushed normal construction brick and sandlime brick aggregates developed satisfactory compressive strengths at the first attempt. Figure 10.1 shows the variation in compressive strength of mixed aggregates concrete as compared to brick aggregate concrete and gravel concrete. 0% of gravel concrete on graph indicates brick aggregate



LB - Normal construction brick
SB - Sandlime brick
G - Gravel

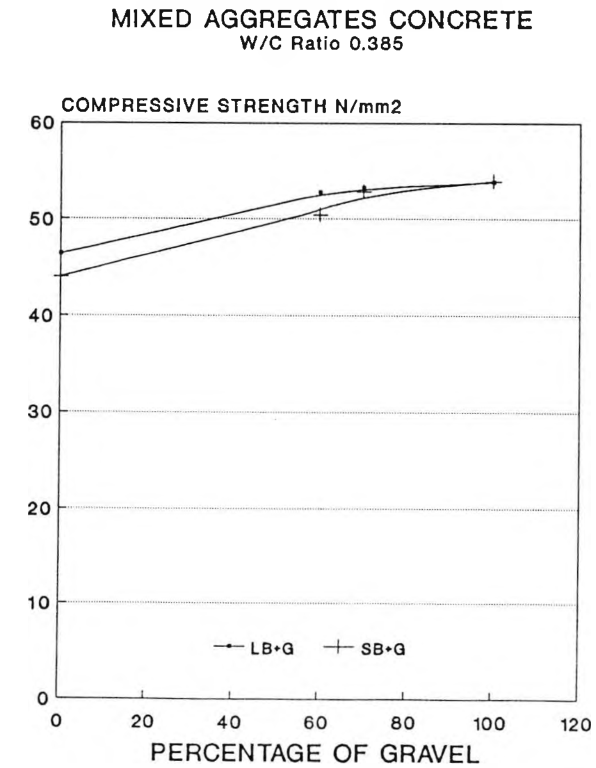


Figure 10.1. Variation in compressive strength of concrete with mixed aggregates from brick concrete to gravel concrete.

TYPE OF MIX	W/C RATIO	COMPRESSIVE STRENGTH 7DAY N/mm^2	COMPRESSIVE STRENGTH 28DAY N/mm^2	CYLINDER STRENGTH N/mm^2	FLEXURAL STRENGTH N/mm^2	ELASTIC MODULUS DYN N/mm^2	ELASTIC MODULUS STATIC N/mm^2
11	0.5	34.00	39.30	29.02	6.46	37902.1	14790.3
12	0.385	48.10	53.24	32.65	7.50	39968.7	18226.5
21	0.5	33.21	37.14	29.33	7.58	40508.1	14660.4
22	0.385	47.33	52.43	31.76	8.17	39057.2	15172.9
31	0.5	34.73	40.31	27.84	6.13	36992.4	13322.7
32	0.385	47.81	52.74	30.71	6.97	38163.7	16269.6
41	0.5	35.66	41.00	27.22	7.61	38676.9	14500.0
42	0.385	42.93	50.87	32.69	7.73	37597.6	14672.1
Gravel	0.5	36.83	41.34	29.3	4.41	46922.8	23480.2
	0.385	46.49	53.81	37.98	5.33	47557.8	24033.5

Table 10.2. Properties of concrete with mixed aggregates.

TYPE OF MIX	W/C RATIO	DENSITY OF CONCRETE(kg/m^3) dry	DENSITY OF CONCRETE(kg/m^3) saturated	ISAT	SHRINKAGE $*10^{-4}$mm	PULSE VELOCITY km/s
11	0.5	2219	2330	Average	3.024	4.279
12	0.385	2276	2363	low	3.73	4.273
21	0.5	2271	2353	low	2.68	4.109
22	0.385	2289	2377	low	3.268	4.230
31	0.5	2184	2297	Average	3.42	4.012
32	0.385	2231	2312	low	3.81	4.103
41	0.5	2227	2314	low	3.01	3.984
42	0.385	2243	2331	low	3.63	4.112
Gravel	0.5	2403	2454.80	low	1.176	4.76
	0.385	2411	2457.70	low	2.976	4.79

Table 10.3. Properties of concrete with mixed aggregates.

Note:
11 - 30% London brick aggregate + 70% Gravel
12 - 30% London brick aggregate + 70% Gravel
21 - 30% Sandlime brick aggregate + 70% Gravel
22 - 30% Sandlime brick aggregate + 70% Gravel
31 - 40% London brick aggregate + 60% Gravel
32 - 40% London brick aggregate + 60% Gravel
41 - 40% Sandlime brick aggregate + 60% Gravel
42 - 40% Sandlime brick aggregate + 60% Gravel

concrete. On testing cylinders for 28 days compressive strength, it was observed that the cylinder strength varied

TYPE OF MIX	W/C RATIO	CUBE STRENGTH N/mm^2	CYLINDER STRENGTH N/mm^2	%
11	0.50	39.30	29.02	73.84
12	0.385	53.24	32.65	61.33
21	0.50	37.14	29.33	78.97
22	0.385	52.43	31.76	60.58
31	0.50	40.31	27.84	69.06
32	0.385	52.74	30.71	58.23
41	0.50	41.00	27.22	66.39
42	0.385	50.87	32.69	64.26
Gravel	0.50	41.34	25.17	60.90
	0.385	53.81	36.37	67.60

Table 10.4. Cube and cylinder strengths of different concretes.

from 58 to 78% of cube strength as compared to 60 to 67% for gravel. Table 10.4 gives the 28 day compressive strengths of cubes and cylinders for concrete with different percentages of brick and gravel-mixed aggregates concrete.

10.3. FLEXURAL STRENGTH

150*150*750mm beams were cast for determining the flexural strength of concrete with brick plus gravel aggregates mixed in the ratio of 30:70 and 40:60 respectively, vide BS 1881: Part 109: 1983. Test beams were cured for 28 days before testing. The test for flexural strength was carried out vide BS 1881: Part 118: 1983 with third point loading. Table 10.5 gives the values of flexural strength against average compressive strength of concrete with mixed aggregates.

It was observed that the flexural strength of concrete with mixed aggregates varied from 6.1 to 7.7N/mm^2 i.e 15 to 20% of the 28 day compressive strength as compared to flexural

TYPE OF MIX	W/C RATIO	COMPRESSIVE STRENGTH 28DAY N/mm^2	FLEXURAL STRENGTH N/mm^2
11	0.5	39.30	6.46
12	0.385	53.24	7.50
21	0.5	37.14	7.58
22	0.385	52.43	8.17
31	0.5	40.31	6.13
32	0.385	52.74	6.97
41	0.5	41.00	7.61
42	0.385	50.87	7.73
Gravel	0.5	41.34	4.41
	0.385	53.81	5.33

Table 10.5. Flexural strength of concrete with mixed aggregates.

strengths varying from 4.4 to 5.3N/mm^2 i.e 9.9 to 10.7% of the 28 day compressive strengths for gravel concrete. Hence flexural strength values for concrete with mixed aggregates are 7% higher on average than concrete with Thames Valley gravel.

Figure 10.2 shows the variation of flexural strength of mixed aggregates concrete as compared to brick aggregate concrete and gravel concrete. It can be observed from Figure 10.2 that flexural strength of concrete with brick aggregates is lower than gravel concrete. The flexural strength of concrete with mixed aggregates is higher than both brick aggregate concrete as well as gravel concrete.

It was observed that failure in flexure across the section of test beams occurred by a crack through the mortar, through the brick aggregate particles and around the gravel particles in case of concrete with brick aggregates plus

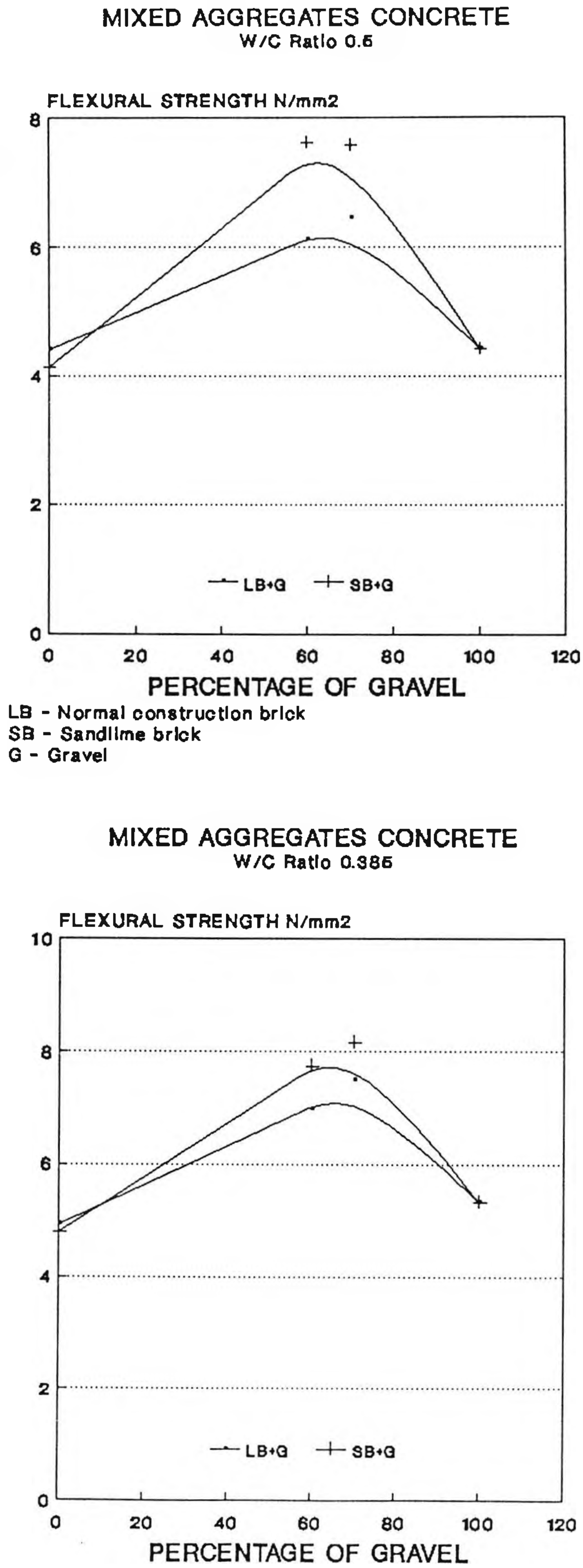


Figure 10.2. Variation in flexural strength of mixed aggregates concrete from brick concrete to gravel concrete.

gravel whereas the failure crack propagated through the mortar and around the gravel particles in the case of the control mix with Thames valley gravel as coarse aggregate. No gravel particles were observed to fail but failure occurred along the bond surface between the mortar and rounded gravel particles.

10.4. STRESS/STRAIN BEHAVIOUR

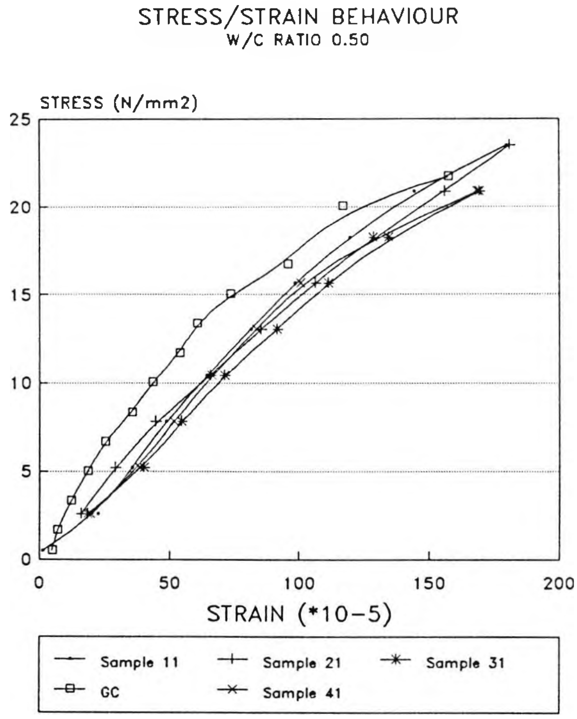
The stress/strain behaviour of mixed gravel and crushed brick aggregate concrete was studied on 150mm diameter, 300mm long cylinders. Increments of load were applied and strains measured for each increment of load. Figure 10.3 shows the stress/strain behaviour of different types of concretes for different strengths.

It was observed that the stress/strain behaviour of concrete with crushed brick plus gravel as coarse aggregates was similar to concrete with Thames Valley gravel as coarse aggregates. The strains were observed to increase for the same load increments with the increase in percentage of brick aggregates in concrete along with the stress/strain curve becoming flatter.

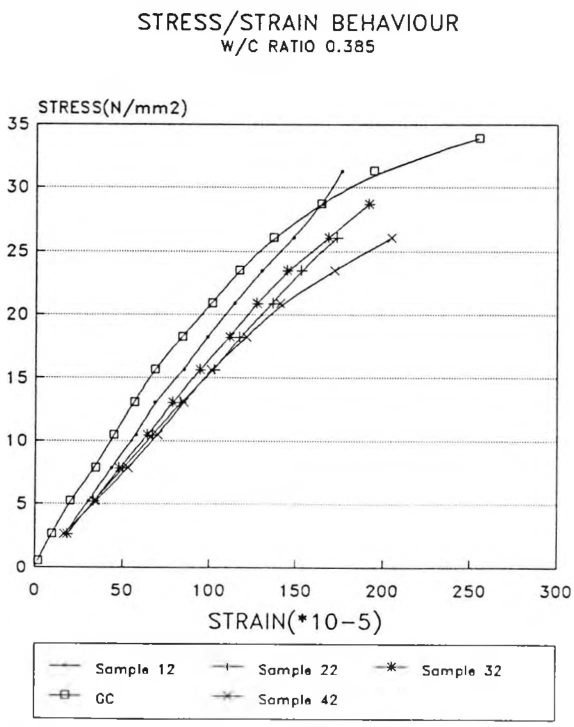
10.5. MODULUS OF ELASTICITY

10.5.1. Static modulus of elasticity

150mm diameter, 300mm long cylinders were prepared for determining the static modulus of elasticity in compression. Strains were recorded for every incremental load increase. Table 10.6 gives the values of static modulus of elasticity for concrete with mixed aggregates.



Sample 11 and 21 - 30:70
Sample 31 and 41 - 40:60



Sample 12 and 22 - 30:70
Sample 32 and 42 - 40:60

Figure 10.3: Stress/strain behaviour - W/C ratio 0.50
Stress/strain behaviour - W/C ratio 0.385

TYPE OF MIX	W/C RATIO	COMPRESSIVE STRENGTH 28DAY N/mm^2	STATIC MODULUS OF ELASTICITY N/mm^2
11	0.5	39.30	14790.3
12	0.385	53.24	18226.5
21	0.5	37.14	14660.4
22	0.385	52.43	15172.9
31	0.5	40.31	13322.7
32	0.385	52.74	16269.6
41	0.5	41.00	14500.0
42	0.385	50.87	14672.1
Gravel	0.5	41.34	23480.2
	0.385	53.81	24033.5

Table 10.6. Static modulus of elasticity of concrete with mixed aggregates.

The average static modulus of elasticity was observed to vary between 60 and 75% for concrete with crushed brick and gravel aggregates mixed in the ratio of 30:70 respectively and between 54 and 66% for concrete with crushed brick and gravel mixed in the ratio of 40:60 respectively, as compared to concrete with gravel aggregates only.

The values of static modulus of elasticity were observed to increase with increase in the compressive strength of concrete. The average static modulus of elasticity for concrete with brick aggregate plus gravel in the ratio 30:70 respectively is 37% lower as compared to concrete with Thames Valley gravel whereas concrete with brick aggregates plus gravel in the ratio of 40:60 respectively is 41% lower. The reduction in static modulus of elasticity of concrete with mixed aggregates is due to lower modulus of elasticity of normal construction brick and sandlime brick aggregate. Figure 10.4 shows the variation of static modulus of elasticity of mixed aggregates concrete as compared to brick aggregate concrete and gravel concrete. 0% gravel on the graph represents brick aggregate concrete.

10.5.2. Dynamic modulus of elasticity

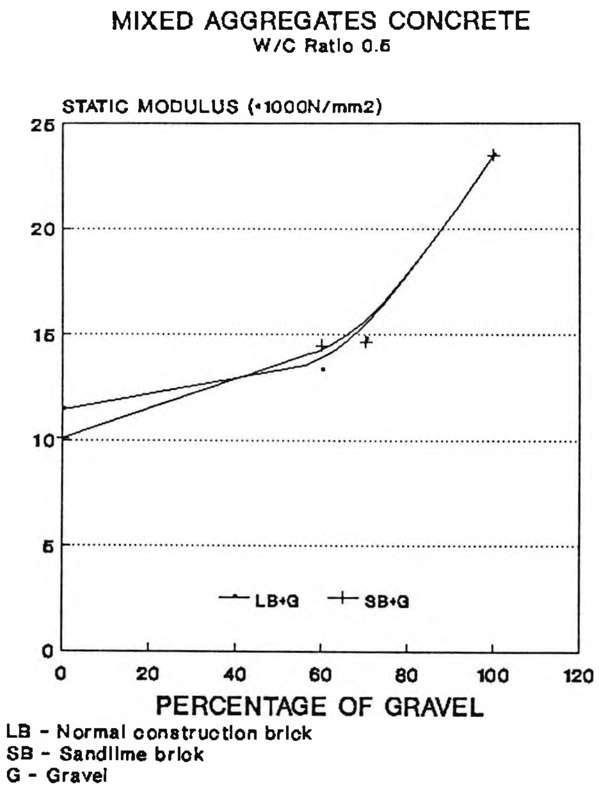
Test beams 150*150*750mm were cast for carrying out the dynamic modulus of elasticity tests. The specimen were cured for 28 days before testing for dynamic modulus of elasticity. Table 10.7 gives the values of dynamic modulus of elasticity for concrete with mixed aggregates.

TYPE OF MIX	W/C RATIO	COMPRESSIVE STRENGTH N/mm^2	DYNAMIC MODULUS OF ELASTICITY N/mm^2
11	0.5	39.30	37902.1
12	0.385	53.24	39968.7
21	0.5	37.14	40508.1
22	0.385	52.43	37597.6
31	0.5	40.31	36992.4
32	0.385	52.74	38163.7
41	0.5	41.00	38676.9
42	0.385	50.87	39057.2
Gravel	0.5	41.34	46922.8
	0.385	53.81	47557.8

Table 10.7. Dynamic modulus of elasticity of concrete with mixed aggregates.

The average resonant frequencies observed for concrete with normal construction brick aggregate plus gravel and sandlime brick aggregate plus gravel were observed to be about 9 to 10% and 8 to 9% lower than for concrete with Thames Valley gravel aggregate only with an average value of 2981Hz.

The dynamic modulus of elasticity for concrete with normal



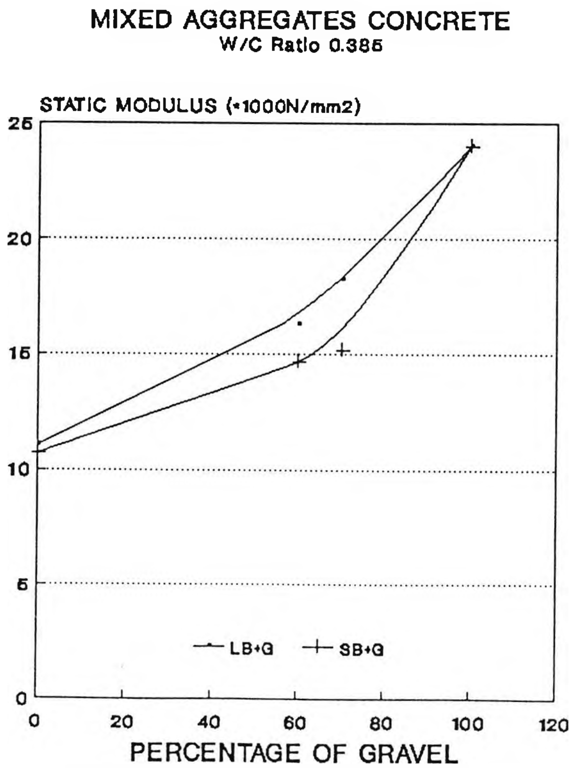


Figure 10.4. Variation in static modulus of elasticity of mixed aggregates concrete from brick concrete to gravel concrete.

construction brick aggregate plus gravel varied from 36992 to 38163N/mm^2 whereas that for concrete with sandlime brick aggregate plus gravel varied from 37597 to 40508N/mm^2. Values of dynamic modulus for concrete with Thames Valley gravel aggregate varied from 46922 to 47557N/mm^2. Hence the average dynamic modulus for concrete with normal construction brick aggregate plus gravel and sandlime brick aggregate plus gravel is 77 and 80% respectively of the value for concrete with Thames Valley gravel aggregate. The reduction in dynamic modulus of elasticity of concrete with mixed aggregates is due to lower resonant frequencies and lower densities of crushed brick aggregates. Figure 10.5 shows the variation of dynamic modulus of elasticity of mixed aggregates concrete as compared to brick aggregate concrete and gravel concrete.

10.6. ULTRASONIC PULSE VELOCITY

Ultrasonic pulse velocity tests for observing the velocity of pulses across the mixed aggregate concrete specimen were carried out as per BS 1881: Part 203: 1986. 150mm cubes were cured for 28 days as per BS 1881: Part 111: 1983 before testing for the pulse velocity. Pulse velocities observed for different concretes are given in Table 10.8.

Average pulse velocity across concrete with normal construction brick aggregate plus gravel was observed to be 4.27km/s for aggregate ratio of 30:70 respectively and 4.05km/s for the aggregate ratio of 40:60 respectively for average values of static moduli of elasticity of 16508N/mm^2

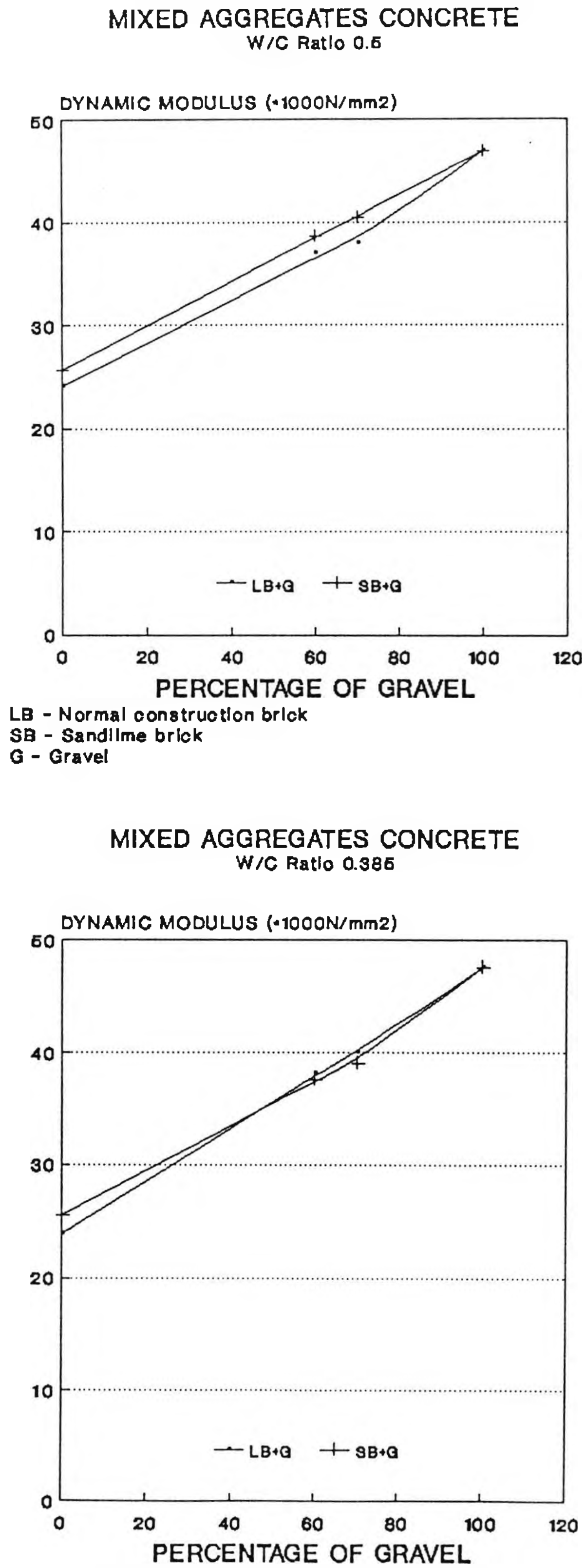


Figure 10.5. Variation in dynamic modulus of elasticity of mixed aggregates concrete from brick aggregate concrete and gravel concrete.

TYPE OF MIX	W/C RATIO	COMPRESSIVE STRENGTH N/mm^2	PULSE VELOCITY km/s
11	0.5	39.30	4.279
12	0.385	53.24	4.273
21	0.5	37.14	4.109
22	0.385	52.43	4.230
31	0.5	40.31	4.012
32	0.385	52.74	4.103
41	0.5	41.00	3.984
42	0.385	50.87	4.112
Gravel	0.5	41.34	4.76
	0.385	53.81	4.79

Table 10.8. Ultrasonic pulse velocities of concrete with mixed aggregates.

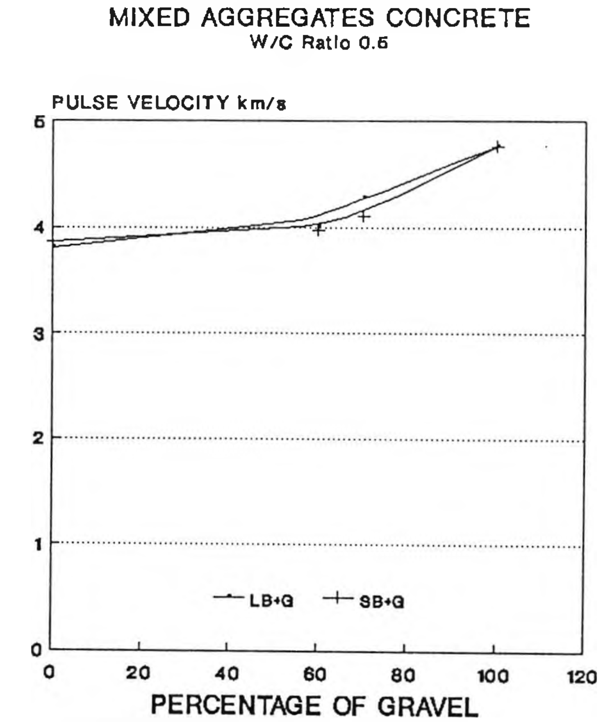
and 14796N/mm^2 dynamic moduli of elasticity of 38935 and 37577N/mm^2 respectively. Similarly, the average pulse velocity with sandlime brick aggregate plus gravel was observed to be 4.15km/s for aggregate ratio of 30:70 respectively and 4.0km/s for the aggregate ratio of 40:60 respectively for average values of static moduli of elasticity of 14916 and 14585N/mm^2 and dynamic moduli of elasticity of 39052 and 38866N/mm^2 respectively. For concrete with Thames Valley gravel as coarse aggregate, average pulse velocity was observed to be 4.8km/s for average values of static modulus of elasticity of 23757N/mm^2 and dynamic modulus of elasticity of 47240N/mm^2. Hence the variation of pulse velocity in the case of concrete with normal construction brick aggregate plus gravel in the ratios 30:70 and 40:60 is 11 and 15.5% lower, respectively, as compared to concrete with gravel. Concrete with sandlime brick aggregate plus gravel in the ratios

30:70 and 40:60 have been observed to have pulse velocities 13.5 and 16.5% lower, respectively, as compared to pulse velocity in concrete with Thames Valley gravel aggregate. It was observed that pulse velocities, static moduli and dynamic moduli of elasticity obtained from experimental investigations did not correlate with the values given in BS 1881: Part 203: 1986 for concrete with different types of brick aggregates mixed with gravel aggregates in different percentages. Figure 10.6 shows the variation in pulse velocity of mixed aggregates concrete from brick aggregate concrete to gravel concrete.

Table 10.9 gives the experimental values and empirical values for the static and dynamic moduli of elasticity for different concretes.

TYPE OF MIX		PULSE VELOCITY km/s	EMPIRICAL MODULI STATIC N/mm^2	DYNAMIC N/mm^2	EXPERIMENTAL MODULI STATIC N/mm^2	DYNAMIC N/mm^2
11		4.3	24500	34000	14790	37902
12		4.3	24500	34000	18226	39968
21		4.1	20000	30500	14660	40508
22		4.2	22000	32000	15173	37597
31		4.0	18000	29000	13322	36992
32		4.1	20000	30500	14660	40508
41		3.98	18000	29000	13322	36992
42		4.1	20000	30500	14660	40508
Gravel	0.5	4.76	30500	39000	23480	46923
	0.385	4.79	43000	49000	24033	47558

Table 10.9. Comparison of empirical and experimental Moduli of elasticity by pulse velocity measurements.



LB - Normal construction brick
SB - Sandlime brick
G - Gravel

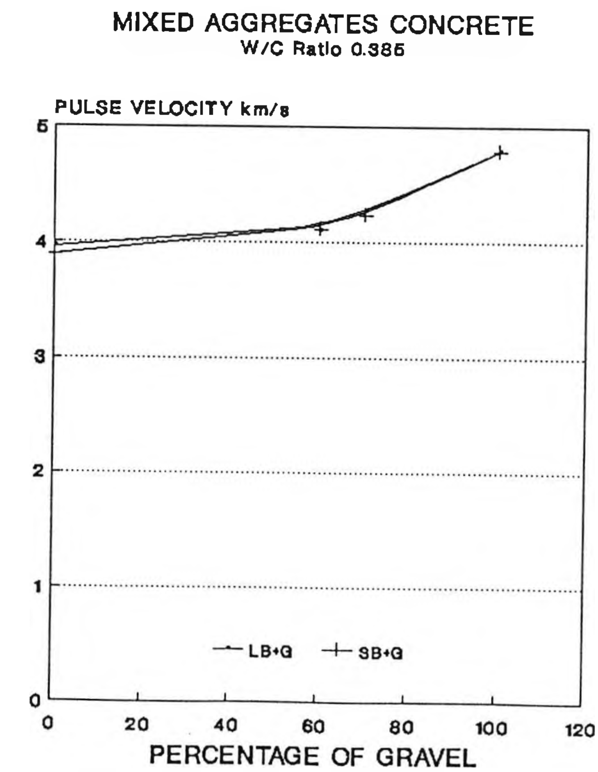


Figure 10.6. Variation in pulse velocity of mixed aggregates concrete from brick aggregate concrete and gravel concrete.

10.7. DENSITY OF HARDENED CONCRETE

Densities of hardened concrete were obtained by weighing the specimen (cubes) accurately at the end of the 28 days curing period to obtain the saturated weight and measuring the dimensions accurately to obtain the volume of test cubes. The cubes were reweighed after heating them at 105°C +/- 5°C for 48 hours, to calculate the dry densities and absorption. Table 10.10 gives the densities of concrete with mixed aggregates.

TYPE OF MIX	W/C RATIO	DENSITY OF CONCRETE (kg/m^3) dry	saturated
11	0.5	2219	2330
12	0.385	2276	2363
21	0.5	2271	2353
22	0.385	2289	2377
31	0.5	2184	2297
32	0.385	2231	2312
41	0.5	2227	2314
42	0.385	2243	2331
Gravel	0.5	2403	2454.80
	0.385	2411	2457.70

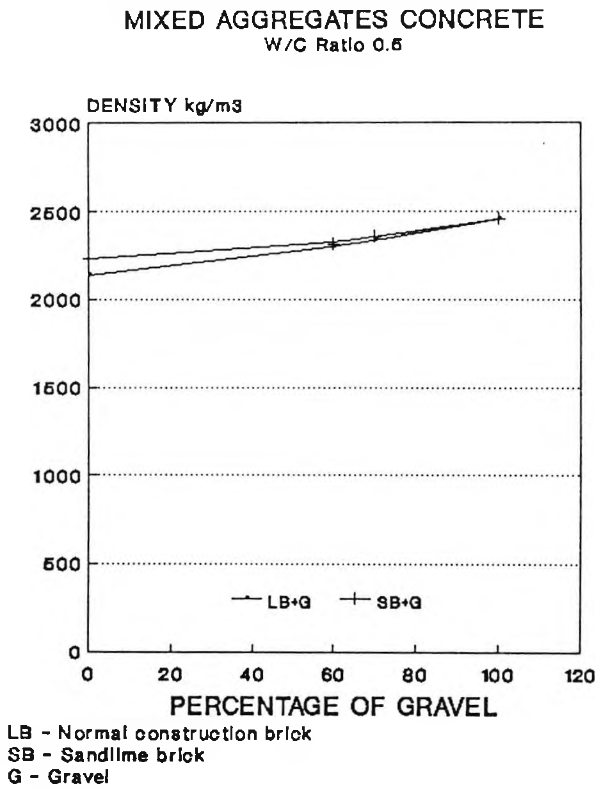
Table 10.10. Densities of concrete with mixed aggregates.

Average dry and saturated densities for concrete with normal construction brick aggregates plus gravel in the ratios 30:70 and 40:60 were observed to be 2247.5, 2346.5kg/m^3 and 2207, 2304.5kg/m^3 respectively. The average values of dry and saturated densities for concrete with sandlime brick aggregate plus gravel in the ratios 30:70 and 40:60 were observed to be 2280, 2365kg/m^3 and 2235, 2322.5kg/m^3 respectively whereas average dry and saturated densities for concrete with Thames Valley gravel were observed to be 2407 and 2456kg/m^3. Hence densities of concrete with gravel and normal construction brick aggregate were observed to be 4 to 8% lower as compared to concrete with gravel only, whereas concrete with gravel and sandlime brick aggregate were lower by 3 to 6%. Figure 10.7 shows the variation in density of mixed aggregates concrete as compared to brick aggregate concrete and gravel concrete. 0% of gravel on graph represents brick aggregate concrete.

10.8. INITIAL SURFACE ABSORPTION

ISAT tests were carried out on cubes as per BS 1881: Part 5: 1970. The results were compared with the typical results of ISAT tests given by Concrete Society Technical Report No.31. Figure 10.8 gives the variation in surface absorption of mixed aggregates concrete as compared to brick aggregate concrete and gravel concrete. 0% of gravel on graph represents brick aggregate concrete.

ISAT results obtained from tests on concrete with normal construction brick aggregates plus gravel mixed in the ratios 30:70 and 40:60 respectively, revealed that surface absorption was average and almost 50% higher amounts of water were absorbed in both cases as compared to concrete with gravel and w/c ratio of 0.50. The absorption was, however, similar to concrete with gravel, for w/c ratio of 0.385. Low surface absorption was observed for concrete with sandlime brick aggregates plus gravel in the ratios of 30:70 and 40:60 for w/c ratios of 0.50 and 0.385, similar



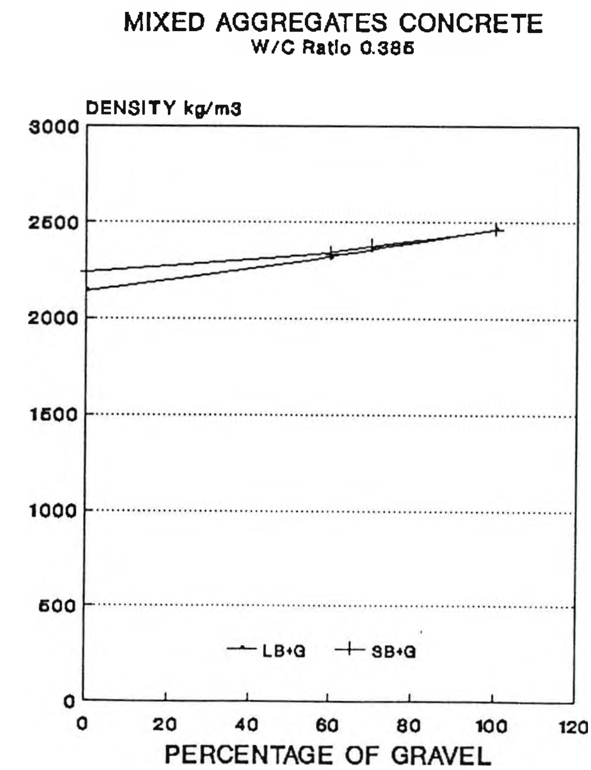
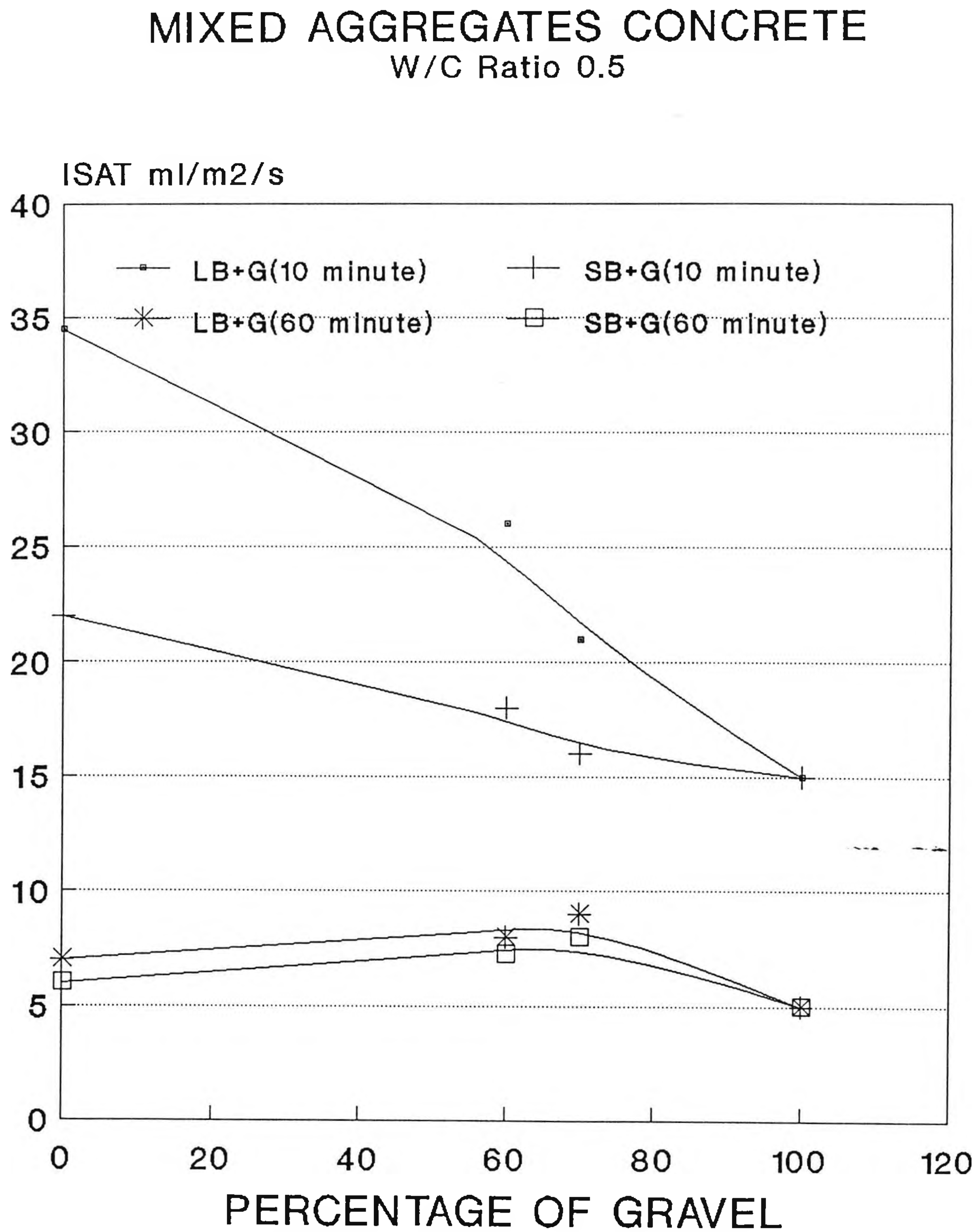


Figure 10.7. Variation in density of mixed aggregates concrete from brick aggregate concrete and gravel concrete.



LB - Normal construction brick
SB - Sandlime brick
G - Gravel

Figure 10.8. Variation in surface absorption of mixed aggregates concrete from brick aggregate concrete and gravel concrete.

to concrete with gravel only.

10.9. SHRINKAGE

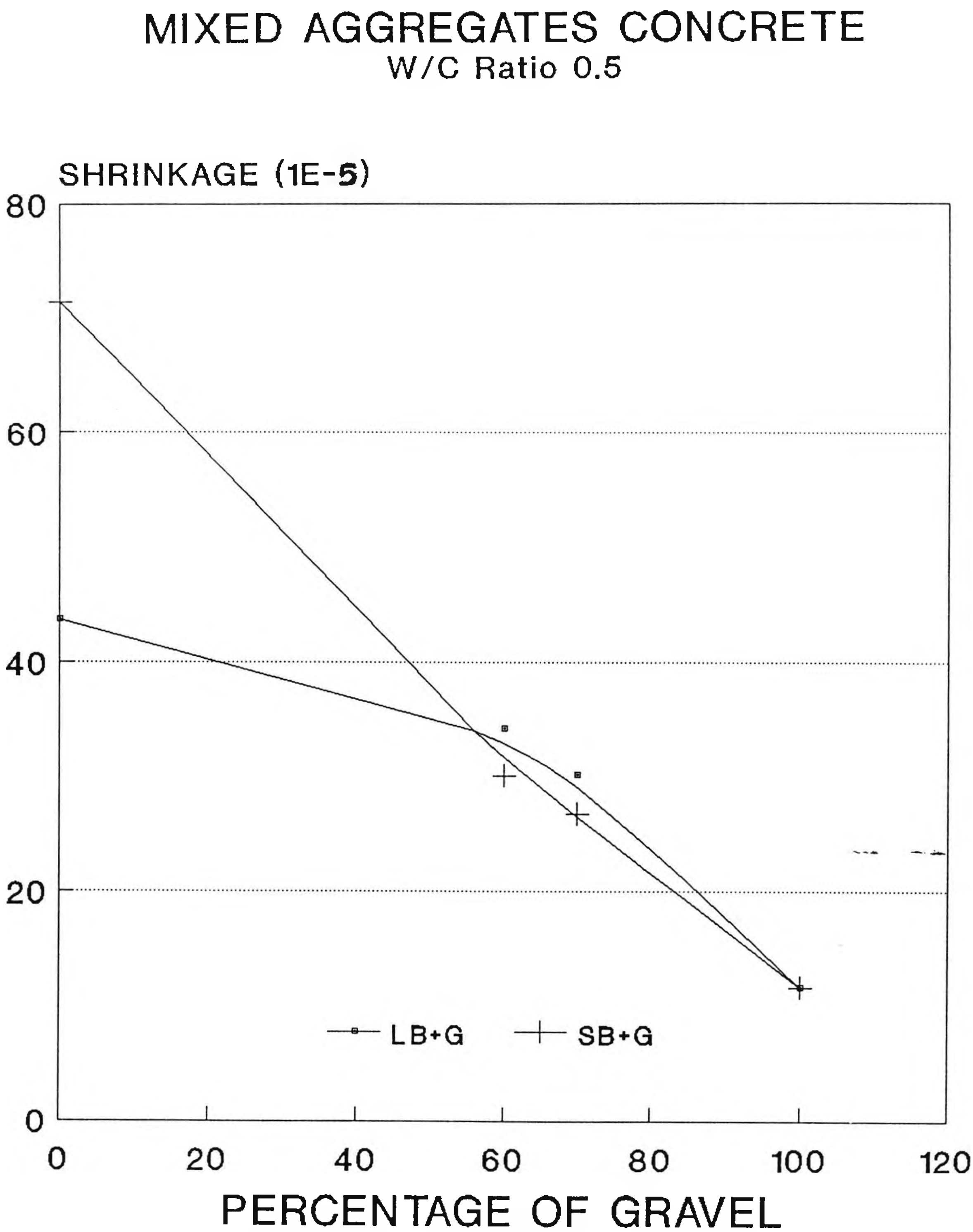
Shrinkage tests were carried out in accordance with RILEM Recommendation CPC 9, Measurement of shrinkage and swelling. 100*100*500mm prismatic specimen were cast and cured in water at 20°C for 28 days. The prisms were then accurately measured and stored at 20°C and 65% relative humidity for ninety days after which they were measured accurately to observe the shrinkage values. Table 10.11 gives the shrinkage of concrete with mixed aggregates.

TYPE OF MIX	W/C RATIO	SHRINKAGE $*10^{-4}$mm
11	0.5	3.024
12	0.385	3.73
21	0.5	2.68
22	0.385	3.268
31	0.5	3.42
32	0.385	3.81
41	0.5	3.01
42	0.385	3.63
Gravel	0.5	1.176
	0.385	2.976

Table 10.11. Shrinkage of concrete with mixed aggregates.

Figure 10.9 shows the variation in shrinkage of mixed aggregates concrete as compared to brick aggregate concrete and gravel concrete.

Shrinkage of concrete with normal construction brick aggregates plus gravel in the ratio of 30:70 was almost one and a half times higher than concrete with gravel only for w/c ratio of 0.50, whereas for w/c ratio of 0.385 shrinkage was 25% higher. For the ratio of 40:60 of normal



LB - Normal construction brick
SB - Sandlime brick
G - Gravel

Figure 10.9. Variation in shrinkage of mixed aggregates concrete from brick aggregate concrete and gravel concrete.

construction brick aggregate and gravel respectively, shrinkage was observed to be twice the value of concrete with gravel only for w/c ratio of 0.50, whereas for w/c ratio of 0.385, shrinkage was observed to be about 30% higher than concrete with gravel only.

Shrinkage of concrete with sandlime brick aggregates plus gravel in the ratio of 30:70 was almost one and a quarter times higher than concrete with gravel only for w/c ratio of 0.50, whereas for w/c ratio of 0.385, shrinkage was about 10% higher. For the ratio of 40:60 of sandlime brick aggregate and gravel respectively, shrinkage was observed to be twice the value of concrete with gravel only, for w/c ratio of 0.50 whereas for w/c ratio of 0.385, shrinkage was observed to be about 22% higher than concrete with gravel only.

10.10. FROST RESISTANCE

The RILEM recommendation on methods of carrying out and reporting freeze thaw tests on concrete without deicing chemicals were followed to carry out an investigation on the comparative performance of concrete with different types of coarse brick aggregates and Thames Valley gravel. 100*100*500mm prisms were cast and cured for 28 days in water at 20°C before subjecting them to freezing and thawing cycles. One specimen of each strength was cast with two thermistors at the centre so as to monitor the temperature of specimen during the test. Length change and variation in dynamic modulus were monitored during the test and the residual compressive strength of each specimen recorded at the end of the test. Table 10.12 gives a summary of the performance of mixed aggregates concrete in frost resistance test. Table 10.13 gives the comparison of compressive strengths of dummy specimens and specimens of frost resistance test after completion of 50 cycles of freezing and thawing. Figures 10.10 and 10.11 show the variation in dynamic modulus and length versus number of freezing and thawing cycles.

TYPE OF MIX	W/C RATIO	EXPANSION %	REDUCTION IN DYNAMIC MODULUS %
11	0.50	0.04	23.7
21	0.50	0.06	15.0
31	0.50	0.076	28.46
41	0.50	0.057	14.8
12	0.385	0.035	24.13
22	0.385	0.036	3.0
32	0.385	0.068	28.53
42	0.385	0.046	5.7
Gravel	0.50	-0.048	7.33
	0.385	0.07	14.40

Table 10.12. Summary - Frost resistance test on concrete with mixed aggregates (50 cycles).

Concrete with normal construction brick aggregate plus gravel mixed in the ratios of 30:70 and 40:60 respectively, both started expanding continously on cyclic freezing and thawing and the large expansions were accompanied by a rapid decrease in dynamic modulus, as shown in Tables 10.14 and 10.15 along with Figures 10.10 and 10.11. The dynamic modulus decreased by almost 20% in the first twenty cycles

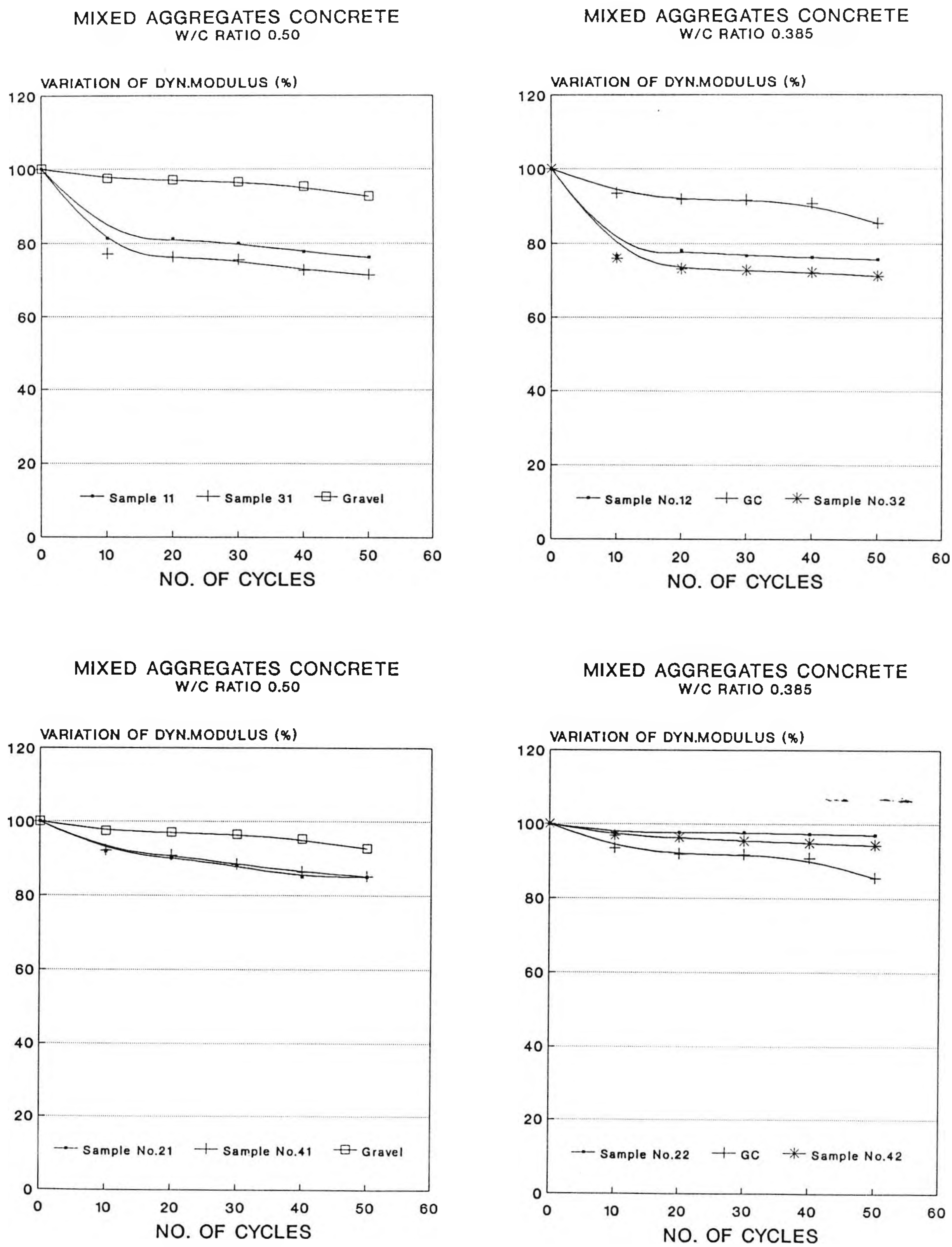
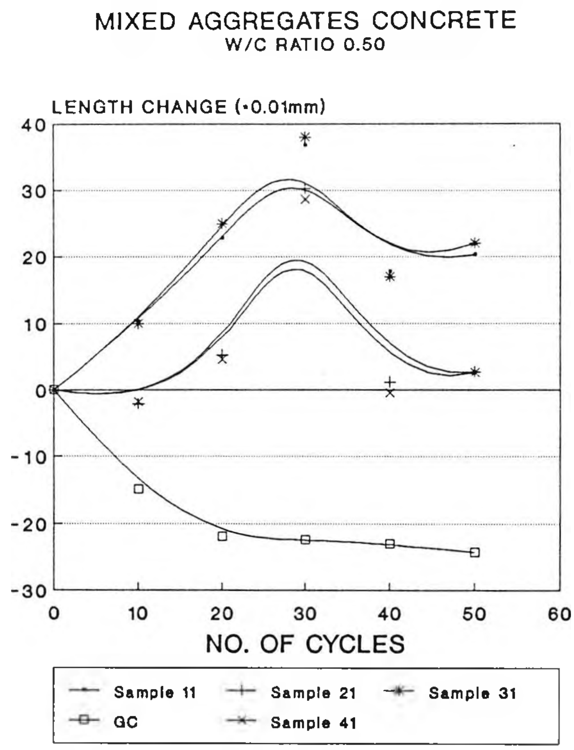


Fig 10.10. Variation of dynamic modulus vs Number of cycles.



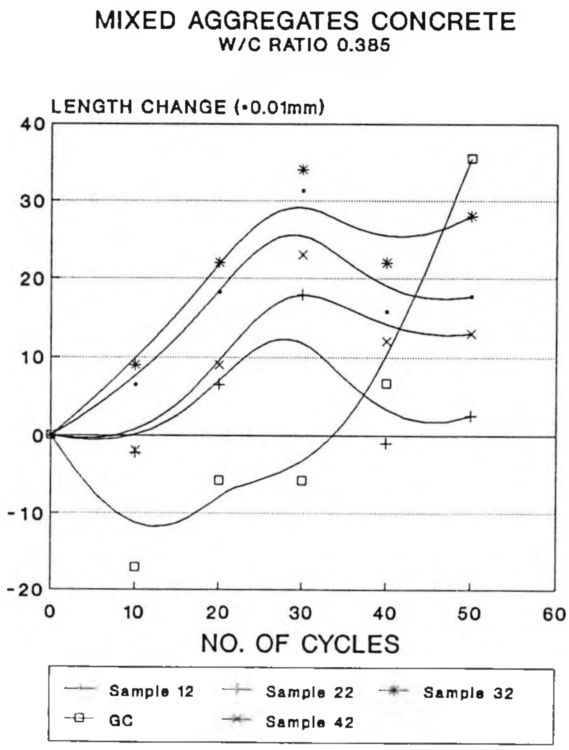


Fig 10.11. Variation in length vs Number of cycles.

TYPE OF MIX	W/C RATIO	DUMMY STRENGTH	RESIDUAL STRENGTH	VARIATION %
Sample 11.	0.50	45.05	43.55	3.33
Sample 12.	0.385	50.85	49.05	3.53
Sample 21.	0.50	47.25	46.05	2.54
Sample 22.	0.385	52.05	51.6	0.86
Sample 31.	0.50	42.51	40.73	4.18
Sample 32.	0.385	50.76	48.53	4.39
Sample 41.	0.50	46.30	45.19	2.39
Sample 42.	0.385	51.64	50.9	1.43
Sample 4 . Gravel	0.50	41.34	40.32	1.02
Sample 4 .	0.385	53.81	53.11	1.3

Table 10.13. Comparison of compressive strengths.

Sample No.11. 30% London brick + 70% Gravel
W/C Ratio 0.50
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	248.25	258.5	271	285	266	268.5
Weight(g):	11870.5	11878	11877	11875	11877.5	11877.5
R frequency(Hz):	4131.5	3725.5	3721	3693	3641.5	3607.5
Dyn.Mod.(N/mm^2):	40522.5	32963	32900	32425	31502.8	30920.4

Reduction in dyn mod = 23.7%, Increase in length =0.04%

Sample No.12. 30% London brick + 70% Gravel
W/C Ratio 0.385
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	255.25	261.7	273.5	286.5	271	273
Weight(g):	11919.5	11926	11926	11904	11874	11925.5
R frequency(Hz):	4104	3594.5	3627	3595	3585	3573.5
Dyn.Mod.(N/mm^2):	40149.5	30807.7	31382	30847	30656	30462.5

Reduction in dyn mod = 24.13%, Increase in length = 0.035%

Table 10.14. Performance of concrete with normal construction brick aggregate and gravel in the ratio of 30:70, respectively, in frost resistance test.

after which the decrease was observed to be gradual for w/c ratios of both 0.50 and 0.385. Net reduction in dynamic modulus after fifty cycles was observed to be 23.7 and 28.46% for w/c ratio of 0.50 against 7.33% for concrete with Thames Valley gravel. The associated maximum increase in length was 0.073% and 0.076% as compared to a decrease in length of 0.048% for concrete with Thames Valley gravel.

Sample No.31. 40% London brick + 60% Gravel
W/C Ratio 0.50
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	239	249	264	277	256	261
Weight(g):	11769	11774	11777	11778	11777	11778
R frequency(Hz):	4011	3523	3501	3483	3421.2	3391
Dyn.Mod.(N/mm^2):	37868	29226	28879	28598	27569	27089

Reduction in dynamic modulus = 28.46%
Increase in length = 0.044% (max 0.076%)

Sample No.32. 40% London brick + 60% Gravel
W/C Ratio 0.385
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	265	274	287	299	287	293
Weight(g):	11817	11821	11824	11828	11794	11801
R frequency(Hz):	4003	3491	3427	3415	3402	3382
Dyn.Mod.(N/mm^2):	37871	28813	27781	27600	27377	27062

Reduction in dynamic modulus = 28.53%
Increase in length = 0.056% (max 0.068%)

Table 10.15. Performance of concrete with normal construction brick aggregate and gravel in the ratio of 40:60, respectively, in frost resistance test.

For w/c ratio of 0.385, the reduction in dynamic modulus was observed to be 24.13 and 28.53% respectively for ratios of 30:70 and 40:60 of normal construction brick aggregate and gravel in concrete. The reduction in dynamic modulus of concrete with Thames Valley gravel with similar compressive strength was observed to be 14.39%. The corresponding increase in length was observed to be 0.035 and 0.068% compared to 0.071% for concrete with Thames Valley gravel. Concrete with normal construction brick aggregate plus gravel showed continously increasing expansions for the first thirty cycles of freezing and thawing. Concrete with normal construction brick aggregate and gravel in the ratio of 40:60 respectively (by weight) showed larger expansions as compared to concrete with normal construction brick aggregate and gravel in the ratio of 30:70 respectively. The large increase in length and accompanying rapid reduction in dynamic modulus is due to the continous expansion of normal construction brick aggregates which have high absorption of about 20% and comprise of large sized pores with higher quantity of freezable water. Since the specimens were fully saturated on start of testing, expansion of water in the aggregates on freezing pressurises excess water out of the aggregate into the surrounding mortar. On further cooling, this water expands and exerts dilative pressures on the mortar resulting in microcracking within the mortar, along the bond surface between mortar and aggregate particles and also within the aggregate particles. The situation is worsened by the differential expansion/contraction between the brick aggregates, mortar and gravel particles hence cyclic freezing and thawing increases microcracking thereby resulting in loss of strength along with length increases.

The length of specimen increased continously over the first thirty cycles after which there was slight decrease in length in the next ten cycles after which again the length started increasing. This behaviour is possibly due to the presence of a few closed pores in brick aggregate which were not open initially. The expansion over the first thirty cycles of freezing and thawing exerted sufficient pressure on these pores to open up and provide some relief for the excess water to be acommodated. After some excess water was acommodated in these pores, the specimen showed slight contractions for the next ten cycles after which the specimen again started increasing in length. The behaviour of concrete with normal construction brick aggregates plus gravel is entirely different from concrete with Thames Valley gravel only, as is evident from Figure 10.11 and 10.12. Concrete with Thames Valley gravel shows slight contraction in the first twenty cycles after which there is a slight increase in length. The corresponding reduction in dynamic modulus is gradual. Concrete with normal construction brick aggregate plus gravel shows large expansions in first thirty cycles with a large reduction in dynamic modulus. Thereafter the expansions are small and continous along with a gradual decrease in dynamic modulus. Table 10.13 shows the variation in compressive strength of the dummy specimen and of the specimen after fifty cycles of freezing and thawing. Concrete with normal construction brick aggregates plus gravel in the ratio of 30:70 by weight respectively shows a variation of 3.33 to 3.53% for w/c ratios of 0.50 and 0.385, respectively. For concrete with ratio of normal construction brick aggregate and gravel of 40:60 respectively, the variation in compressive strength is 4.18 to 4.39% for w/c ratios of 0.50 and 0.385, respectively. Concrete with Thames valley gravel shows a variation of 1.02 to 1.3% for w/c ratios of 0.50 and 0.385 respectively. Hence the reduction of compressive strength for concrete with normal construction brick aggregate plus gravel in the ratio of 30:70 by weight respectively is three times and for the ratio of 40:60 by weight respectively is four to four and a half times as compared to concrete with Thames Valley gravel only.

Tables 10.16 and 10.17 gives the performance of sandlime brick plus gravel aggregate concrete in frost resistance test.

For concrete with sandlime brick aggregate plus gravel mixed in the ratios of 30:70 and 40:60 respectively, the reduction in dynamic modulus after fifty cycles was observed to be 15 and 14.8% for w/c ratio of 0.50 against 7.33% for concrete with Thames Valley gravel. The associated maximum increase in length was 0.06 and 0.057% as compared to a decrease in length of 0.048% for concrete with Thames Valley gravel. For w/c ratio of 0.385, the reduction in dynamic modulus was observed to be 3 and 5.7% respectively for ratios of 30:70 and 40:60 of normal construction brick aggregate and gravel in concrete. The

Sample No.21. 70% Gravel + 30% Sandlime brick
W/C Ratio 0.50
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	214.7	212.7	220	245	216	217.5
Weight(g):	11962	11966	11967.5	11968	11967	11968.5
R frequency(Hz):	4186.	4012.5	3971.5	3926	3860.5	3859
Dyn.Mod.(N/mm^2):	41931	38514.8	37742.8	36920	35656.8	35631.3

Reduction in dyn mod = 15%
Increase in length = 0.005% (max 0.06%)

Sample No.22. 70% Gravel + 30% Sandlime brick
W/C Ratio 0.385
Observations

Cycles	Start	10	20	30	40	50
Length(*0.01mm):	235.5	233.25	242	253.5	234.5	238
Weight(g):	11947.5	11949.5	11949	11949.5	11949	11947
R frequency(Hz):	4112	4064	4064.5	4063	4057.5	4051
Dyn.Mod.(N/mm^2):	40402.9	39461.6	39485	39474.2	39337	39217

Reduction in dyn mod = 3%
Increase in length = 0.005% (max 0.036)

Table 10.16. Performance of concrete with sandlime brick aggregate and gravel in the ratio of 30:70, respectively, in frost resistance test.

reduction in dynamic modulus of concrete with Thames Valley gravel with similar w/c ratio was observed to be 14.39%. The corresponding increases in length were observed to be 0.036 and 0.046% compared to 0.071% for concrete with Thames Valley gravel.

Concrete with sandlime brick aggregate plus gravel behaved somewhat similarly to concrete with Thames Valley gravel. There was a slight contraction in the first ten cycles after which the specimen started expanding gradually until thirty cycles of cyclic freezing after which there was again a slight decrease in length over the next ten cycles followed by gradual expansion. This behaviour is possibly

Sample No.41. 60% Gravel + 40% Sandlime brick						
W/C Ratio 0.50						
Observations						
Cycles	Start	10	20	30	40	50
Length(*0.01mm):	203.4	201.6	208	232	203	206
Weight(g):	11859	11864	11867	11869	11867	11869
R frequency(Hz):	4166	4001	3970	3916	3873	3844
Dyn.Mod.(N/mm^2):	41164	37965	37388	36413	35577	35050
Reduction in dynamic modulus = 14.8%						
Increase in length = 0.005% (max 0.057%)						

Sample No.42. 60% Gravel + 40% Sandlime brick						
W/C Ratio 0.385						
Observations						
Cycles	Start	10	20	30	40	50
Length(*0.01mm):	231	229	240	254	243	244
Weight(g):	11938	11939	11942	11943	11942	11943
R frequency(Hz):	4104	4041	4027	4008	3997	3984
Dyn.Mod.(N/mm^2):	40214	38985	38733	38390	38162	37916
Reduction in dynamic modulus = 5.7%						
Increase in length = 0.026% (max 0.046%)						

Table 10.17. Performance of concrete with sandlime brick aggregate and gravel in the ratio of 40:60, respectively, in frost resistance test.

due to the presence of a few closed pores inside the brick aggregates which open up on exertion of dilative pressures of cyclic cooling. The slight contraction later on is due to acommodation of some excess expanding water in these pores which open up after about thirty cycles. Later on, the specimen again start expanding due to dilative pressures on cooling.

The reduction in dynamic modulus in concrete with sandlime brick aggregate plus gravel is gradual and is one-third to half the value for concrete with Thames Valley gravel. The lower loss of strength is due to the fine pores present in sandlime brick aggregate which, although having an absorption of 10%, has little of freezable water. The expansion of brick aggregates could be similar to the expansion of mortar thereby reducing the microcracking inside the concrete as compared to concrete with Thames Valley gravel only, thereby reducing the loss of strength. Concrete with sandlime brick aggregates plus gravel in the ratio of 30:70 by weight respectively shows a variation in compressive strength of 2.54 to 0.86% for w/c ratios of 0.50 and 0.385, respectively. For concrete with ratio of sandlime brick aggregate and gravel of 40:60 respectively, the variation in compressive strength is 2.39 to 1.43% for w/c ratios of 0.50 and 0.385, respectively. Concrete with Thames Valley gravel shows a variation of 1.02 to 1.3% for w/c ratios of 0.50 and 0.385, respectively.

10.11. CONCLUSIONS

The rate of development of strength of mixed aggregate concrete was observed to be similar to that of normal aggregate concrete. Mixed aggregates concrete developed satisfactory compressive strengths as compared to concrete with gravel aggregate. Flexural strengths were higher by about 5%, the average static modulus of elasticity was observed to decrease by 35 to 40%, and average dynamic modulus for concrete with brick aggregate plus gravel was 20 to 23% lower than the value for concrete with Thames Valley gravel aggregate. The variation of pulse velocity in the case of concrete with brick aggregate plus gravel is 7 to 13% lower as compared to concrete with gravel. Average densities for concrete with brick aggregates plus gravel were 4 to 6% lower than concrete with gravel. ISAT results obtained from tests on concrete with brick aggregates plus gravel showed that surface absorption was almost 50% higher for higher w/c ratio but was however similar to concrete with Thames Valley gravel, for lower w/c ratio. Shrinkage of concrete with brick aggregates plus gravel was almost one and a half times higher than concrete with gravel for higher w/c ratio whereas for lower w/c ratio shrinkage was 25% higher.

Frost resistance of mixed aggregate concrete depends on the absorption and pore size of brick aggregate. Mixed aggregate concrete with normal construction brick aggregate mixed with gravel started expanding continously on cyclic freezing and thawing and large expansions resulted in rapid decrease in dynamic modulus whereas concrete with sandlime brick aggregate mixed with gravel showed better frost resistance than gravel concrete, for w/c ratio of 0.385.

PART 6

CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 11

CONCLUSIONS AND RECOMMENDATIONS

11.1. CONCLUSIONS

11.1.1. BRICK AGGREGATES

Crushed brick aggregates have angular shape and honeycombed texture hence, in spite of more compaction effort to pack, they result into better bonding and interlocking which makes higher compressive strengths possible depending upon the strength of brick aggregates.

The absorption of crushed brick aggregates varies from high to low absorption depending on the absorption of bricks from which they are obtained. The absorption of brick aggregates may vary from a maximum of 20% for normal construction brick aggregates to about 1.5% for high quality engineering bricks. Highly absorptive brick aggregates should preferably be used in saturated surface dry state to avoid any loss of workability by absorption of moisture by aggregates during and immediately after mixing.

The density of crushed brick aggregates varies from 839kg/m^3 for highly absorbent normal construction brick aggregates to 1125kg/m^3 for less absorptive and stronger engineering 'B' brick aggregates as compared to 1550kg/m^3 for Thames Valley gravel.

The strength of brick aggregates based on 10% fines value, varies from 41kN for weaker sandlime brick aggregates to 144kN for stronger engineering brick aggregates as compared to 391kN for gravel. Aggregates from normal construction bricks and sandlime bricks can be satisfactorily used for normal concrete up to characteristic strength of 35N/mm^2. Aggregates obtained from engineering brick can be used for compressive strength of concrete as high as 80N/mm^2. Specifying the strength of bricks is a better guide to specify brick aggregates for different usage rather than 10% fines value since it is easier to test the crushing strength of bricks.

It was observed that brick aggregates can be used for compressive strengths of concrete having twice the value of crushing strength of bricks from which the aggregates are obtained.

As regards toughness, brick aggregates from normal construction bricks(LBC) and sandlime bricks qualify for normal concrete as per BS 882: 1983. Aggregates from engineering bricks qualify for concrete for pavement wearing surfaces in addition to normal concrete. None of the brick aggregates tested qualify for aggregates for heavy duty floor finishes whereas engineering brick aggregate has been successfully used for high strength concrete with compressive strength of 80N/mm^2.

Large amounts of sulphates and chlorides were observed in normal construction brick aggregates which can affect the durability of concrete made from such aggregates. Quantities of sulphates and chlorides present in sandlime brick and engineering brick aggregates were very low.

11.1.2. MIX DESIGN

Concrete with crushed brick aggregates cannot be designed using Design of Normal Concrete Mixes method without modification. A design method for concrete with crushed brick aggregates is suggested in Chapter 3.

Mix design for low workability is impractical for brick aggregates. Medium workability mixes are desirable to avoid any segregation. By maintaining a fines content between 29 to 33% of the total aggregates results in workabilities within the desired range, where fines are of medium grading. In the case of loss of workability immediately after mixing, retempering with about 5% water to improve workability does not affect the strength of brick aggregate concrete.

Due to different bulk densities of brick aggregate and sand, fresh concrete tends to segregate on compaction for higher workabilities especially if there is a large number of flaky particles in brick aggregate, however it can be avoided by dryer consistencies.

The unit weight of fresh, compacted brick aggregate concrete is about 7 to 12% lower than normal weight concrete. Brick aggregate from softer bricks or highly fractured aggregates may crush during the process of mixing or compaction of concrete thereby further reducing the workability.

11.1.3. CONCRETE WITH BRICK AGGREGATES

The density of concrete with normal construction brick, sandlime brick and engineering brick aggregates is 12.6, 9 and 5% lower, respectively, as compared to normal concrete with hardened density of 2400kg/m^3. The density of concrete with brick aggregates increases with increase in the density of brick aggregates. Lower densities for concrete with brick aggregates are due to lower densities of brick aggregates as compared to gravel aggregate.

Brick aggregate concrete of satisfactory strength can be produced. The compressive strength of brick aggregate concrete depends upon the crushing strength of the bricks from which the aggregates have been obtained. Concrete with engineering brick aggregates obtained from engineering 'B' bricks with crushing strength of 40N/mm^2 developed 25 to 30% higher compressive strength as compared with normal concrete.

Average cylinder strengths developed by concrete with brick aggregates were observed to be 10% lower as compared to concrete with gravel aggregate.

The splitting tensile strength of concrete with brick aggregates increases with the increase in crushing strength of the bricks from which the aggregates have been obtained. Lower splitting tensile strengths of concrete with normal construction brick of 18% and sandlime brick aggregates of 22% are due to lower tensile strengths of the normal construction bricks and sandlime bricks from which these aggregates were obtained. The 20% higher tensile strength for concrete with engineering brick aggregates was due to higher tensile strength of engineering bricks.

Average flexural strength values for concrete with normal construction brick and sandlime brick aggregates were 13.5 and 5%, lower, respectively, than concrete with gravel aggregate whereas concrete with engineering brick aggregates had 22% higher flexural strength as compared to concrete with gravel aggregate.

Average strains at failure for concrete with normal construction brick, sandlime brick and engineering brick aggregates were observed to be 83%, 28.5% and 10% higher, respectively, as compared to concrete with Thames Valley gravel, due to lower moduli of elasticity of brick aggregates.

The average static modulus of elasticity for concrete with normal construction brick(LBC) aggregate, sandlime brick aggregate and engineering brick aggregate is 55%, 59% and 28% lower, respectively, as compared to concrete with Thames Valley gravel.

The average dynamic modulus for concrete with normal construction brick aggregate, sandlime brick aggregate and engineering brick aggregate is 26, 25 and 13% lower, respectively, than the value for concrete with Thames Valley gravel aggregate.

Coefficient of thermal expansion for concrete with sandlime brick aggregate was observed to be 5% higher than concrete with Thames Valley gravel whereas coefficient of thermal expansion of normal construction brick aggregate and engineering brick aggregate were observed to be 35 and 32% lower, respectively, as compared with the value for concrete with gravel aggregate. The lower coefficient of thermal expansion of normal construction brick aggregate and engineering brick aggregate along with the greater strain capacity at failure explains higher fire resistance of such concrete as compared to concrete with Thames valley gravel.

11.1.4. TIME-DEPENDANT PROPERTIES OF BRICK AGGREGATE CONCRETE

Shrinkage for concrete with normal construction brick aggregate was observed to be four to five times higher than concrete with Thames Valley gravel whereas concrete with sandlime brick showed seven to ten times greater shrinkage. Concrete with engineering brick aggregates was observed to vary between a half to twice the value of shrinkage for concrete with Thames Valley gravel.

Brick aggregates expand on absorbing water and contract on drying hence resulting in higher shrinkage whereas gravel has negligible shrinkage thereby restraining the shrinkage of cement paste. Increased values of shrinkage for concrete with brick aggregates is also due to higher absorption of the brick aggregates like 20% for normal construction brick aggregate, 10% for sandlime brick aggregate and 3% for engineering brick aggregate along with lower modulus of elasticity as compared to gravel.

Average creep strains for concrete with normal construction brick aggregates were observed to be about 18% higher than those for concrete with Thames Valley gravel. Creep strains for concrete with sandlime brick aggregate were observed to be approximately 46% higher than concrete with Thames Valley gravel. Concrete with engineering bricks developed an average of 39% lower creep strains as compared to concrete with Thames Valley gravel.

The larger creep strains developed by concretes with normal construction brick aggregates are due to high porosity, lower modulus of elasticity and lower strength of their aggregates whereas the lower creep strains produced in concrete with engineering brick aggregates appear to be due to almost 30% higher compressive strengths shown by its specimen during strength tests.

11.1.5. PERMEABILITY

Capillary rise tests revealed that pore sizes for normal construction bricks are large and vary between 100 to 1,000 nm. Sandlime bricks were observed to have finer pores varying between 10 to 100nm. Similarly engineering bricks were also observed to have fine pores in the range of 10 to 100nm.

For similar w/c ratios, concrete with normal construction brick aggregate shows almost three times the rate of surface absorption as compared to concrete with gravel aggregate whereas concrete with sandlime brick aggregate initially shows twice the values of surface absorption thereafter reducing to similar values as of concrete with gravel aggregate. Concrete with engineering brick aggregate gives similar values of surface absorption as gravel concrete, for similar w/c ratios.

Cores cut from concrete were thought to give a more realistic value of diffusion of chloride ions as compared to moulded specimen. The rate of chloride diffusion was observed to be three times higher for concrete with normal construction brick aggregate in the first three days after which it steadied to 42% higher values as compared to gravel concrete. This is possibly due to the presence of almost 0.2375% of chlorides present originally in the normal construction brick aggregates and due to the fact that it is easier for the ions to move through the more porous normal construction brick aggregates.

The rate of chloride diffusion through concrete with sandlime brick aggregate concrete was observed to be about two and a quarter times higher than the value for concrete with gravel, after seven days. Diffusion of chloride ion was observed to be at a very high rate for the first four days.

Concrete with engineering brick aggregates showed a gradual increase in the rate of chloride ion diffusion over a period of seven days similar to concrete with gravel. Similar amount of current was observed to pass through concrete with gravel and engineering brick aggregate. The rate of chloride ion diffusion through concrete with engineering brick aggregate was observed to be almost twice as compared to concrete with gravel aggregates.

11.1.6. FROST RESISTANCE

Concrete with normal construction brick aggregates is highly frost susceptible and shows significant expansion along with a large reduction in dynamic modulus when subjected to cyclic freezing and thawing. This behaviour is due to high absorption of normal construction brick aggregate of 20%.

Concrete with sandlime brick aggregates has better frost resistance as compared to concrete with gravel with similar w/c ratio, since there is negligible loss in dynamic modulus inspite of some expansion on cyclic freezing. Sandlime bricks were observed to have fine capillary structure which reduces the amount of freezable water thereby reducing the amount of damage due to frost.

Concrete with engineering brick aggregates behave somewhat similar to concrete with Thames Valley gravel when subjected to cyclic freezing and thawing.

Hence with the reduction in absorption of crushed brick aggregates, definite improvements in the frost resistance of concrete with crushed brick aggregates were observed.

11.1.7. SULPHATE RESISTANCE

When subjected to sulphate attack, concrete with normal construction brick aggregates show twice as much expansions as compared to concrete with gravel aggregate but the loss in weight is about one fourth and reduction in dynamic modulus is negligible. Concrete with sandlime brick aggregate shows almost half the value of expansion and reduction of dynamic modulus as compared to gravel concrete but the loss of weight was slightly over twice the value for gravel concrete. The large loss of weight in concrete with sandlime brick aggregate was due to leaching of large amounts of $Ca(OH)_2$ present in the aggregates. Concrete with engineering brick aggregate shows almost similar expansions as compared to concrete with gravel. The average reduction in dynamic modulus for concrete with engineering brick aggregate was 30 to 50% and the weight loss was 15% lower than for concrete with gravel aggregate.

The expansion/contraction characteristic of brick aggregates on saturation/drying helps in reducing the damage due to sulphate attack, along with lower modulus of elasticity of brick aggregates which is more compatible with the modulus of elasticity of cement paste.

11.1.8. HIGH STRENGTH CONCRETE WITH BRICK AGGREGATES

Higher compressive strengths of concrete are possible with crushed brick aggregates. Brick aggregate obtained by crushing engineering 'B' bricks with a crushing strength of $40N/mm^2$ was successfully used for high strength concrete up to a maximum characteristic strength of $80N/mm^2$. Higher compressive strengths are likely to be achieved by further improving the quality of crushed brick aggregates i.e. by crushing higher strength bricks.

Compressive strengths of 60 and $80N/mm^2$ were successfully achieved. The flexural strength of brick aggregate concrete in the high strength range was observed to be between 8 to 11% of the compressive strength, similar to high strength concrete with round gravel as aggregate. The average static modulus of elasticity for concrete with engineering brick aggregate was observed to be 36% lower than concrete with Thames Valley gravel and the average dynamic modulus of elasticity for concrete with engineering brick aggregate was 38% lower. About 6% lower density was observed for high strength brick aggregate concrete as compared to high strength concrete with Thames Valley gravel.

11.1.9. CONCRETE WITH MIXED GRAVEL AND BRICK AGGREGATES

The rate of development of strength of mixed aggregate concrete was observed to be similar to normal aggregate concrete. Mixed aggregates concrete developed satisfactory compressive strengths as compared to concrete with gravel aggregate. Flexural strengths were higher by about 5%, the average static modulus of elasticity was observed to decrease by 35% to 40%, and the average dynamic modulus for concrete with brick aggregate plus gravel was 20% to 23% lower than the value for concrete with Thames Valley gravel aggregate. The variation of pulse velocity in the case of concrete with brick aggregate plus gravel is 7% to 13% lower as compared to concrete with gravel. The average density for concrete with brick aggregates plus gravel was 4 to 6% lower than concrete with gravel. ISAT results obtained from tests on concrete with brick aggregates plus gravel showed that surface absorption was almost 50% higher for higher w/c ratio but was however similar to concrete with Thames Valley gravel, for lower w/c ratio. Shrinkage of concrete with brick aggregates plus gravel varies from almost one and a half times higher than concrete with gravel for higher w/c ratio to 25% higher for low w/c ratios.

Frost resistance of mixed aggregate concrete depends on the absorption and pore size of brick aggregate. Mixed aggregate concrete with normal construction brick aggregate mixed with gravel started expanding continously on cyclic freezing and thawing and large expansions resulted in rapid decrease in dynamic modulus whereas concrete with sandlime brick aggregate mixed with gravel showed better frost resistance than gravel concrete, for w/c ratio of 0.385.

11.2. RECOMMENDATIONS

Concrete with brick aggregates from normal construction brick and sandlime brick is suitable for most structural applications where the compressive strength required is up to $40N/mm^2$. The structural elements of low rise buildings will normally fall within this category. Concrete structures such as walkways and foundations of light buildings which are continually supported and have no deflection problems can also be made from concrete with normal construction brick and sandlime brick aggregates. Concrete with normal construction brick aggregate has 35% lower coefficient of thermal expansion than concrete with gravel, hence, together combined with its higher limiting strain capability, leads to improved fire resistance for beams and columns. Concrete with normal construction brick aggregate performs well in sulphate environments but should be avoided in freezing and thawing conditions. Concrete with sandlime brick aggregate can be used under frost conditions but is not recommmended under sulphate environment.

Concrete with brick aggregates from engineering bricks is suitable for all structural uses. Concrete with engineering brick aggregate has 32% lower coefficient of thermal expansion as compared to normal concrete hence it will perform better towards fire resistance of columns and beams. The frost resistance of concrete with engineering bricks is similar to gravel concrete whereas it performs better in sulphate environments.

A design procedure for concrete with crushed brick aggregates is recommended in Chapter 3.

Coarse aggregates obtained by crushing engineering bricks can be used for the manufacture of high strength concrete. Engineering bricks with a crushing strength of $40N/mm^2$ were successfully used for compressive strengths of concrete up to $80N/mm^2$. Improved crushing strength of crushed brick aggregates is likely to result in further higher compressive strengths. A design procedure for high strength concrete with brick aggregates is recommended in Chapter 9.

Brick aggregates from weaker, more porous bricks when mixed with gravel and used in concrete tend to adversely affect the properties of concrete including its frost resistance.

Aggregates from normal construction bricks with high absorptions are not recommended to be mixed with gravel for use in frost environments.

11.3. FUTURE WORK

The following is suggested for future research:

a. Mechanical crushing of brick aggregates and its effect on grading and mico-cracking in aggregates.

b. Gas and water permeability of concrete with brick aggregate especially engineering brick aggregate.

c. Use of engineering brick aggregate in air entrained concrete and its performance under cyclic freezing and thawing conditions.

d. Use of engineering brick aggregate with Portland cement mixed with pozzolans and with sulphate resisting cements and performance of such concrete in sulphate environment.

e. Investigations on the performance of high strength concrete with brick aggregates obtained by crushing bricks with higher crushing strengths than $40N/mm^2$.

f. The performance of high strength brick aggregate concrete in frost and sulphate environments along with investigations on its permeability.

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