Use of Masonry Construction & Demolition Waste in Concrete

Tahir Kibriya[1], Leena Tahir[2]

[1]Ex Faculty/Head of Civil Engineering Department, NUST, Risalpur, Pakistan (Presently Senior Consulting Engineer, Black & Veatch, Toronto, Canada)
[2]MSc Structural Engineering, City University, London, UK
Email: t_kibriya@yahoo.com

Abstract

Massive amounts of brick waste are obtained from demolition of old buildings and structures around the world. With the increased stress on sustainable construction, and environmentally friendly materials and greener concreting practices, a large proportion of such waste bricks are crushed and mixed with normal aggregates for use in concrete. The performance of concrete containing waste brick aggregates partially replacing normal aggregates have not been investigated for their performance. This paper covers investigations carried out on concrete with such aggregates obtained from demolition waste and mixed with varying proportions of normal aggregates to produce concrete. Two types of crushed brick aggregates were mixed with gravel in the ratios of 30:70 and 40:60 by weight and specimen were cast for investigations. Two w/c ratios were investigated. Various tests were carried out to assess the compressive strength of cubes and cylinders of mixed aggregates concrete along with f1exural strength, stress/strain behavior, 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 normal aggregates (gravel) with similar w/c ratios. While the strength tests and durability tests more or less gave satisfactory results however the larger moisture absorption by the waste brick aggregates reduces the frost resistance capacity somewhat thereby care needs to be exercised in using these mixes in regions/areas susceptible to frost.

Keywords

Demolition Waste, Construction Waste, Recycled Aggregates, Recycled Aggregates Concrete, Sustainable Construction, Environmental Friendly Waste, Green Concrete

1. Introduction

Huge amounts of demolition waste were generated in the world wars. After the Second World War, Germans were the first ones to initiate research on use of waste materials in construction. Massive efforts have gone in research on disposal/ recycling of waste products being generated through various processes. Explorations of possible usage of such wastes in various industries have been carried out extensively. Shortage of development budgets in developing/ under developed countries forces them to make efforts to find cheaper substitutes that are locally available. Furthermore, most of the masonry construction which was built years ago has already outlived their lives and are being demolished thereby creating large quantities of waste brick. Crushed brick aggregates from bricks obtained from demolition/construction waste are usually added to normal aggregates and used for concreting in many countries however, there has been no information nor research on the performance of such concrete in which normal aggregates have been partly replaced with crushed waste brick aggregates exists in literature neither any information on acceptable percentages of such waste aggregates to be used in various concrete mixes are evaluated, to keep the resulting concrete properties acceptable, though concrete with 100% crushed brick aggregates have been investigated [1]-[8].

2. Research Significance

The significance of this research is to investigate the properties of concrete made from partial replacement of natural aggregates in various proportions with abundantly available masonry construction waste from demolition of masonry construction and its use in quality concrete along with requisite care to be practiced in use of such concretes.

3. Concrete Mixes Used for Experimental Testing

To investigate the performance of concrete with normal aggregates replaced with a percentage of crushed waste brick aggregates, two sets of specimen were prepared for experimental investigation by replacing 30% and 40% by weight of gravel aggregate with crushed waste brick coarse aggregates. The w/c ratios of two characteristic strengths of 35 and 50 N/mm^2 of concrete with gravel were investigated for concrete with mixed gravel and crushed waste brick aggregates. The concrete specimens used as standard to carry out comparative study were prepared by using Thames Valley gravel as coarse aggregates. Water/cement ratio, quality of water, curing conditions and test methods were kept constant for all specimen. Table 1 gives the quantities per cubic meter of concrete. Table 2 and Table 3 give the properties of concrete with mixed aggregates.

4. Experimental Testing Regime

Testing regime followed is given below. Four sets of specimen from four different batches were used in all tests:-

Compressive strength/density	150 mm cubes, 150 mm Diameter, 300 mm long cylinders.
Flexural strength/Shrinkage	150 × 150 × 750mm beams.
Stress/strain behavior	150 mm diameter, 300 mm long cylinders.
Static modulus of elasticity	150 mm diameter, 300 mm long cylinders.
Dynamic modulus of elasticity	150 × 150 × 750 mm beams.
Ultrasonic pulse velocity	150 mm cubes.

Table 1. Quantities per cubic meter of concrete.

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	59F	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 2. Properties of concrete with mixed aggregates.

TYPE OF MIX	W/C RATIO	COMPRESSIVE STRENGTH 7DAY N/mm^2	28DAY N/mm^2	CYLINDER STRENGTH N/mm^2	FLEXURAL STRENGTH N/mm^2	ELASTIC MODULUS DYN STATIC N/mm^2 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	0.385	36.83	41.34	29.3	4.41	46922.8 23480.2
0.5		46.49	53.81	37.98	5.33	47557.8 24033.5

Table 3. Properties of concrete with mixed aggregates.

TYPE OF MIX	W/C RATIO	DENSITY OF CONCRETE (kg/m³)		ISAT	SHRINKAGE ×10⁻⁴ mm	PULSE VELOCITY
		dry	saturated			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	3.9g4
42	0.385	2243	2331	Low	3.63	4.112
Gravel	0.5	2403	2454.80	Low	1.17	4.76
	0.385	2411	2457.70	Low	2.97	4.79

Note: a) 11% - 30% London brick aggregate +70% Gravel; b) 12% - 30% London brick aggregate +70% Gravel; c) 21% - 30% Sand-lime brick aggregate +70% Gravel; d) 22% - 30% Sand-lime brick aggregate +70% Gravel; e) 31% - 40% London brick aggregate +60% Gravel; f) 32% - 40% London brick aggregate +60% Gravel; g) 41% - 40% Sand-lime brick aggregate +60% Gravel; h) 42% - 40% Sand-lime brick aggregate +60% Gravel.

Initial surface absorption	150 mm cubes.
Shrinkage	150 mm cubes.
Frost Resistance	150 mm cubes.

All specimen were cured in water at 20˚C for 42 days before testing.

5. Experimental Testing Results

Results obtained from testing of various test samples are summarized below and are also shown in Tables 3-17.

5.1. Compressive Strength

Compressive strength tests on cubes at 7 days and 28 days showed that the rate of development of strength of mixed aggregate concrete was similar to normal aggregate concrete.

Specimen with 30% and 40% of gravel replaced by coarse crushed waste construction brick and waste sand-lime brick aggregates developed satisfactory compressive strengths at the first attempt.

On testing cylinders for 28 days compressive strength, it was observed that the cylinder strength varied from 58% to 78% of cube strength as compared to 60% to 67% for gravel. Table 4 gives the 28 day compressive strengths of cubes and cylinders for concrete with different percentages of brick and gravel mixed aggregates concrete.

5.2. Flexural Strength

l50 × 150 × 750 mm 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

Table 4. Cube and cylinder strengths of different concretes.

TYPE OF MIX	W/C RATIO	CUBE STRENGTH N/mm²	CYLINDER STRENGTH N/mm²	%
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	36.3 7	67.60

Table 5. Flexural strength of concrete with mixed aggregates.

TYPE OF MIX	W/C RATIO	COMPRESSIVE STRENGTH 28DAY N/mm²	FLEXURAL STRENGTH N/mm²
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 6. Static modulus of elasticity of concrete with mixed aggregates.

TYPE OF MIX	W/C RATIO	COMPRESSIVE STRENGTH 28DAY N/mm²	STATIC MODULUS OF ELASTICITY N/mm²
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 7. Dynamic modulus of elasticity of concrete with mixed aggregates.

TYPE OF MIX	W/C RATIO	COMPRESSIVE STRENGTH N/mm²	DYNAMIC MODULUS OF ELASTICITY N/mm²
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 8. Ultrasonic pulse velocities of concrete with mixed aggregates.

TYPE OF	W/C RATIO	COMPRESSIVE STRENGTH	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 9. Comparison of empirical and experimental moduli of elasticity by pulse velocity measurements.

Type of Mix	Pulse Velocity Km/s	Empirical Moduli Static Dynamic N/mm²		Experimental Moduli Static Dynamic N/mm²	
11	4.3	24,500	34,000	14,790	37,902
12	4.3	24,500	34,000	18,226	39,968
21	4.1	20,000	30,500	14,660	40,508
22	4.2	22,000	32,000	15,173	37,597
31	4.0	18,000	29,000	13,322	36,992
32	4.1	20,000	30,500	14,660	40,508
41	3.98	18,000	29,000	13,322	36,992
42	4.1	20,000	30,500	14,660	40,508
Gravel 0.5	4.76	30,500	39,000	23,480	46,923
0.385	4.79	43,000	49,000	24,033	47,558

Table 10. Densities of concrete with mixed aggregates.

TYPE OF MIX	W/C RATIO	DENSITY OF CONCRETE (kg/m³)	
		Dry	Saturated
11	0.5	2219	2330
12	0.385	2276	2363
21	0.5	2271	2353
22	0.385	2289	2377
31	O.5	2184	2297
32	0.385	2231	2312
41	0.5	2227	2314
42	0.385	2243	2331
Gravel	0.5	2403	2454.8
	0.385	2411	2457.7

Table 11. Shrinkage of concrete with mixed aggregates.

TYPE OF MIX	W/C RATIO	SHRINKAGE $\times 10^{-4}$ 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	3.69
Gravel	0.5	1.176
	0.385	2.976

Table 12. Summary-Frost resistance test on concrete with mixed aggregates (50 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	28.4
41	0.50	0.057	14.8
12	0.385	0.035	24.1
22	0.385	0.036	3.0
32	0.385	0.068	28.5
42	0.385	0.046	5.7
Gravel	0.50	0.048	7.1
	0.385	0.07	14.4

Table 13. Comparison of compressive strengths of concrete specimen before and after Frost Resistance Tests.

TYPE OF	W/C	INITIAL	RESIDUAL	VARIATION
MIX	RATIO	STRENGTH N/mm^2	STRENGTH N/mm^2	%
11	0.50	45.05	43.55	3.33
12	0.385	50.85	49.05	3.53
21	0.50	47.25	46.05	2.54
22	0.385	52.05	51.6	0.86
31	0.50	42.51	40.73	4.18
32	0.385	50.76	48.53	4.39
41	0.50	46.30	45.19	2.39
42	0.385	51.64	50.9	1.43
Gravel	0.50	41.34	40.32	1.02
Gravel	0.385	53.81	53.11	1.3

Table 14. Performance of concrete with normal construction brick waste aggregate and gravel in the ratio of 30:70, respectively, in frost resistance.

Sample No.31. 40% London brick + 60% Gravel W/C Ratio 0.50 Observations						
Cycles	Start	10	20	30	40	50
Length (*0.0l mm)	248.25	258.5	271	285	266	268.5
Weight (g):	11870.5	11,878	11,877	11,875	11877.5	1877.5
R frequency (Hz):	4131.5	3725.5	3721	3693	3641.5	3607.5
Dyn. Mod. (N/mm'):	40522.5	32,963	32,900	32,425	31502.8	30920.4

Reduction in Dyn. Modulus-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 (*0.0l mm):	255.2	261.7	273.5	286.5	271	273
Weight (g):	11919.3	11,926	11,926	11,904	11,874	11925.5
R frequency (Hz):	4104	3594.5	3627	3595	3585	3573.5
Dyn. Mod. (N/mm')	40149.5	30807.7	31,382	30,847	30,656	30462.5

Reduction in Dyn. mod. = 24.13% Increase in length = 0.035%

respectively, vide BS 1881: Part 109: 1983. Test beams were cured for 28 days before testing. The tests for flexural strength was carried out vide BS 1881: Part 118: 1983 with third point loading. Table 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 7.7 N/mm^2 *i.e.* 15% to 20% of the 28 day compressive strength as compared to flexural strengths varying from 4.4 to 5.3 N/mm^2 *i.e.* 9.9% to 10.7% of the 28 day compressive strengths for gravel concrete. Hence flexural

Table 15. Performance of concrete with normal construction brick aggregate and gravel in the ratio of 40:60, respectively, in frost resistance test.

Sample No.31. 40% London brick + 60% Gravel W/C Ratio 0.50 Observations						
Cycles	Start	10	20	30	40	50
Length (*0.0l mm)	239	249	264	277	256	261
Weight (g):	11,769	11,774	11,777	11,778	11,777	11,778
R frequency (Hz)	4011	3523	3501	3483	3421.2	3391
Dyn. Mod. (N/mm'):	37,868	29,226	28,879	28,598	27,569	27,089

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(*0.0lmm):	265	274	287	299	287	293
Weight(g) :	11,817	11,821	11,824	11828	11,794	11,801
R frequency(Hz):	4003	3491	3427	3415	3402	3382
Dyn. Mod.(N/mm')	37,871	28,813	27,781	27,600	27,377	27,062

Reduction in dynamic modulus = 28.53% Increase in length = 0.056% (max 0.068%)

Table 16. Performance of concrete with sand-lime brick aggregate and gravel in the ratio of 30:70, respectively, in frost resistance test.

Sample No.21. 70% Gravel + 30% Sand-lime brick U/C Ratio 0.50 Observations						
Cycles	Start	10	20	30	40	50
Length (*0.0l mm) :	214.7	212.7	220	245	216	217.5
Weight (g):	11,962	11,966	11967.5	11,968	11967	11968.5
R frequency (Hz)	4186	4012	3971.5	3926	3860.5	3859
Dyn. Mod. N/mm^2):	4193	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% Sand-lime brick W/C Ratio 0.385 Observations						
Cycles	Start	10	20	30	40	50
Length (*0.01 mm)	235.5	233.25	242	253.5	234.5	238
Weight (g):	11947.5	11949.5	11,949	11949.5	1949	11,947
R frequency (Hz):	4112	4064	4064.5	4063	4057.5	4051
Dyn.Mod. (N/mm'):	40402.9	39461.6	39,485	39474.2	39,337	39,217

Reduction in Dyn. mod. − 3% Increase in length = 0.005% (max 0.036)

strength values for concrete with mixed aggregates are 7% higher on average than concrete with Thames Valley gravel.

Table 5 shows the variation in flexural strength of mixed aggregates concrete as compared to brick aggregate concrete and gravel concrete. It can be observed from Table 5 that flexural strength of concrete with brick aggregates is slightly lower than gravel concrete. The flexural strength of concrete with mixed aggregates is higher than both brick aggregate concrete as well as gravel concrete.

Table 17. Performance of concrete with sand-lime brick aggregate and gravel in the ratio of 40:60, respectively, in frost resistance test.

Sample No.41. 60% Gravel + 40% Sand-lime brick W/C Ratio 0.50 Observations						
Cycles	Start	10	20	30	40	50
Length (*0.01 mm)	203.4	201.6	208	232	203	206
Weight (g):	11,859	11,864	11,867	11,869	11,867	11,869
R frequency (Hz):	4166	4001	3970	3916	3873	3844
Dyn. Mod. (N/mm'):	41,164	37,965	37,388	36,413	35,577	35,050

Reduction in dynamic modulus = 14.8% Increase in length = 0.005% (max 0.057%)

Sample No.42. 60% Gravel + 40% Sand-lime brick W/C Ratio 0.385 Observations						
Cycles	Start	10	20	3 O	40	50
Length (*0.01 mm)	231	229	240	254	243	244
Weight (g):	11,938	11,939	11,942	11,943	11,942	11,943
R frequency (Hz):	4104	4041	4027	4008	3997	3984
Dyn. Mod. (N/mm'):	40,2l4	38,985	38,733	38,390	38,162	37,916

Reduction in dynamic modulus = 5.7% Increase in length = 0.026% (max 0.046%)

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 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.

5.3. Stress/Strain Behavior

5.3.1. Static Modulus of Elasticity

150 mm diameter, 300 mm long cylinders were prepared for determining the static modulus of elasticity in compression. Strains were recorded for every incremental load increase. Table 6 gives the values of static modulus of elasticity for 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 sand-lime brick aggregate.

5.3.2. Dynamic Modulus of Elasticity

Test beams $150 \times 150 \times 750$ mm were cast for carrying out the dynamic modulus of elasticity tests. The specimens were cured for 28 days before testing for dynamic modulus of elasticity. Table 7 gives the values of dynamic modulus of elasticity for concrete with mixed aggregates.

The average resonant frequencies observed for concrete with normal construction brick aggregate plus gravel and sand-lime 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 2981 Hz.

The dynamic modulus of elasticity for concrete with normal construction brick aggregate plus gravel varied from 36,992 to 38,l63 N/mm^2 whereas that for concrete with sand-lime brick aggregate plus gravel varied from 37,597 to 40,508 N/mm^2. Values of dynamic modulus for concrete with Thames Valley gravel aggregate varied from 46,922 to 47,557 N/mm^2. Hence the average dynamic modulus for concrete with normal construction brick aggregate plus gravel and sand-lime 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.

5.4. 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. 150 mm 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 8.

Average pulse velocity across concrete with normal construction brick aggregate plus gravel was observed to be 4.27 km/s for aggregate ratio of 30:70 respectively and 4.05 km/s for the aggregate ratio of 40:60 respectively for average values of static moduli of elasticity of 16,508 N/mm^2 and 14,796 N/mm^2 dynamic moduli of elasticity of 38,935 and 37,577 N/mm^2 respectively. similarly, the average pulse velocity with sand-lime brick aggregate plus gravel was observed to be 4.15 km/s for aggregate ratio of 30:70 respectively and 4.0 km/s for the aggregate ratio of 40:60 respectively for average values of static moduli of elasticity of 14916 and 14,585 N/mm^2 and dynamic moduli of elasticity of 39,052 and 38,866 N/mm^2 respectively. For concrete with Thames Valley gravel as coarse aggregate, average pulse velocity was observed to be 4.8 km/s for average values of static modulus of elasticity of 23,757 N/mm^2 and dynamic modulus of elasticity of 47,240 N/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 sand-lime brick waste 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.

5.5. Initial Surface Absorption (ISAT)

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.3l.

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 sand-lime brick aggregates plus gravel in the ratios of 30:70 and 40:60 for w/c ratios of 0.385 & 0.5 similar to concrete with gravel only.

5.6. Shrinkage

Shrinkage tests were carried out in accordance with RILEM Recommendation CPC 9-Measurement of shrinkage and swelling. $100 \times 100 \times 500$ mm 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 11 gives the shrinkage of concrete with mixed aggregates.

Shrinkage of concrete with normal construction brick waste 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 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 Sand-lime brick waste 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 sand-lime brick waste 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.

5.7. 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 waste aggregates and Thames Valley gravel. 100 × l00 × 500 mm 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 12 gives a summary of the performance of mixed aggregates concrete in frost resistance test. Table 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. Concrete with normal construction brick waste aggregate plus gravel mixed in the ratios of 30:70 and 40:60 respectively, both started expanding continuously on cyclic freezing and thawing and the large expansions were accompanied by a rapid decrease in dynamic modulus, as shown in Table 14 and Table 15. The dynamic modulus decreased by almost 20% in the first twenty cycles 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.

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 waste aggregate plus gravel showed continuously increasing expansions for the first thirty cycles of freezing and thawing. Concrete with normal construction brick waste aggregate and gravel in the ratio of 40:60 respectively (by weight) showed larger expansions as compared to concrete with normal construction brick waste 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 continuous 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 pressurizes 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 cyc-

lic freezing and thawing increases microcracking thereby resulting in loss of strength along with length increases.

The length of specimen increased continuously 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 behavior 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 accommodated. After some excess water was accommodated in these pores, the specimen showed slight contractions for the next ten cycles after which the specimen again started increasing in length. The behavior of concrete with normal construction brick waste aggregates plus gravel is entirely different from concrete with Thames Valley gravel only. 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 waste aggregate plus gravel shows large expansions in first thirty cycles with a large reduction in dynamic modulus. Thereafter the expansions are small and continuous along with a gradual decrease in dynamic modulus. Table 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 waste 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 waste 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.

Table 16 and Table 17 gives the performance of sand-lime brick waste plus gravel aggregate concrete in frost resistance test. For concrete with sand-lime brick waste 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 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 sand-lime 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 behavior is possibly 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 accommodation of some excess expanding water in these pores which open up after about thirty cycles. Later on, the specimen again starts expanding due to dilative pressures on cooling.

The reduction in dynamic modulus in concrete with sand-lime brick waste 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 sand-lime 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 micro cracking inside the concrete as compared to concrete with Thames Valley gravel only, thereby reducing the loss of strength. Concrete with sand-lime brick waste 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 sand-lime brick waste 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

6. 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 continuously on cyclic freezing and thawing and large expansions resulted in rapid decrease in dynamic modulus whereas concrete with sand-lime brick aggregate mixed with gravel showed better frost resistance than gravel concrete for w/c ratio of 0.385.

Keeping in view the characteristics of concrete with waste brick aggregates mixed with normal aggregates, in the ratios of 30:70 respectively, there are no appreciable differences while in the ratios of 40:60 respectively, shrinkage is larger along with lower moduli of elasticity and loss of strength on cyclic freezing and thawing. Such concrete is well suited for low rise construction, pavements and other structures not lying in the areas subjected to freeze thaw in cold regions.

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