BUILDING ON A PERFORMANCE RELATED APPROACH TO USE NORMAL WEIGHT AGGREGATES IN CONCRETE: RECYCLED AGGREGATE

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ABSTRACT. This paper builds on research and development projects undertaken and published in several papers by the authors on the use of recycled and manufactured aggregates during the past 15 years. This paper compares strength, load-dependent and load-independent deformation characteristics of concrete made from normal-weight, natural, recycled and manufactured aggregates. The main aim of the paper is to promote the work that has and continues to be undertaken regarding a performance related approach of all normal-weight aggregates within the framework of BS EN 12620, the United Kingdom aggregate standard. Thereby having the implication of removing the stigma commonly associated with the recycled and manufactured materials.

Keywords: Normal Weight Aggregates, Recycled Aggregates, Performance Related Approach, BS EN 12620, EN 206

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INTRODUCTION

Aggregates for use in concrete applications typically account for approximately 40% of this product demand. Due to the depletion of natural aggregate reserves in some countries this demand is being increasingly met through the use of recycled and manufactured aggregates (RMA). This is being further driven by increasingly stringent environmental and land use regulations in some countries. Nevertheless, the use of RMA in concrete remains low. The use of RMA in concrete in Europe is permitted by EN 12620 which classifies aggregates as natural, recycled or manufactured. Examples of recycled and manufactured aggregates are provided in Table 1, which can be classified as normal weight aggregates.

- Natural aggregates are from mineral sources and subject to nothing more than mechanical processing,
- Manufactured aggregates are of mineral origin resulting from industrial process involving thermal or other modifications, and
- Recycled aggregates result from the processing of inorganic material previously used in construction.

Table 1 Examples of types of recycled and manufactured aggregates.

RECYCLED	MANUFACTURED	NATURAL
Recycled Concrete Aggregate	Recycled Glass	Slate aggregate
Recycled Aggregate	Blastfurnace slag	China Clay Sand
Recycled Asphalt	Steel slag	Colliery Spoil
Recycled Asphalt Planings	Pulverized fuel-ash	Oil Drill Cuttings
Spent rail ballast	Incinerator bottom ash	
	Sewage Sludge Ash	
	Furnace bottom ash	
	Used Foundry Sand	
	Spent Oil Shale	
	Recycled Plastic	
	Recycled Tyres	

The use of recycled concrete aggregate (RCA) and recycled aggregates (RA) in concrete have been extensively researched [1]. In general, if RCA and RA are used appropriately, taking into account their respective physical and chemical properties, then they can be used in concrete for most environmental exposure conditions [2,3]. The effect of other manufactured aggregates on the performance of concrete has not been concisely amalgamated; presumably because of the much wider range in performance.

Although the use of RMA in concrete is permitted by EN 12620, there is currently no guidance on how RMA should be used in concrete. A classification system for recycled aggregates based on constituents is given that requires users to determine the crushed concrete (RC), crushed masonry (RB), unbound stone (RU), crushed asphalt (RA), and crushed glass (RG) contents, in addition to determining the mass of floating and non-floating stony material. However, there is no methodology by how these categories should be used either alone or in combination to assist with appropriate selection of aggregates, nor any research to demonstrate whether recycled aggregate meeting a specific category provides a given level of performance. Therefore, it is currently unclear how these categories should be used.

As an alternative to a composition based classification system, Paine and Dhir [4] have suggested a methodology based on performance related properties which has shown that the effect of a given recycled aggregate on the strength, deformation characteristics and durability performance of concrete can be ascertained through knowledge of the aggregate's: (i) Los Angeles coefficient, (ii) particle density, (iii) water absorption, ≤ 3.5% and (iv) drying shrinkage value, as determined by standard European test methods [3-6].

Although BS EN 12620 specifies no upper limit on aggregate density, BS EN 206 (BSI, 2013a) classifies normal-weight aggregates to have oven-dry particle density ranging from 2000 kg/m3 to 3000 kg/m3. Consequently, aggregates with an oven-dried particle density between 2000 and 3000 kg/m3 may be classified as normal-weight aggregates.

The research described in this paper builds and improves on the database of research published in 2015 "Establishing rational use of recycled aggregates in concrete":[5] represents work to: (i) investigate whether it can be used or broadened to cover the use of the whole family of normal-weight coarse aggregates permitted by EN 12620 for use in concrete.

MATERIALS AND METHODOLOGY

Two aggregates were added to the existing research database [4] to strengthen the range of aggregate characteristics regarding normal weight coarse aggregates and performance related approach. They help to reflect the range of differences in shape, texture, porosity and flakiness of commonly used normal weight aggregates. Carboniferous limestone was used as the natural aggregate. The second aggregate was a recycled aggregate and when its compositions was assessed it was classified as RCA under BS 8500-2. These aggregates were characterised in accordance with BS EN 12620 and BS 812 with respect to aggregate impact value (AIV) in order to examine the geometrical, physical and chemical properties. The aggregates were used to produce concretes with a range of w/c ratios (0.35, 0.50 and 0.70) and recycled and manufactured aggregate replacement levels were 25, 50 and 100%. Detailed mix design methodology is provided in previous published research [5].

Standard or otherwise well-established tests were carried out to examine the main engineering properties of concrete: compressive strength (BS EN 12390-3), static modulus of elasticity (BS 1881-121), drying shrinkage (BS EN 1367- 4), and basic/creep (established test method at University of Dundee) [6].

CONCRETE PROPERTIES

Compressive strength

The effects of normal weight aggregate on the compressive strengths of concrete is illustrated in Figure 1. The data in Figure 1 represents the mean values of three w/c ratios for each concrete given as a percentage value, the natural gravel concretes compressive strength is used as the 100% base point, indicating the range and effects that normal weight aggregates have on the compressive strength of concrete. The natural gravel concrete was used as it is a mid-range normal weight aggregate. The range of compressive strength is not surprising given the range of the normal weight aggregate properties, similar findings have been reported by Alexander and Mindess [7].

Investigating equal strength concretes of 40 N/mm² from NG and RA1 at 100% replacement concretes are shown in Figure 2. This illustrates the different w/c ratio's that are required to achieve the design strength shown by the vertical lines, RA1 requires a w/c ratio of 0.41 and NG a w/c ratio of 0.57. Evidently, this indicates the effect aggregate type/properties have on the compressive strength of concrete. As the quality of the aggregate deteriorates, a clear reduction in compressive strength is observed, similar findings were reported [8, 9].

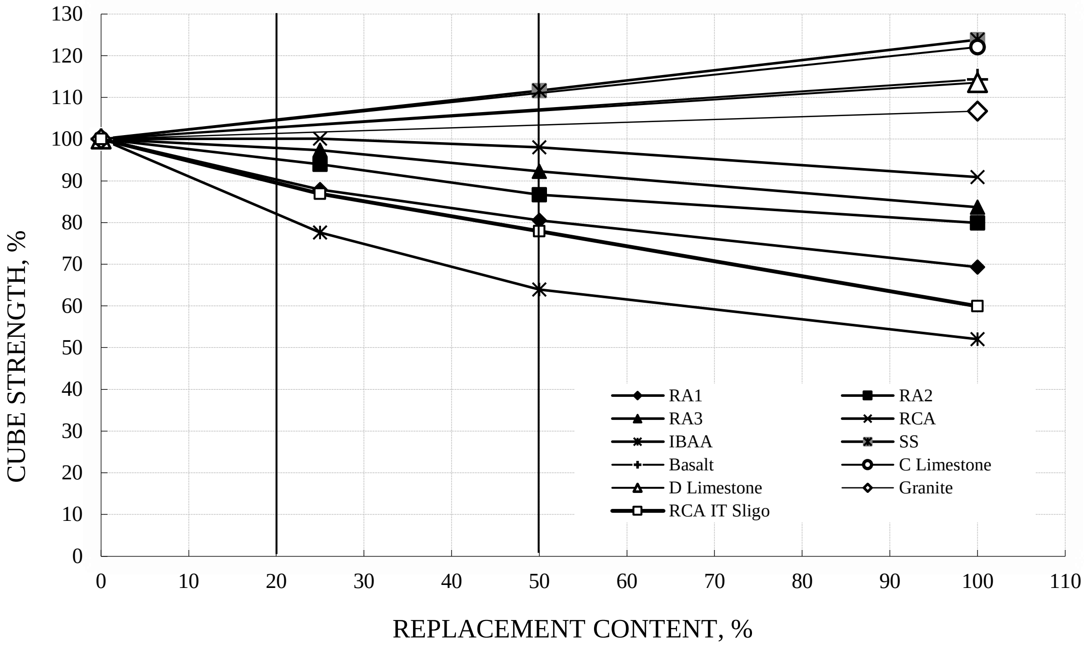

Figure 1 Cube strengths for range of normal weight aggregates as a percentage compared to base natural gravel aggregate concrete

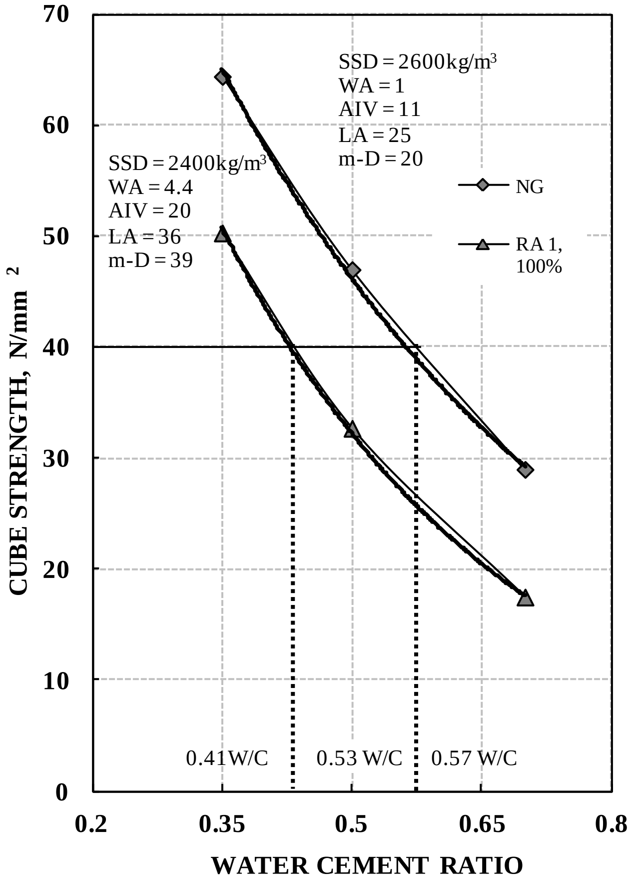

Figure 2 illustrates the effect that coarse aggregate properties have on the w/c ratio design curve

Modulus of Elasticity

Aggregates are reported to have the greatest effect on modulus of elasticity of all the constituents of concrete [10,11 and 12,]. The width and depth of the hysteresis loop, which is used to calculate the modulus of elasticity, is affected by the strength and age of the concrete, together with the volumetric content of the coarse aggregates within the concrete. All concretes assessed in this research have similar coarse aggregate volumetric contents (41% to 43% of all the constituents for the concretes) therefore variation in modulus of elasticity values is dependent on the coarse aggregate characteristics.

Considering the nature of modulus of elasticity and the range of characteristics of normal weight aggregates, consequently, assortment of modulus of elasticity values was expected within this research. The effects of three aggregate properties – aggregate density, water absorption and Los Angeles Coefficient for three water cement rates are presented in Figure 3. As the aggregate properties deteriorate, reduction in modulus of elasticity is recorded, similar findings were reported [13,14 and 24].

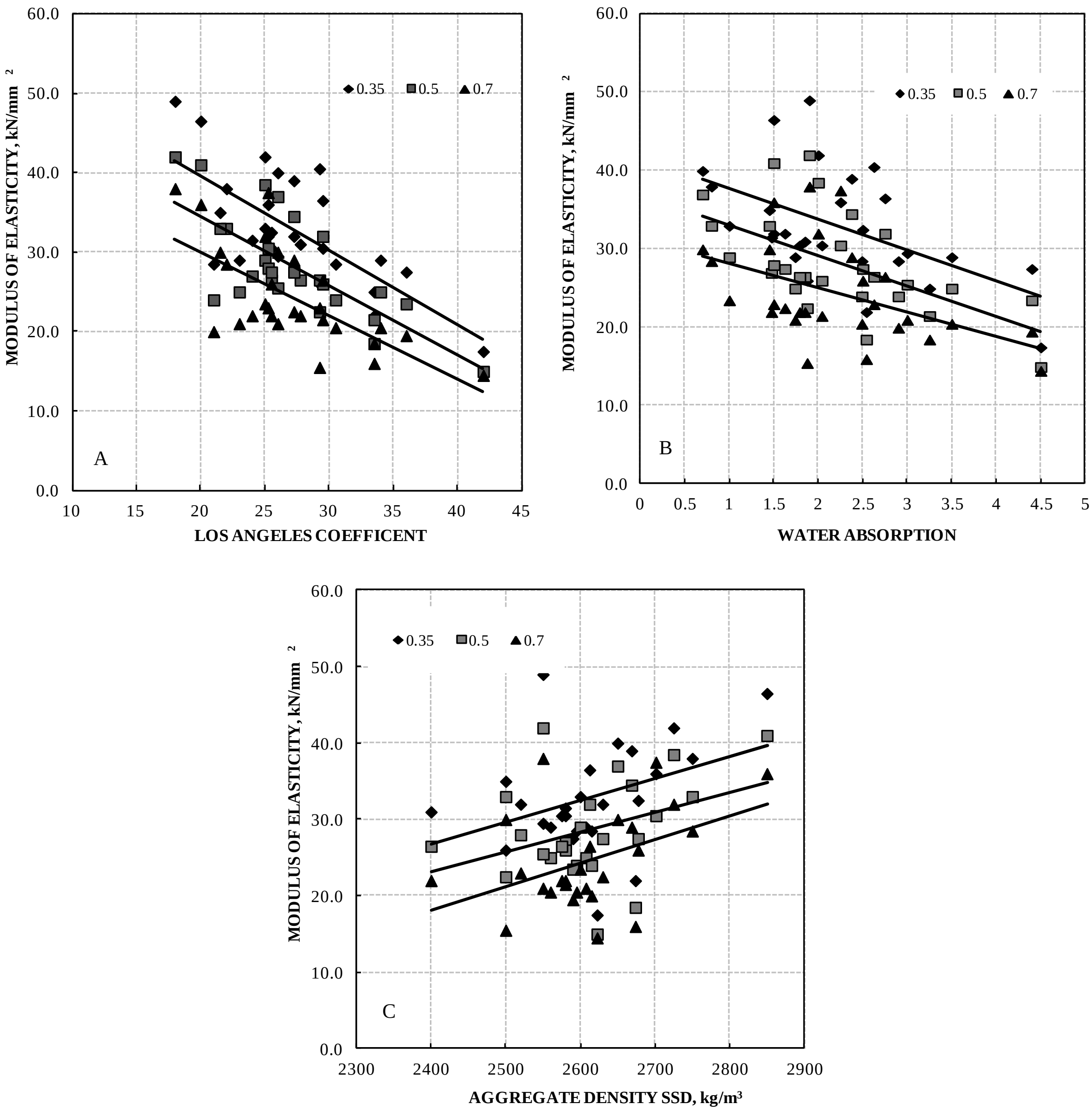

Figure 3 Correlation between aggregates properties and the modulus of elasticity for concretes

Creep of concrete

Concrete creep is influenced by mixture proportions, type of aggregate, age of loading, aggregate volume content, cement content and w/c ratio [16]. All concrete specimens were tested after 28 days water curing. All concretes were loaded to 40% of 28-day cube compressive strength.

Researchers have reported that lower grade normal weight aggregates (RA) increase creep in concrete compared to higher grade normal weight aggregates (NA) concretes [17, 18, 19 and 20]. This can be attributed to RA containing bricks, masonry rubble, wood and other impurities. With a low modulus of elasticity of aggregates, a lower modulus of elasticity of the corresponding concrete will result, therefore, giving a lower resistance to creep formation of the concrete. The results presented in this research show that as the inferior aggregate replacement level increases, a corresponding increase in creep strain is evident (Figure 4).

Two types of graphs are illustrated in Figure 4, these are creep strain and creep coefficients. The creep coefficient is calculated as creep strain divided by the initial elastic strain. Examining the results given in Figure 4, the creep strain gives similar trends to that of the modulus of elasticity for the same concretes, showing that a relationship between these two engineering properties exists. This may be expected as the modulus of elasticity of aggregates contributes to the modulus of elasticity of the concrete and helps restrain the cement paste from undergoing creep, indicating that in general the higher the modulus of elasticity of concrete the lower the creep strain.

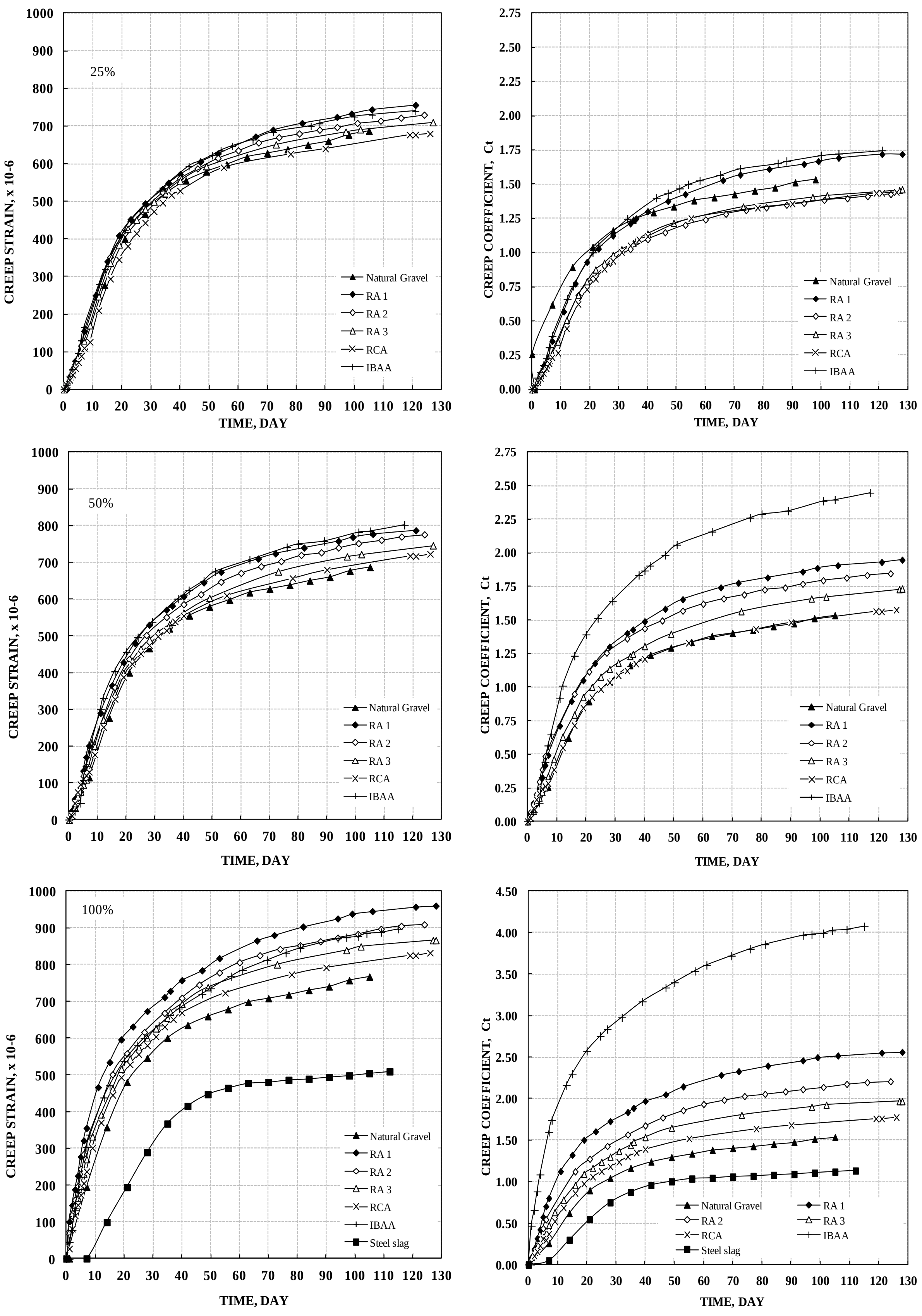

Figure 4 Creep strain and creep coefficient of normal weight aggregate concretes

PERFORMANCE RELATED APPROACH FOR NORMAL WEIGHT AGGREGATES

Data within this research database has shown the wide range of aggregate properties that can be categorised as normal weight aggregates. However, only the upper limits of these normal weight aggregates are commonly used for aggregates in concrete. The current specifications BS EN 206-1. Specification for constituent materials and concrete (BS 8500-2- UK) classifies many normal weight aggregate as recycled aggregates. It is generally assumed, that as a result the performance of concrete containing recycled aggregates can vary significantly. Thus, to ensure satisfactory concrete performance, specifications are strict on the composition of recycled aggregates that may be used.

However, research has shown that it is possible in many circumstances to satisfactorily use normal weight aggregate (lower limits) not meeting the current specifications in BS 8500-2 [4, 9, 21 22 and 23]. A proposed approach, which may encourage wider use of normal weight aggregate and promote sustainability, is to base selection of aggregates on performance-related characteristics that relate the properties of aggregates to concrete performance across the whole range of normal weight aggregate quality, independent of constituents and source.

The concept is to use aggregate categories given in EN 12620 (Aggregates for concrete) to estimate w/c ratio for a design compressive strength based on the aggregate property/category. Aggregates for concrete (EN 12620) specifies the properties of aggregates for use in concrete and specific categories for different aggregate properties. Given this approach, normal weight aggregates that are currently not fully specified for use in BS 8500, may be classified and considered for relevant applications. This should remove the main technical barrier that is preventing the uptake of wider range of normal weight aggregates in concrete, and lead to greater confidence in specifying and use of these materials.

Aggregate characteristics were measured in order to assess if the engineering properties of concrete could be predicted from knowledge of these characteristics. Five aggregate characteristics were examined: aggregates particle density, Los Angeles coefficient, micro-Deval coefficient, aggregate impact value, and water absorption. The use of these aggregate characteristic categories was assessed to ascertain if these could be integrated into concrete design, to give reasonable approximations of compressive strength for a designed concrete (Figure 5).

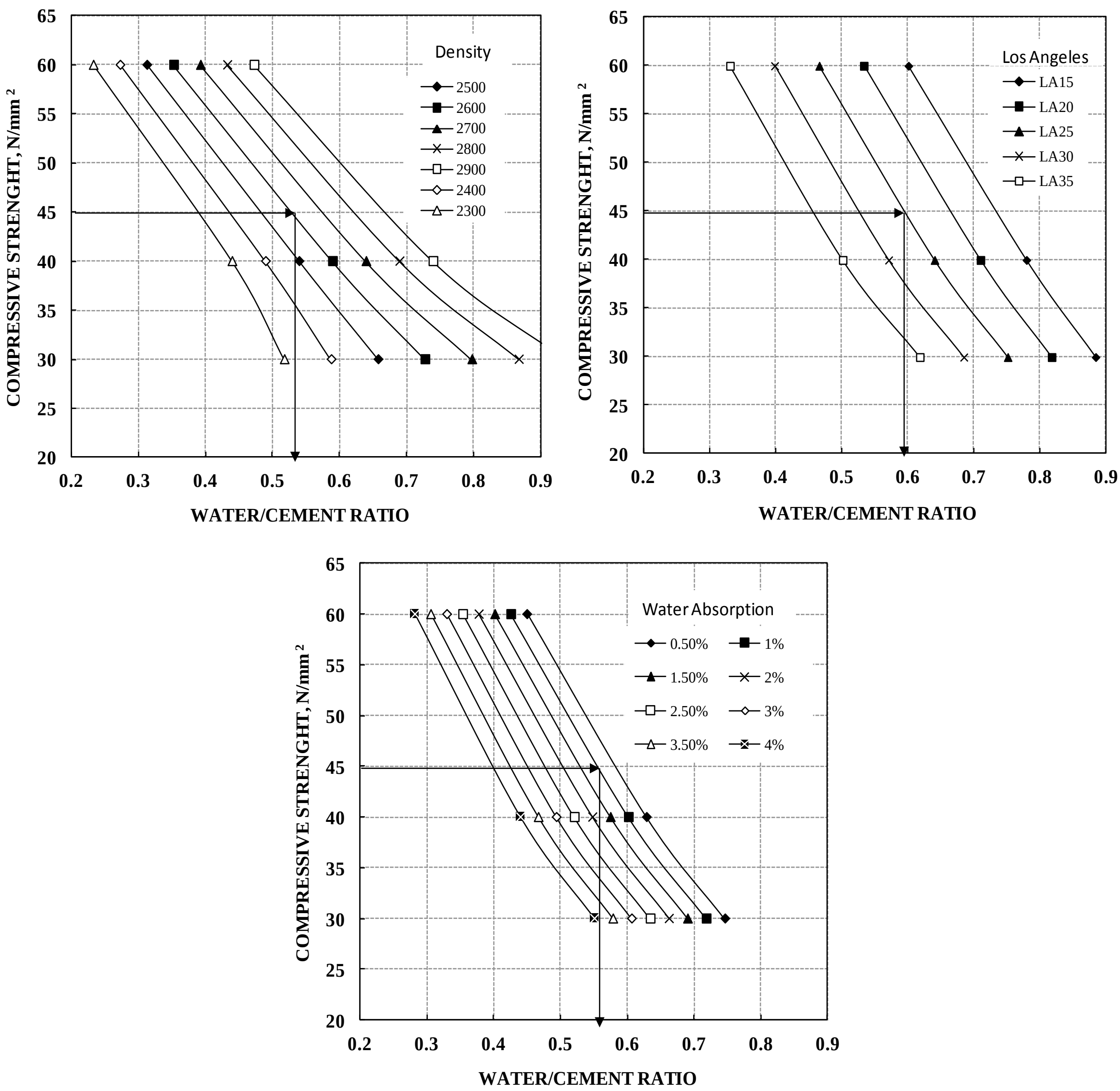

Figure 5 The w/c ratios obtained from different aggregate properties required to achieve 45 N/mm^2 concrete (A) Density, (B) Los Angeles, (C) water absorption

The following is a step by step method of how aggregate characteristic categories can be integrated into concrete mix design.

- Three compressive strengths were chosen at 30, 40 and 60 N/mm^2 to assess the w/c ratio for each aggregate concrete.
- The w/c ratios required to achieve the design strengths (30, 40, or 60 N/mm^2) were graphed against corresponding aggregate properties and a linear regression line was used to determine their relationship.
- The w/c ratios relating to the different characteristic categories were calculated using the liner equation for the three compressive strengths.
- The three w/c ratios calculated for 30, 40 and 60 N/mm^2 concretes for the aggregate characteristic categories are shown in Figure 7.
- Figure 5 gives knowledge of aggregate characteristic categories given in BS EN 12620, the appropriate w/c ratio can be chosen for a required compressive strength of concrete based on the aggregate property.

On all three graphs illustrated in Figure 5, horizontal and vertical lines are shown, these lines represent the design of a concrete with a compressive strength of 45 N/mm^2 with a coarse aggregate similar to natural gravel. The natural gravel properties are used to determine the appropriate design line therefore the w/c ratio required to achieve design strength. The 0.53 w/c ratio was the lowest given by aggregate particle density for all the aggregate properties. This indicates that 45 N/mm^2 concrete can be produced with w/c of 0.53 with NG coarse aggregates used in this research, demonstrating how aggregate properties can be incorporated into concrete design. The actual w/c ratio that would be required for 45 N/mm^2 is 0.53 as indicated in Figure 2, indicating a good correlation between design and actual values. This should remove the main technical barrier that is preventing the uptake of lower grade normal weight aggregates in concrete, and lead to greater confidence in specification and use of normal weight aggregates in concrete.

CONCLUDING REMARKS

This research and previous research published by the author's report has shown that:

- Normal weight aggregates have a range of effects on concrete performance, however this can be predicated by the use of classifications used in BS EN 12620.

Consequently, it is clear that all normal weight aggregates, regardless of origin, are part of a broad family that may be treated in a similar way with respect to predicting the performance of concrete. Subsequently, a proposed approach is to base selection of aggregates on performance-related characteristics that relate the properties of aggregates to concrete performance across the whole range of normal weight aggregate quality, independent of constituents and source.

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