The performance characteristics of no-fines concrete in social housing

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The Performance Characteristics of No-fines Concrete in Social Housing

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1. Abstract

No-fines concrete (NFC) is an open textured cellular concrete obtained by eliminating either fines or sand from the normal concrete mix. The alleged advantages of this type of light weight porous concrete include its lower cement content (resulting in lower cost), lower density, lower thermal conductivity, no segregation and, better insulating characteristics, than conventional concrete.

This paper presents the results of exploratory work carried out to determine the performance characteristics of NFC as used in social housing units. The work includes both laboratory test and site investigations to identify the physical, thermal, visual and quality characteristics of NFC in cores taken from existing housing stock in Irvine, Scotland. The findings from the tests discuss the performance characteristics of NFC and highlight the nature of pores in NFC and, their influence on the heat loss through the external fabric.

Keywords: No-fines concrete, social homes, performance characteristics, pore structure, thermal performance.

2. Introduction

No-fines construction is a non-traditional form of construction adopted in the UK prior to 1980, to build a variety of house types. Scotland has about 33,000 no-fines homes, mainly in the social-housing sector, and these have the potential to suffer fuel poverty issues. These houses had their external walls constructed of concrete without fines. In theory, the absence of fines in these structures would lead to the formation of voids (air pockets and channels within the structure) which would act as insulation and prevent the flow of air, water and heat through the structure. Abadjieva and Sephiri (2000) identified NFC to have no capillary movement of water because of the large continuous pores and rough open textured structure.

This paper examines the performance characteristics of NFC from randomly selected no-fines homes, located in Irvine, Scotland (120mm diameter cores were made available as the housing association was fitting gas flues) and from panels cast in laboratory. The findings discuss on the characteristics of NFC and highlight the nature of voids in NFC, their influence on the heat loss through the external fabric.

3. No- Fines Construction in Social Housing

NFC is an open textured cellular concrete (Moss 1979). This structure is formed as a result of the absence of fine aggregate and lack of compaction (William and Ward, 1991). NFC panels are cast in-situ by pouring cement and coarse aggregate slurry from a height of 7.5 meters. Concrete construction (1961) identified that some builders casted NFC walls 7.5 meters high and 18 meters long. Moss (1979) pointed out the benefits of this approach through relatively low hydrostatic pressure of the NFC, creating even grading, eliminating segregation even when the materials are discharge from this height. Moss (1979) also indicated that fresh NFC compacts well inside formwork under its own weight and needs no mechanical compaction (Concrete Construction, 1961). The absence of fine aggregate in the mix is identified as advantageous by Concrete Construction (1961), as the mix cannot segregate and consequently it can be dropped from height. However, literature has not suggested a definite height on the casting of NFC walls since the level of compaction depends on the casting height and thus influences the percentage and nature of voids within the structure. However, questions arise as to the water cement ratio and the quality of workmanship. The ideal water cement ratio suggested by the Building Research Establishment (BRE) is 0.36 to 0.40: if the mix is dry, the cement-coarse aggregate binding would be lean. Concrete Construction (1961) noted the only compaction required in NFC construction is a light rodding to ensure the form is filled completely without bridges around obstructions. Height plays an important part in providing sufficient compaction by gravity alone. Discussion on the variations in the compaction of NFC walls leads to the issue of capillarity.

Maclean and Scott (1995) define capillarity as the tendency of water (or any fluid) to be sucked into a narrow space such as the tiny inter-connected holes of a porous material, or any close joint. However, in the case of NFC wall, Concrete Construction (1961) identified the nature of NFC construction to have relatively high proportion of inter-connected voids but practically no fine capillary pores. As the NFC wall is not compacted the structure of the NFC takes the form of the formwork leaving voids. In theory, the formation of each structure is dependent on each panel and its workmanship because the method of construction does not follow a standard criterion. If such is the case, it will be interesting to see if NFC has capillarity or not in practice; if so, is capillarity advantageous/ disadvantageous for NFC in terms of heat loss.

3.1 Physical Characteristics:

Physical characteristics relate to the sensory (physical) attribute of a substance and are generally measurable Maclean and Scott (1995). Abadjieva and Sephrir (2000) identified NFC as having a density of 1600 – 2000 kg/m³, and thermal conductivity of 0.7 W/mK: compared to dense concrete (k=2.0 W/mK). They also indicate NFC as having a relatively low drying shrinkage (one half of that of dense concrete) and a compressive strength of 1.1 to 8.2 MPa (after 28 days). The compressive strength of NFC depended mainly on aggregate – cement ratio, lower than the compressive strength of conventional normal weight concrete due to increased porosity (Cement and Concrete Association of Australia, 1999). Tensile and flexural strength of NFC are also considerably lower than those of conventional concrete Williams and Ward (1991); the highest strength is at aggregate – cement ration of 7:1 and decreases with an increase in aggregate – cement ratio (Abadjieva and Sephrir, 2000).

3.2 Thermal characteristics:

Focusing on capillarity and heat loss through the voids, the Centre for Sustainable Energy (CSE, 2005) pointed out concrete as a material, has an extremely low thermal resistivity, poor thermal performance and the poor u-values of the walls, eventually resulting in low SAP (Standard Assessment Procedure ratings) and high running costs. Good Practice Guide 183 (1996) has identified the u-value for a 250mm thick NFC wall with wet plaster finish to be 1.7 W/m²K, similar to a brick/cavity/brick wall. Good practice guide 183 (1996) also points out the influence the wall thickness of NFC has on the thermal performance of the wall (200 mm thick wall with an independent cellular core plasterboard lining achieves a u-value of about 1.1w/m²K and a 250mm thick NFC wall will have a u-value of 1.23 W/m²K). Wong *et.al*., (2007) indicated Air Permeability Concrete (APC) is similar to NFC but the main difference being the greater interconnectivity of voids in APC is achieved by manipulating aggregate sizing, cement paste, volume and the rheological properties of the fresh mix. It is useful then to consider the following characteristics of NFC to better understand and determine the void size and nature of the voids in NFC.

3.3 Visual Characteristics:

The Cement and Concrete Association (1999) see NFC as characterised by uniformly distributed voids and therefore it is not suitable for reinforced or pre-stressed concrete construction. However, within the literature there is little available material on the internal structure of NFC. NFC has not been well documented leaving little in the way to identify the internal composition of voids (are the voids interconnected or closed). Moss (1979) identified NFC as open cellular structures with large interconnected voids, depending on compaction by gravity alone and the property of cement mix for segregation. This research finds it useful to investigate the internal structure of NFC.

3.4 Quality:

Abadjieva and Sephrir (2000), and Willams and Ward (1991), observed NFC to exhibit little cohesion and no segregation, and can be dropped from a considerable height during placing. In relation to capillarity, the BRE report and Moss (1979) identified NFC to have no capillarity because of the open interconnected voids. However, Abadjieva and Sephrir (2000) pointed out that although NFC has no capillary action, because of the large size of continuous pores and rough open textured structure, high water permeability would be an issue to consider.

4. Methodology

To determine the performance characteristics of NFC, an exploratory research method was adopted. As very little literature was available on the performance characteristics of NFC, this research included both site investigations and laboratory work. The series of test performed for identifying the performance characteristics of NFC has been tabulated with the intended test results in table 1.

The goal of exploratory research is to learn "what is going on" and investigate the phenomena without explicit expectations (Russell, 2009). Kumar (2005) describes exploratory research helps in gaining information on a subject previously known little about and furthermore provides a platform upon which a formalise research project can be built. Versatility and wide range approach to the preliminary investigations are the main benefits of this genre of research (Russell, 2009). Punch (2005) suggests exploratory research can draw on interviews, observations, group interviews, secondary data sources and case histories. In relation to NFC, a literature review indicated that very little information has been delivered on the performance characteristics of NFC: in this case, site investigations and laboratory work was carried out to investigate the performance characteristics of the material as observed on site, and then tested in the laboratory.

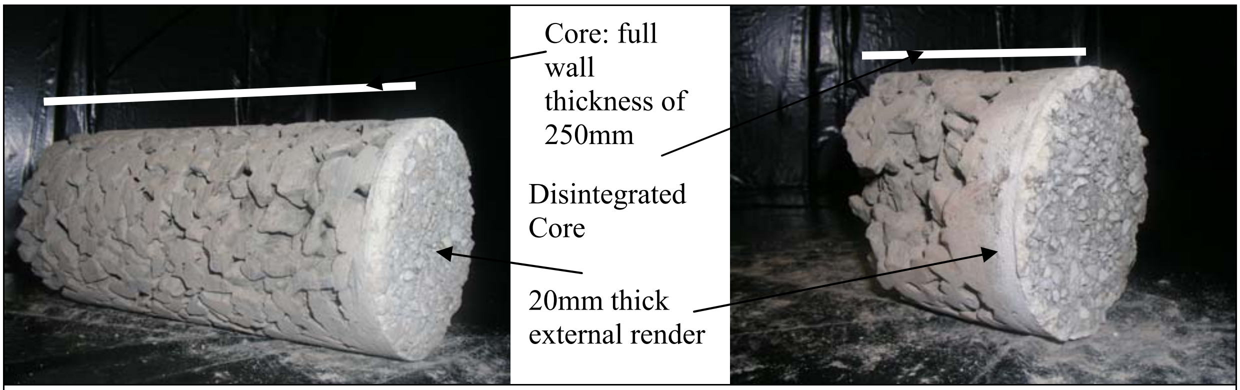
To evaluate the physical characteristics of NFC, both laboratory cast samples and cores from housing site were tested. The laboratory samples were 150mm cubes, made of river gravel as coarse aggregate and Portland cement in the ratio (6:1) and 0.45 water cement ratio. The cubes were cured for a 28 days period under water and were subjected to a series of tests (BS 1881-3:1970). Three nos. cubes were cast with one compacted and two un-compacted. To identify the volume of the voids in both the compacted and un-compacted NFC cubes, they were weighed in air and fully saturated with water. To determine the difference between what was done on site and what was quoted in the literature, NFC from the site was also tested (the sample cores were collected from the housing stock in Irvine, Scotland).

Table 1: Synopsis of test performed

Performance Characteristics	Test	Samples	Results
Physical	Density Compressive test Capillary rise test	3 nos. laboratory cast panels of which 2 nos. were not compacted and 1no. compacted. 3 nos. cores from site. 3 nos. laboratory cast panels (replicated samples) 3 nos. cores from site (replicated samples)	To determine the percentage of voids in compacted and uncompacted samples. Level of porosity between compacted and uncompacted samples To determine the nominal pore size.
Thermal	Heat flow meter	2 nos. lab cast panel of which one is compacted and the other not compacted. Note: separate samples of 300x300x100 (mm) were made to suite the instrument's requirements.	To identify the thermal conductivity of a compacted sample and compare it to an uncompacted sample and determine whether the voids act as air capsules.
Visual	Thermal imaging camera	Randomly selected samples from the Irvine housing stock	To identify cold bridging and heat loss.
Quality	Ultrasonic pulse velocity	The 3 nos. lab cast panels (replicated samples)	To determine the homogeneity, uniformity, internal flaws, cracks and segregation.

These cores are 120mm diameter and 250mm thickness (excluding the render coat). They were randomly collected from three different streets in Irvine and totalled to 20 nos. The cores collected were from both the ground and the first floor of different properties. As the cores obtained were not of full thickness (resulting from the nature of workmanship) refer to Figure 1, only three cores were suitable for the testing (according to BS2846 Part 4&5). These cores were collected from the existing stock (almost 40yrs old), and were stored at room temperature of 20º C and relative humidity 24%.

Figure 1: Nature of the samples:



Selected for testing	Rejected

To determine the thermal conductivity of NFC, 300 x 300 x 100 (mm) panels were cast to fit the FOX heat flow instrument. For the test, one panel was compacted with 35 strokes and the other un - compacted. The panels were cured for 28 days and tested in the heat flow meter. As the surface of the NFC panels were not smooth, cling film was wrapped over the panel. Temperature set points were set for ten differences and the average temperature difference being 12.5°C. The difference in the k-value signifies the influence of voids acting as air capsules.

Visual examination was carried out initially on site using a FLIR thermal imaging camera: the Infra-red (IR) images of the NFC properties in Irvine were taken to identify the performance of NFC walls from where the core had been extracted (to understand the composition of the wall from where the core had been extracted). From these initial investigations, the nature of voids was to be determined. The samples used for visual analysis were photographed using an Olympus 10 mega pixel camera and analysed based on their structure, cement aggregate mix, bonding and nature of voids. To determine the mean notional void radius and the porosity of NFC, capillary rise tests were adopted. The Concrete Society (2008), see the rate of absorption as providing a useful indication of the void structure of concrete. For this test three number cores were randomly selected as samples (according to guidelines within BS2846 Parts 4&5). It should be noted that the samples were restricted as the in-situ cores obtained from these housing sites disintegrated. It appeared (visually) that the external end of the wall was held with render/rough cast (refer to Figure 1) whereas the interior end of the wall disintegrated:

from a total of 20 samples collected only two cores were of full thickness. Reconstruction of these cores was considered as an alternative, but pouring resin to reconstruct these samples would affect the results, especially in relation to capillarity. For the test, the sides of the cores were sealed with cling film to eliminate evaporative flow from the sides adjoining the inflow face of the core; therefore ensuring flow is in one direction only (Concrete Society, 2008). The NFC core sample was placed on filter paper in a dish containing distilled water (of 10°C) to saturate the filter paper (Concrete Bridge Development Group, 2002). As the sample absorbed the water its mass increased, the increase in mass was recorded for different time intervals as was the rise of water. The data obtained was incorporated in Microsoft excel to identify the relationship between the depth of water ingress and void radius in relation to time. The notional void radius was calculated from the following equation (Concrete Society, 2008):

$d = \text{sqrt}\,(r^2 Po\ T/ 4\mu)$

Where, r is the radius of the void

Po is the atmospheric pressure (101.325 kP) and μ is the viscosity of water at 10°C (1.308 Pa.s)

To determine the porosity of the cores, the following formula was used (Horgan, 1999):

$\Phi = V_v / V_t$

Where, Φ is the porosity of the sample

V_v – volume of the void

V_t - total or bulk volume of the material

The Concrete Bridge Development Group (2002) identified the results from capillarity tests to be sensitive to the moisture content of the concrete at the start of the test. In order to overcome the influence of moisture content of the concrete, the exposed surface of the structure was placed in contact with the filter paper (as suggested by the Concrete Bridge Development Group, 2002). Working on a small sample, the findings of this study relate to the selected location of the sample stock, however the methodology for determining the void size and the influence of un-compaction on the void size/ porosity of NFC is applicable in a wider context.

To determine the quality of the NFC, an ultra-sonic pulse velocity test was adopted; Zeitun (1986) suggests the pulse velocity test is a useful quality control tool. For this test, the sample was placed on a uniform surface and the transducers (transmitter and receiver) were placed in contact with faces on the sample (opposite faces). Concrete Bridge Development Group (2002) mention that the ultra-sonic pulse generated from the equipment is transmitted through the NFC from the transmitter to the receiver: information recorded is the time taken by the pulse to pass through the NFC. Measuring the distance between the transmitter and the receiver, the ultra-sonic pulse velocity can be calculated. This result helps identify the homogeneity of the structure, uniformity in bonding, density, absence of internal flaws and cracks, segregation, and the level of workmanship.

5. Results and Discussion

5.1 Physical characteristics

To evaluate the physical characteristics of NFC, a comparison was made between the samples cast in the laboratory and samples cored from the site.

Figure 2: No-fines Samples

Sample 1: cast in laboratory in 150mm moulds	Sample 2: cored from site
	

Figure 2 illustrates the difference in the NFC structure of the samples made in laboratory and cored from sites. The laboratory samples were made of river gravel (rounded edges) as coarse aggregate and cores from the site were made of crushed whinstone (sharp edges): the densities of both samples are shown in Table2

Table 2: Densities of the samples

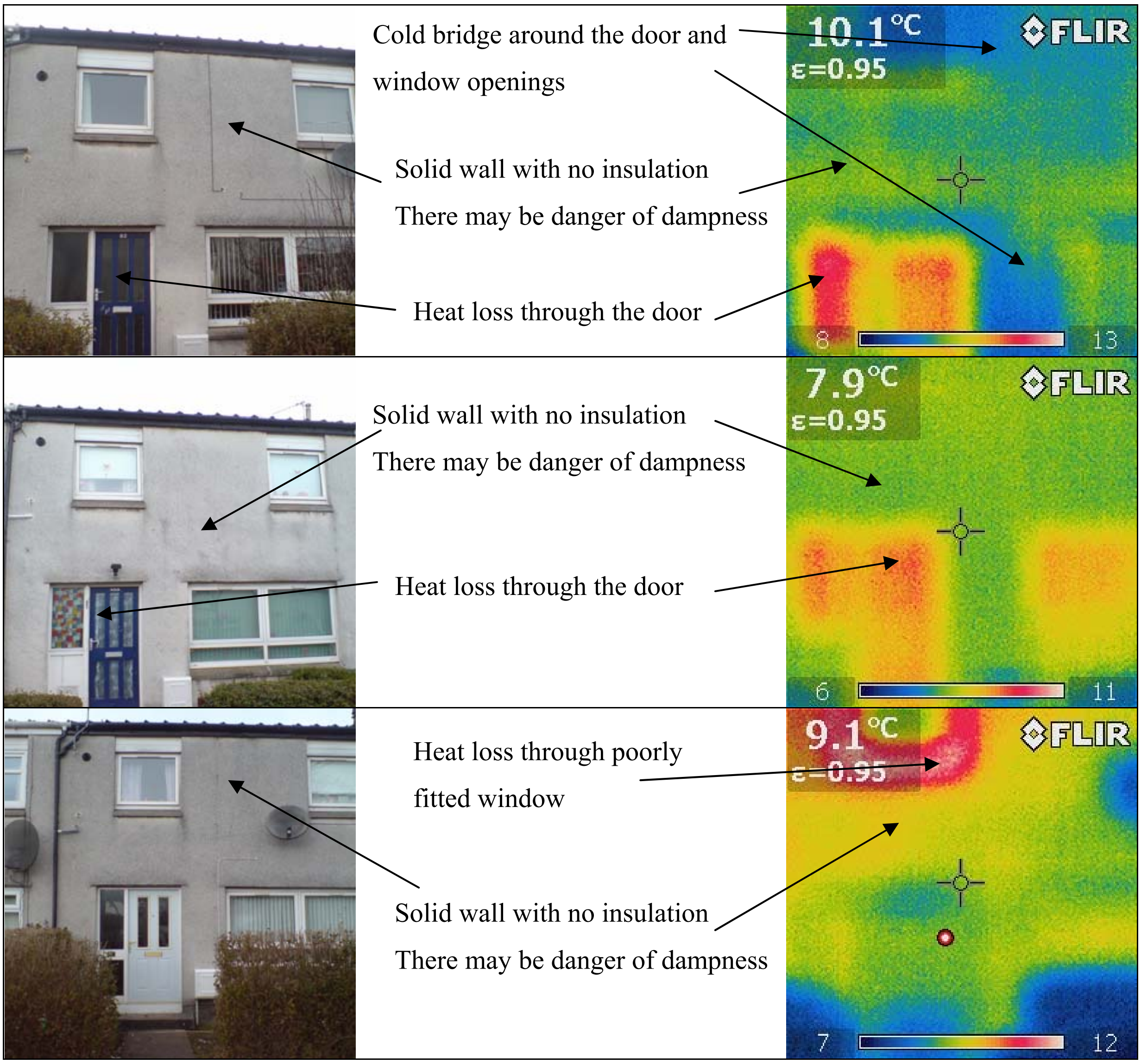
Sample	1	2
Density in air (D_{air}) kg/m^3	1542.51	1644.27
Density in water (D_{water}) kg/m^3	2479.00	2822.00

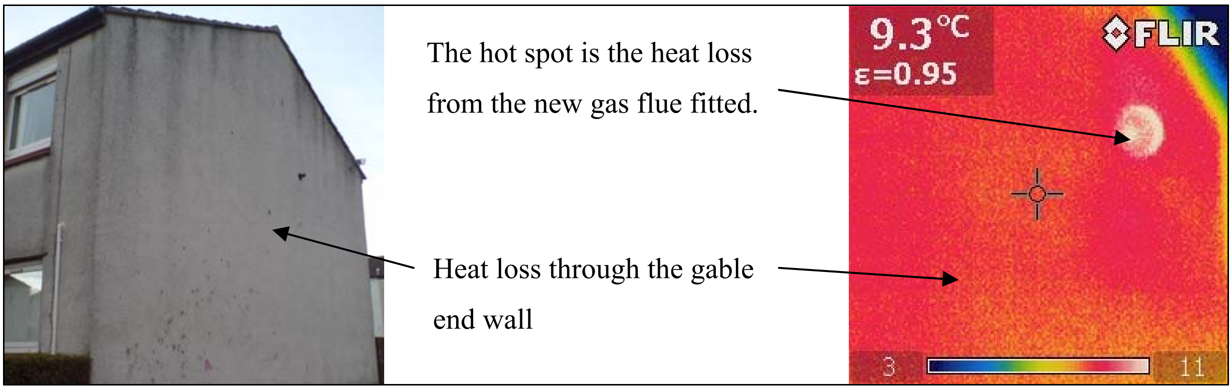
For both the samples, the saturated density is more than density in air: the voids filled with water and increased the total density of the samples. Relating the density of voids in each sample with the percentage of voids; sample 1 has 37% voids to the total density, and sample 2 has 66% voids. These results indicate the influence height of casting of NFC has on the structure of NFC i.e. the entrapment of air and thus the resulting voids or channels. To evaluate the difference in the structure of NFC, compacted and un-compacted lab-cast cubes were weighed. The compacted cube had 25% voids and the un-compacted had 37% of voids: demonstrating the effect compaction has on the structure of the NFC. The compressive strength was also calculated for the compacted and un-compacted cubes: compacted cube 8.8 N/mm^2 and the un-compacted cube 2.3 N/mm^2 , indicating the increased porosity of the un-compacted cube. To summarise, the structure of NFC is influenced by the nature of compaction (arising from the height of casting).

5.2 Thermal characteristics

To determine the thermal characteristics of NFC, thermal images of the NFC properties were taken. The Thermal Imaging Survey (2010) observed heat loss from buildings can be caused by a combination of drafts from poorly fitted windows and doors and or insulation integrity. The images shown in Figure 3 were taken from the NFC social housing in Irvine. These images were taken using a FLIR thermal imaging camera during the winter season (February 2010) at 15:00 hrs with an external temperature of 8° C. All the houses illustrated below were occupied and internal spaces heated.

Figure 3: Thermal images of existing NF housing stock, Irvine





**Note the difference in the cold bridging in the facade walls and the gable end walls.*

Having identified the nature of the NFC wall, the thermal conductivity of this material was calculated. Abadjieva and Sephrir (2000) identified the k-value for the NFC as 0.7 W/mK for coarse aggregate from Kgale hill quarry. As in-situ u-values of these properties required permission from the tenants (they will be conducted in winter 2010) NFC panels of dimensions 300x300x100 (mm) were cast in the laboratory to fit the FOX heat flow meter, and used to determine the k-value of compacted and un-compacted panels as indicated in Table 3.

Table 3: K-Value (thermal conductivity) of laboratory cast NF panels

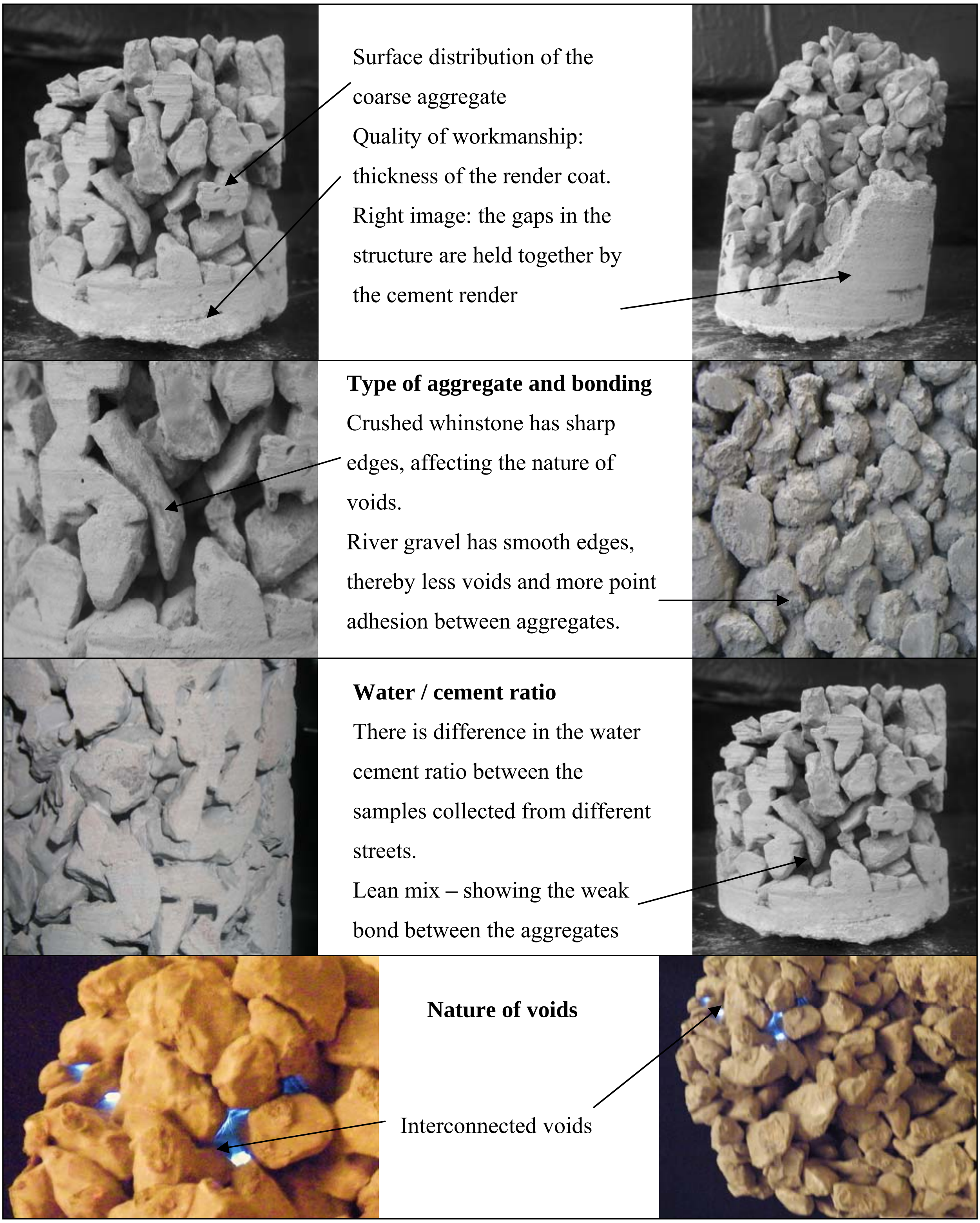
Sample	k-value (W/mK)
Compacted	0.4308
Un compacted	0.3521

From the results, it appears that un-compacted NFC has a better thermal conductivity than a compacted panel of the same coarse aggregate and cement mix and water cement ratio. However, it has a poor thermal performance level as a result of the elements (doors and windows) in the façade. It will be useful to determine the in-situ u-values from these properties to identify why NFC with a low thermal conductivity performs poorly on site; is it the homogeneity of the structure or the details in construction?

5.3 Visual characteristics

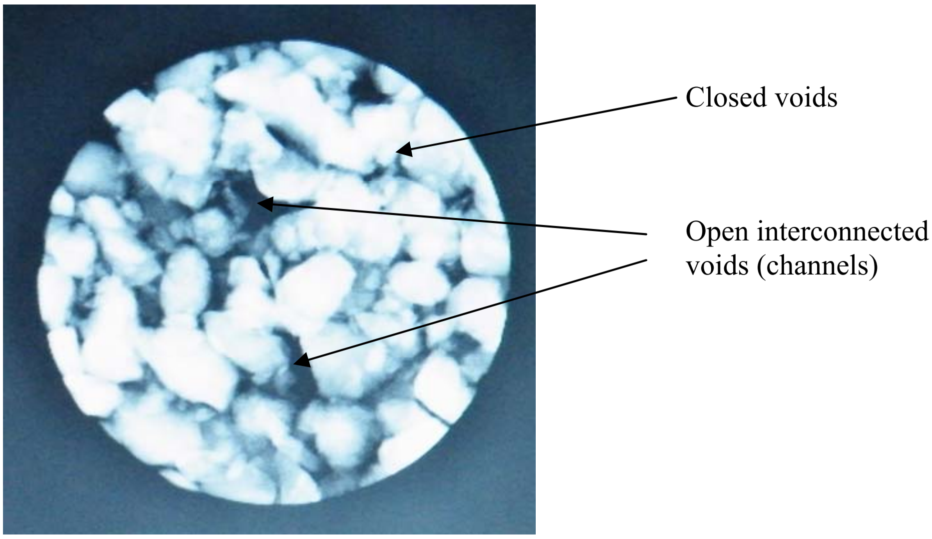
Very little has been documented on the appearance of NFC in terms of their bonding, the nature of voids and the effect of workmanship on the thermal performance of the wall. Figure 4 illustrates the structure of NFC and the nature of their voids.

Figure 4: NFC cores from the housing stock, Irvine: NFC cores of 120mm diameter.



For a clearer picture of the nature of voids in NFC, an x-ray of the section of the core was captured as can be seen in Figure 5.

Figure 5: X-ray image of NFC



NFC cores analysed show the cores have both closed and open voids. To identify the nominal void size of these NFC cores a capillary rise test was used (see Figures 6, 7 and 8). This section also discusses the relationship between the void size and depth of water ingress, in relation to time. It will also determine the porosity of the NFC cores and the percentage of voids in each core (refer to Figure 9).

Figure 6: The relationship between the depth and the nominal void radius of the Sample A is represented below

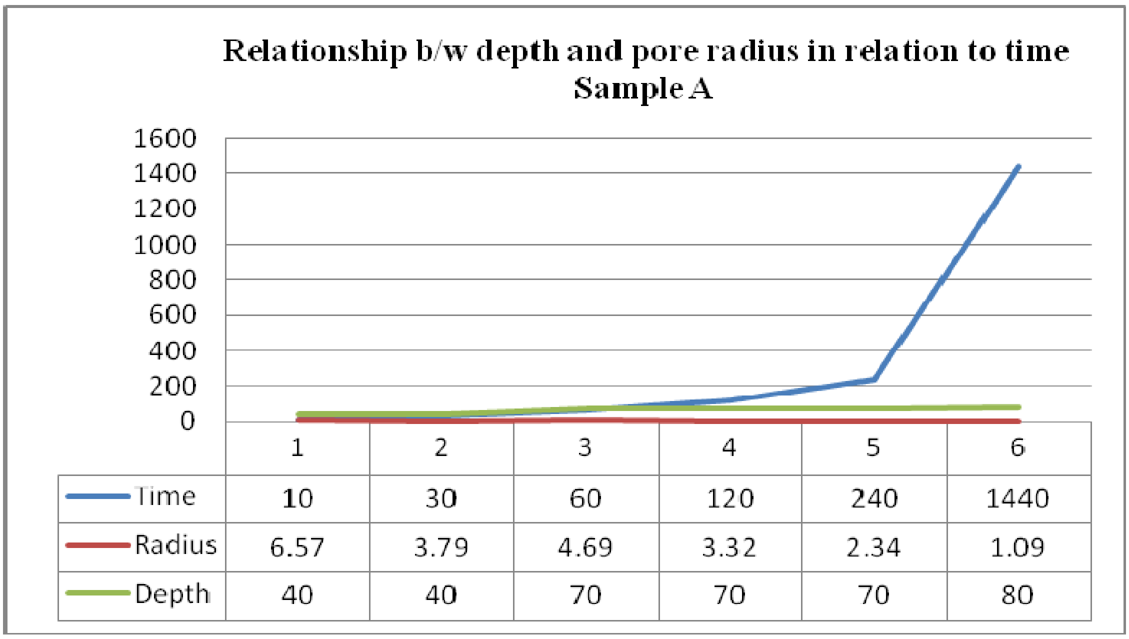
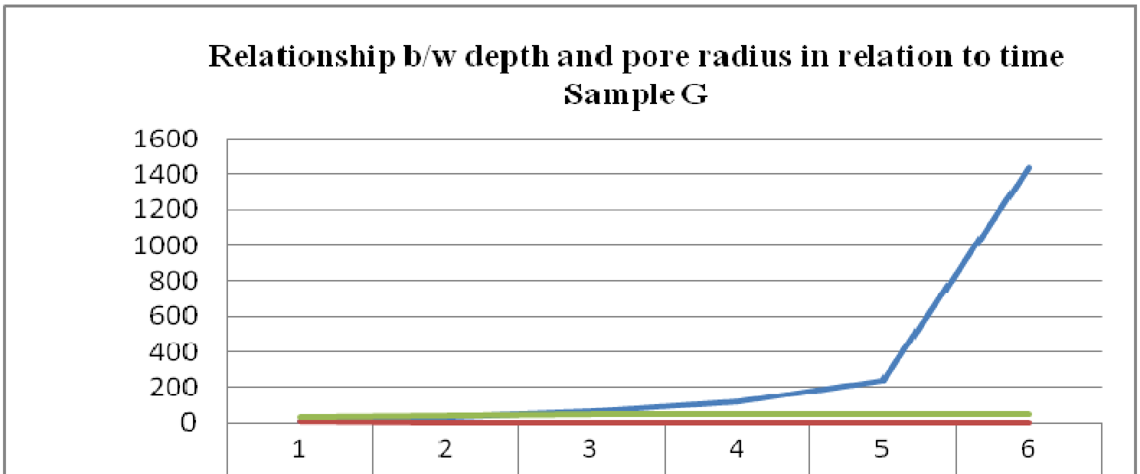
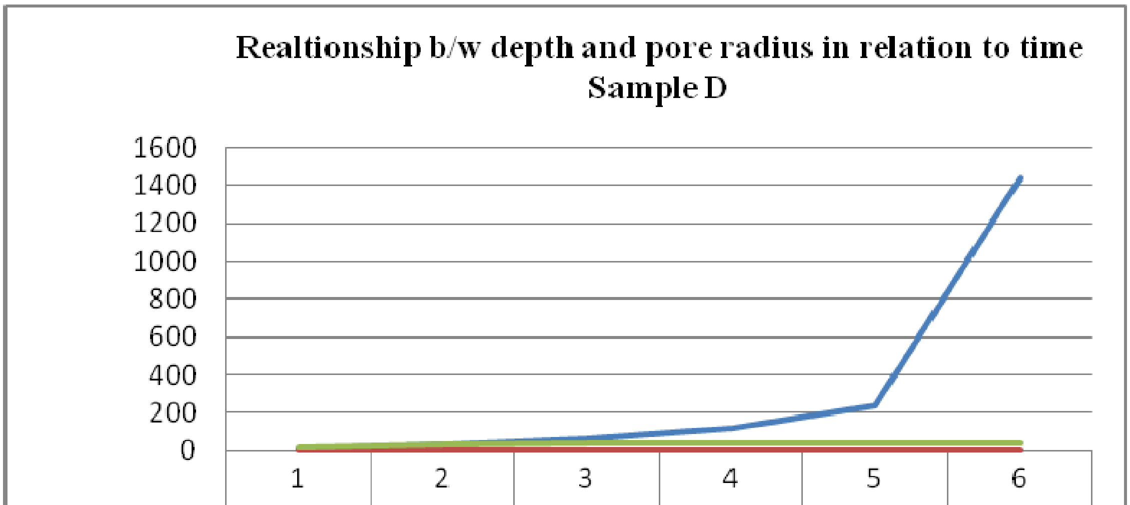


Figure 7: The relationship between the depth and the nominal void radius of the Sample G is represented below



	1	2	3	4	5	6
Time	10	30	60	120	240	1440
Radius	5.75	3.79	3.01	2.13	1.5	0.68
Depth	35	40	45	45	45	50

Figure 8: The relationship between the depth and the nominal void radius of the Sample D is represented below

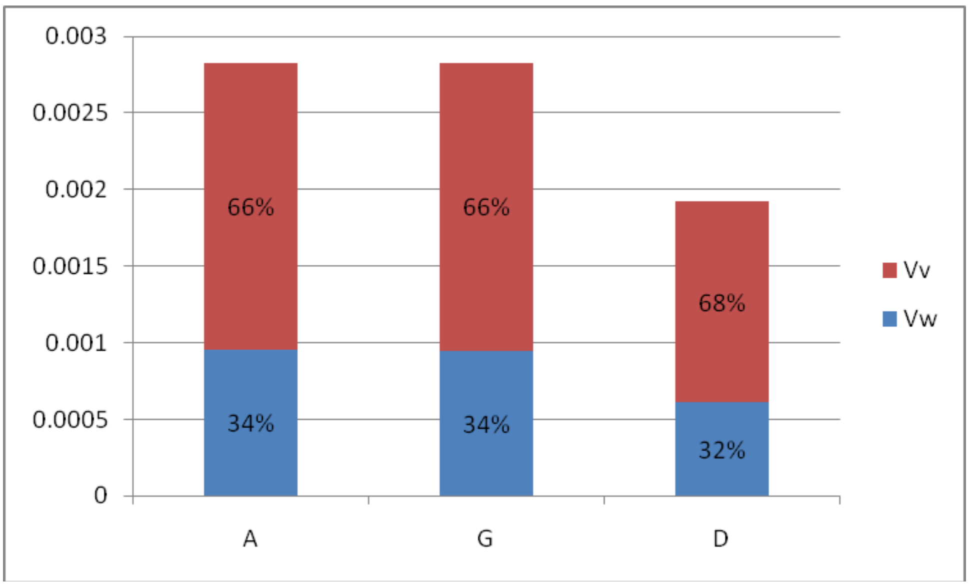


	1	2	3	4	5	6
Time	10	30	60	120	240	1440
Radius	3.28	2.84	2.68	1.89	1.34	0.54
Depth	20	30	40	40	40	40

From the graphs, the following relationship can be identified: as the time increases the depth of water penetration also increases but becomes constant after 60 minutes (for all the three samples). Secondly, as the depth of water ingress increases the void radius decreases, showing the interconnected voids are not continuous. If the voids are large and interconnected, the radius should either be constant or increase with the depth of ingress. However, as this structure was formed by compaction due to gravity, NFC has both open and closed voids. As identified by Wong *et al.,* (2008), the shape of the aggregate particles (the aggregate used was crushed whinstone) affect the packing structure and packing influences the fraction of space available for cement filling.

From the capillarity test, the nominal void size ranges from 1.89 and 6.57 mm for a 24 hrs period (refer to Figures 6, 7 and 8). Tavaman (1996) points out, when the diameter of the voids >1cm the effect of heat convection is significant and radiation between different interfaces within the material will become important when temperatures are well above ambient. Wong *et al.,* (2007) in relation to APC states that with void diameters between 0.5 and 5mm, that the material operates at / near ambient temperatures but the heat radiation and convection are negligible when considering static heat transfer in APC. In short, in relation to NFC with void radius ranging between 1.89 and 6.57 mm, heat is not lost through radiation or convection but static heat transfer. Wong *et al.,* (2007) mentions, since air is a poor conductor of heat (k=0.025W/mK at standard temperature), most of the heat will be conducted through the solid composite phase and it is thus reasonable to ignore conduction through air. In other words, compaction is not good for thermal performance of NFC and the air voids act as insulation capsules.

Figure 9: Illustration of the ratio of volume of voids (V_v) to the volume of the sample in water (V_w).



For all the three samples, the porosity level of the NFC cores was 0.66. Everett (1993) indicates the porosity of peat and clay to be more than 0.5 and for stones i.e. granite 0.01. To determine the percentage of the voids refer to Appendix 1.

The findings indicate that 66% of the NFC structure is composed of open and closed voids. The nominal void size is between 1.89 and 6.57 (mm) and these voids act as air capsules. Referring to the IR images of the NFC properties, heat loss is evident as a result of cold bridging around the doors and windows (William and Ward, 1991). It must be acknowledged that NFC in these properties are a single skin external shell with no insulation. To suggest further recommendations to improve the u-value of the wall, in-situ u-values of these properties must be calculated.

5.4 Quality:

The ultra sonic pulse velocity test was adopted to test the quality of NFC. This test was conducted to test the laboratory cast cubes for the homogeneity of the structure, uniformity, absence of internal flaws, cracks, segregation, and the quality of workmanship (see Table 4)

Table 4: Ultrasonic pulse velocity test results

ULTRASONIC PULSE VELOCITY TEST	
Compacted	Un-compacted
4.15	3.39
INFERENCE: a. This test helps us to identify the quality of the cube in terms of density, homogeneity, uniformity, absence of internal flaws, cracks, segregation and level of workmanship. b. In these terms Cube 1 is categorised as Good quality.	a. In these terms Cube 3 is categorised as Medium quality.

The results from this test indicate un-compacted NFC to have a medium quality in comparison to the good quality of the compacted NFC cubes. Concrete bridge development group (2002) pointed out the ultrasonic pulses do not travel through air and thus voids and cracks in the NFC structure can be detected through this method. In relation to un-compacted cube, as the NFC structure has 37% voids, the ultrasonic pulses had to travel around the air filled voids, so the transit time was longer in the un-compacted NFC than in the compacted cube.

6. Conclusions

NFC is an open textured cellular concrete obtained by eliminating fines/ sand from the normal concrete mix. Tests conducted to analyse the physical characteristics of NFC indicated the product has a density of 1500- 1600 kg/m^3. The cores from the NFC housing sites had 66% of voids compared to the laboratory cast cubes of 37%. It can be suggested that the casting height of the NFC influenced the level of compaction and thereby the percentage of voids. Comparing the percentage of voids between compacted and un-compacted laboratory samples, the un-compacted sample had 37% voids and the compacted sample had 25% voids. In short, demonstrating the effect compaction has on the structure of NFC. The compressive strength calculated through crush tests indicate the compacted cube to have a compressive strength of 8.8 N/mm^2 compared to 2.3N/mm^2 for the un-compacted sample. Test results indicate NFC to have a cellular structure with open and closed voids between the sizes of 1.89 – 6.57 (mm) and it was also observed that NFC does not have capillarity.

Thermal images of the properties indicate the performance level of the NFC wall and highlighted the problem areas in the wall. For detailed analysis, the thermal conductivity was calculated in the FOX heat flow meter. The results suggested the k-value of the un-compacted panel to be lower than the compacted panel of the same coarse aggregate-cement mix and water/cement ratio. Discussing the quality of NFC and the level of workmanship, ultra-sonic pulse velocity tests graded NFC (un-compacted) under medium quality: NFC as a construction material has good thermal conductivity but is of medium quality in terms of homogeneity of the structure and quality of workmanship.

Relating the results to the existing NFC housing stock, this research recommends future work in evaluating the in-situ u-values of NFC properties. Also, the thermal performance of NFC walls with different insulation materials requires to be investigated e.g. polymers. Similarly, the cost factor in refurbishing NFC homes to low carbon homes and the indoor quality of life and air in the NFC homes needs further investigation.

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Appendix 1: Test results from the laboratory to determine the porosity of the samples and the percentage of voids in each core

Sample no:	Density (in air) kg/m³	Density (water) kg/m³	Volume (void) Va-Vw m³	Density (void) Dw-Da kg/m³	Saturated Mass kg	Porosity Φ = Vv/ Vt	Percentage of voids
A	1644.27	2822.00	0.001871232	1177.73	4.69	0.66	66%
G	1633.66	2814.00	0.00187973	1180.34	4.65	0.66	66%
D	1348.95	2508.00	0.001305965	1159.05	2.60	0.68	68%