

PROPERTIES OF LIGHTWEIGHT CONCRETE MANUFACTURED WITH FLY ASH, FURNACE BOTTOM ASH, AND LYTAG

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Abstract

Fly ash (FA), furnace bottom ash (FBA) and Lytag (LG) were used in the current study to replace ordinary portland cement (OPC), natural sand (NS) and coarse aggregate (CA), respectively, and thereby to manufacture lightweight concrete (LWC). Two control mixes containing no replacement materials were designed with a 28-day compressive strength of 20 N/mm² and 40 N/mm². For each compressive strength, three different mixes, viz. (a) 100%OPC+100%NS + 100%CA, (b) 100%OPC + 100%FBA + 100%LG and (c) 70%OPC + 30%FA + 100%FBA + 100%LG, were manufactured with slump in the range of 30 ~ 60 mm. The density, compressive strength, pull-off surface tensile strength, air permeability, sorptivity and porosity of the concretes were investigated.

The results indicated that it is possible to manufacture lightweight concrete with density in the range of 1560-1960 kg/m³ and 28-day compressive strength in the range of 20-40 N/mm² with various waste materials from thermal power plants. However, the introduction of FBA into concrete would cause detrimental effect on the permeation properties of concrete. With part of OPC replaced with FA, the strength decreased, but the permeability of the resulting concrete improved.

1. Introduction

Lightweight concrete (LWC) has been successfully used since the ancient Roman times and it has gained its popularity due to its lower density and superior thermal insulation properties [1]. Compared with normal weight concrete (NWC), LWC can significantly reduce the dead load of structural elements, which makes it especially attractive in multi-storey buildings. However, most studies on LWC concern "semi-lightweight" concretes, i.e. concrete made with lightweight coarse aggregate and natural sand. Although commercially available lightweight fine aggregate has been used in investigations in place of natural sand to manufacture the "total-lightweight"

concrete [2, 3], more environmental and economical benefits can be achieved if waste materials can be used to replace the fine lightweight aggregate.

Lyttag is one of the most commonly used lightweight aggregates, which is manufactured by pyro-processing fly ash (FA), while FA and furnace bottom ash (FBA) are two waste materials from coal-fired thermal power plants. They are, respectively, lighter than traditional coarse aggregate, OPC and natural sand. The previous investigations carried out by the authors on using FBA from a thermal power plant in Northern Ireland as a sand replacement material indicated that FBA could be a potential fine aggregate in NWC for certain applications [4, 5]. However, the application of FBA in structural LWC is not well defined. Therefore, the current study investigates the possibility of manufacturing structural LWC with FA, FBA and Lytag

2. Experimental Program

2.1 Materials

The cement used was the Class 42.5N portland cement supplied by Blue Circle, U.K., complying with BS 12: 1991 [6].

For the control mixes, the coarse aggregate used was 10 mm crushed basalt and the fine aggregate used was medium graded natural sand complying with BS 882: 1992 [7]. Both materials are from the local sources in Northern Ireland. They were oven dried at 40°C for 24 hours and cooled to 20°C before using in the manufacture of concrete. The FA and FBA used were supplied by Kilroot Power Station in Northern Ireland, U.K. The FBA was dried firstly in an oven at 105°C for 24 hours and then allowed to cool for 24 hours at 20°C. The FBA that passed 5 mm sieve (hereafter FBA sand) was used to replace natural sand. The Lytag used was with a size of 8 mm and was supplied by Finlay Concrete Products, Northern Ireland, U.K. It was also oven dried at 40°C for 24 hours and cooled to 20°C before casting. Table 1 reports the chemical compositions of OPC, FA, FBA and Lytag. The specific gravity and 1-hour water absorption of basalt, natural sand, FBA sand and Lytag are reported in Table 2. Fig. 1 presents the particle size distribution of basalt, natural sand, FBA sand and Lytag.

2.2 Mix proportions

Two control mixes containing OPC, basalt and natural sand were designed for a 28-day compressive strength of 20 N/mm² (Series M) and 40 N/mm² (Series H) respectively, for a slump in the range of 30-60 mm. For each control mix, 30% of OPC, 100% of natural sand, and 100% of basalt were then replaced with FA, FBA, and Lytag, respectively. The binder content (OPC or OPC + FA) was kept the same as that of the control mix for each series when the natural sand and basalt were replaced with FBA and Lytag, respectively.

Table 1: Chemical composition of cement, PFA, FBA, and Lytag

Oxide composition (%)	OPC	FA	FBA	Lytag
SiO ₂	20.6	59.01	61.78	53.19
Al ₂ O ₃	5.7	22.8	17.8	26.3
Fe ₂ O ₃	2.9	8.8	6.97	10.26
CaO	63.6	2.38	3.19	2.02
MgO	1.8	1.39	1.34	1.45
Na ₂ O	0.12	0.74	0.95	0.96
K ₂ O	0.75	2.8	2	3.99
SO ₃	3.2	0.27	0.79	-
Cl	0.01	0.01	-	-
LOI	1.5	6.7	3.61	4

Table 2: Property of aggregates

Property	Basalt	Natural sand	FBA sand	Lytag
Specific gravity (S.S.D.)	2.91	2.66	1.58	1.52
1-hour water absorption (%)	1.1	1.1	32.2	12.31

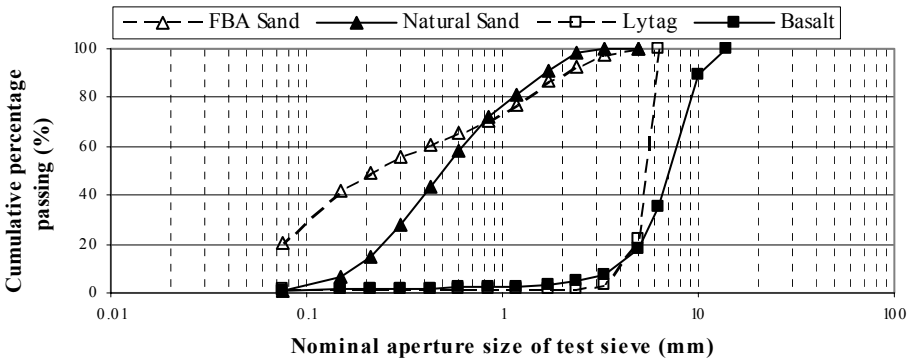


Fig. 1: Particle distribution of FBA sand, natural sand, Lytag, and basalt

For each series, three different mixes were studied. Mix 1: 100%OPC+100%NS+100%CA (control). Mix 2: 100%OPC+100%FBA+100%LG. Mix 3: 70%OPC+30%FA+100%FBA+100%LG. The water content (and therefore W/C) of Mix 2 and Mix 3 was adjusted by carrying out trials so that the workability measured in terms of slump was in the range of 30-60mm. The volume ratio between the fine aggregate and the coarse aggregate for each test series was kept the same as

that obtained for the respective control mix. The resulting mix proportions, which were used in this investigation, are reported in Table 3.

Table 3: Mix proportions (kg/m^3) and properties of fresh concretes

Mix No	W/C	Cement	FA	Free Water	Sand	FBA	Basalt	Lytag	Measured Slump (mm)	Measured Air Content (%)
M1	0.65	330	-	215	820	-	1040	-	27	2
M2	0.4	330	-	132	-	552	-	616	51	5
M3	0.32	231	99	106	-	562	-	627	43	5
H1	0.47	460	-	215	715	-	1025	-	50	1.2
H2	0.32	460	-	147	-	477	-	602	30	5
H3	0.29	322	138	133	-	473	-	599	34	5

2.3 Batching and mixing

For each mix, the required quantities of the constituents were batched by weight. The water required for 1-hour absorption by the aggregates (basalt, natural sand, FBA sand and Lytag) was added to the mix water in addition to the free water shown in Table 3. Different mixing procedures were used for NWC and LWC, which are described below.

Mixing procedure for NWC (control): The manufacturing of NWC was carried out based on reference 8. Approximately half the basalt, all the natural sand and the remaining basalt were added, in this order, evenly into the pan. The aggregates were mixed for 30 seconds. The mixing was continued and about half the mixing water (i.e. free water as shown in Table 3 plus that required for 1 hour water absorption) was added during the next 15 seconds. After mixing for a total of 3 minutes, the mixer was stopped and the contents were left covered for 15 minutes. The cement was then added evenly over the aggregate. The mixer was started and the mixing was continued for 30 seconds. The mixer was then stopped and any material adhering to the mixer blades were cleaned off into the pan. Without delay, the mixing was recommenced and the remaining mixing water was added over the next 30 seconds. The mixing was continued for 3 minutes after all the materials were added.

Mixing procedure for LWC: The procedure given in the Lytag Information Document [9] was used to modify the manufacturing procedure for the LWC. About half the mixing water (free water as shown in Table 3 plus that required for 1 hour water absorption) was added. Then all the Lytag and all the FBA were added in this order, evenly into the pan [9] and mixed for 3 minutes. The mixer was stopped and left covered for 15 minutes. Thereafter, the procedure was the same as that for the NWC.

2.4 Specimen preparation and curing

For each mix, nine 100-mm size cubes were cast to determine the compressive strength at the age of 3, 7, and 28 days. At 28 days, the same cubes used for compressive strength were also used to test the density at saturated-surface dried (SSD) condition. Three 250x250x110-mm slabs were cast to investigate pull-off tensile strength, permeation properties and porosity of the concrete at the age of 28 days.

All specimens were cast in two layers and compacted on a vibrating table until air bubbles appearing on the surface stopped. They were left in the mould in the laboratory at $20(\pm 1)^{\circ}\text{C}$ for one day and then removed from the moulds. After that, they were cured in water at $20(\pm 1)^{\circ}\text{C}$ for two days, and then wrapped in polythene sheet and left in the laboratory at $20(\pm 1)^{\circ}\text{C}$ until they were tested. (The three-day specimens were tested immediately after removing from the water bath, instead of wrapping in polythene sheet.)

2.5 Details of tests

For each mix, the air content and workability (in terms of slump) of the fresh concrete were measured. The air content was measured by following a procedure given in BS 1881: part 106: 1983 [10]. The slump test was carried out in accordance with BS 1881: Part 102: 1983 [11].

At the age of 3, 7, and 28 days, the compressive strength was determined by crushing three 100-mm cubes in accordance with BS 1881:Part 116: 1983 [12] and an average of the three values was obtained. Prior to the compressive strength test at the age of 28 days, the cubes were used to test the SSD density by following BS 1881: Part 114: 1983 [13].

At the age of 28 days, the slabs were dried at $40(\pm 1)^{\circ}\text{C}$ and 22(± 1)% Relative Humidity (RH) in a drying cabinet for two weeks and then cooled to room temperature $20(\pm 1)^{\circ}\text{C}$ for one day. The air permeability and water absorption (sorptivity) were tested on three slabs per mix by using the "Autoclam Permeability System" [14] on the mould finished face and average values of both the air permeability and the sorptivity were calculated. The surface tensile strength was measured by carrying out the Limpet pull-off test [15] at two locations on the mould finished surfaces of the three slabs immediately after the permeation test. All the six results were averaged and reported. After the pull-off test, one $\Phi 75$ -mm core was taken from each of the slab and the water absorption test was carried out by following BS 1881: Part 122: 1983 [16]. The porosity of the concretes was then calculated based on the volume of the voids occupied by the absorbed water.

3. Results and Discussion

3.1 Properties of fresh concrete

Fig. 2 shows the free water content for different mixes. It can be seen that when the FBA sand and Lytag were used to replace natural sand and basalt, respectively, the water demand of the concrete decreased. This is attributable to the spherical/round particle shape of both FBA sand and Lytag [4, 17], which, compared to the angular particles of sand and basalt, have a “ball-bearing effect” and thus reduce the water demand of the fresh concrete. When 30% of the OPC was replaced with FA in both series, there was also a water reduction compared to the mix 2. This is again attributable to the “ball-bearing effect” of the FA particles. Therefore, it can be seen from the above results that when FA, FBA and Lytag were used to manufacture lightweight concrete, the water demand of the concrete decreased.

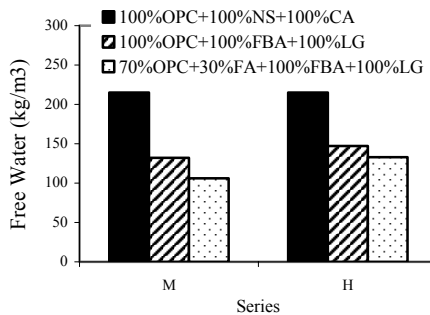


Fig. 2: Free water content of NWC and LWC

3.2 Density

Table 4 reports the density of hardened concrete at saturated-surface dried (SSD) condition measured at 28 days. It can be seen that when natural sand and basalt were replaced with FBA sand and Lytag respectively, there was a significant reduction in the density of hardened concrete for both series. This suggests that the low density of both FBA sand and Lytag is beneficial to produce LWC. When FA was used in mix 3 to replace 30% of the OPC, the density was further reduced. This, again, is due to the lower density of FA compared to that of OPC. Thus, it can be concluded that the low density of FA, FBA and Lytag is a benefit for manufacturing lightweight structural concretes. In the current study, the SSD density in the range of 1560-1960 kg/m³ was achieved.

Table 4: Density (kg/m^3) of hardened concrete at 28 days (SSD)

M1	M2	M3	H1	H2	H3
1977	1725	1559	2471	1952	1819

3.3 Compressive strength

Fig. 3 presents the compressive strength of both series at 3, 7, and 28 days. Fig. 4 illustrates the relationship between the 28-day compressive strength and the SSD density. In Fig. 5, the contribution of different mix to the compressive strength is compared in terms of the specific strength, i.e., ratio of strength to relative density.

From Fig. 3 it can be seen that when the FBA sand and Lytag were used to replace natural sand and basalt respectively, different effects can be observed for series M and H. In series H, the compressive strength decreased from H1 to H3 at all the ages. However, in series M, this trend was visible only for the 3-day results. At the age of 7 and 28 days, there was an increase in strength when the NS and CA were replaced with FBA and Lytag, respectively.

As indicated in Fig. 4, except for one data point corresponding to mix M1, there is a linear relationship between the density and the compressive strength, i.e. the compressive strength is directly proportional to the SSD density of hardened concrete. This indicates that the lightweight was achieved at the cost of reduction in the compressive strength. Nevertheless, it is still possible to manufacture LWC with SSD density in the range of $1560\text{-}1960 \text{ kg/m}^3$ and 28-day compressive strength in the range of $20\text{-}40 \text{ N/mm}^2$.

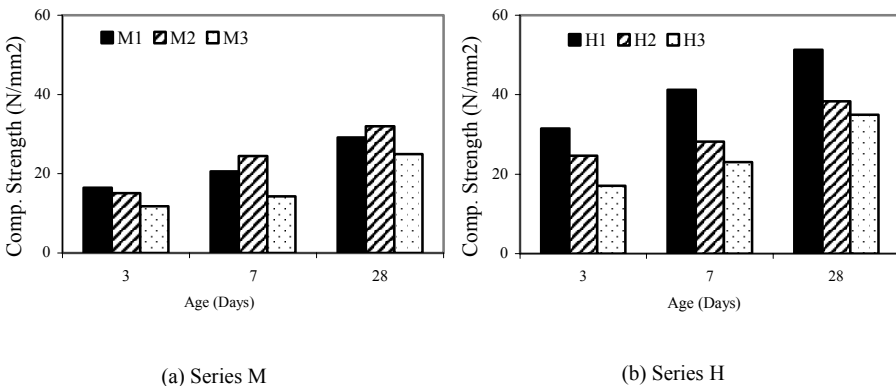


Fig. 3: Compressive strength of NWC and LWC

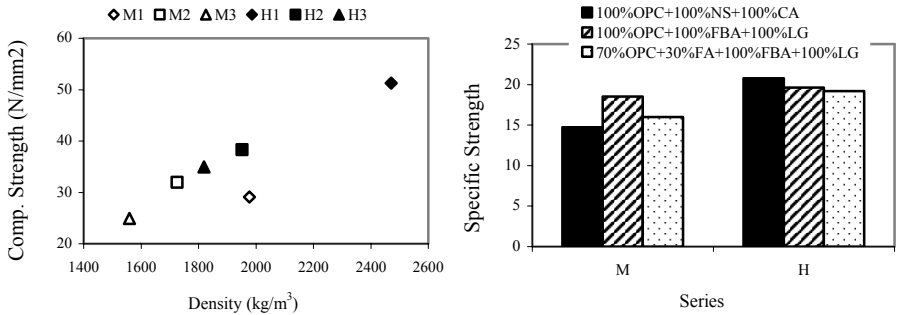


Fig. 4: Compressive strength vs. density Fig. 5: Specific strength of NWC & LWC

Fig. 5 indicates that the specific strength for M2 and M3 are higher than M1, which suggests that for the same weight of concrete, LWC provided marginally higher compressive strength than NWC. For series H, the specific strength for H2 and H3 are lower than H1. However, the difference was small. Therefore, it can be concluded that FA, FBA and Lytag can be favorably used to manufacture medium strength LWC. In the case of high strength concrete, these replacements would result in decrease in compressive strength of the concrete.

3.4 Pull-off surface tensile strength

Fig. 6 presents the results of the pull-off test. It can be seen that, for Series M, the surface tensile strength of M2 and M3 are higher than that of M1, and that of M2 is equal to that of M3. However, for Series H, the pull-off tensile strength of H2 and H3 are lower than that of H1, and the value for H3 is also lower than that for H2. Thus, in terms of the pull-off surface tensile strength, FA, FBA and Lytag have a beneficial effect on medium strength LWC, but a slightly adverse effect on high-strength LWC.

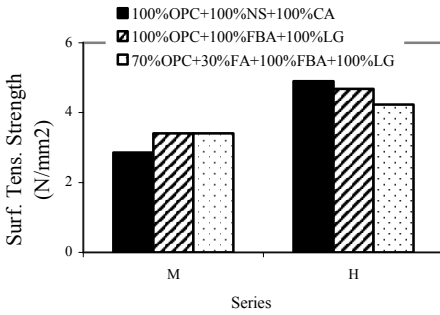


Fig. 6: Surface tensile strength of NWC and LWC

3.5 Permeability

The near surface permeation property was evaluated by using the “Autoclam Permeability System.” Figs. 7 and 8 show the air permeability and sorptivity results, respectively.

It can be seen that when FBA sand and Lytag were used to replace natural sand and basalt to manufacture LWC, the air permeability dramatically increased. From Fig. 2, it can be seen that, due to the water reduction effect of FBA and Lytag, the free water of mix 2 for both

series is lower than mix 1. Since the binder content was the same for all the mixes in each series, the decreased free water content would result in a decreased free water-binder ratio, which should have decreased the air permeability [18]. In addition, although the particles of Lytag are quite porous [17], they have no effects on the air permeability of LWC [19]. Thus, the increased air permeability should be attributable to the porous particles of the FBA sand [5]. However, the air permeability indices of Mix 3 for both series are lower than mix 2, but still higher than mix 1. The decrease of the air permeability indices of mix 3 can be considered to be due to the physical filling effect and pozzolanic reaction of FA, leading to the densification of the pore structure. This reveals that the increased air permeability caused by the porous FBA particles can partly be compensated by the FA. However, since the slabs were only 28 days old, the pozzolanic reaction has not fully developed. Thus, a long-term study is required in order to investigate any possible further beneficial effect of FA on the LWC.

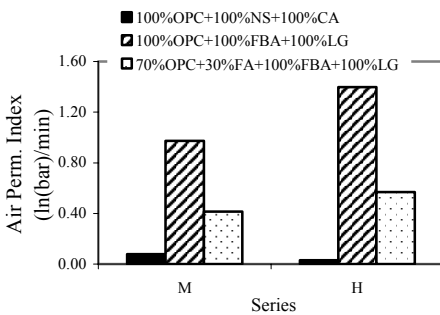


Fig. 7: Air permeability of NWC & LWC

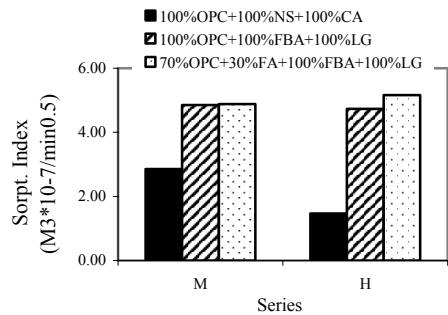


Fig. 8: Sorptivity of NWC & LWC

The sorptivity result in Fig. 8 indicates that when natural sand and basalt were replaced with the FBA sand and Lytag, the sorptivity indices for both series were higher than the corresponding control (mix 1). This is mainly attributable to the porous FBA and Lytag particles. However, when FA was used in mix 3 to replace 30% of the OPC, the sorptivity did not decrease as it did in air permeability. Thus, the FA has no beneficial effect on reducing the sorptivity of LWC at 28 days. On the contrary, the sorptivity increased. Again a long-term study is required to investigate any further beneficial effect.

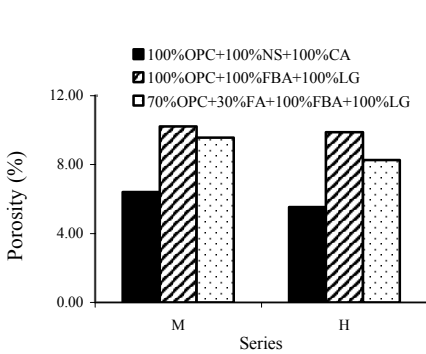


Fig. 9: Porosity of NWC & LWC

3.6 Porosity

The porosity result is reported in Fig. 9. The trend was similar to that of air permeability in Fig. 7, i.e., when natural sand and basalt were replaced by the FBA sand and Lytag respectively, the porosity of LWC increased. However, when FA was used in mix 3 to replace cement, the porosity was lower than mix 2, but still higher than mix 1 for both series. The result further confirms that whereas FBA sand and Lytag increase the porosity of LWC, the FA would partly compensate the detrimental effect caused by FBA sand and Lytag on the porosity and air permeability.

4. Conclusions

- By using FA, FBA and Lytag, it is possible to manufacture lightweight concrete with density in the range of 1560-1960 kg/m³.
- In terms of contribution to the compressive strength by per unit weight of concrete, FA, FBA, and Lytag can be beneficially used to manufacture medium strength concrete.
- LWC incorporating FBA and Lytag resulted in an increase in the permeability; by replacing 30% of OPC with FA, the permeability of LWC could be improved.
- In order to manufacture durable LWC, measures should be taken to further improve the permeation property.

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