Coventry University and
The University of Wisconsin Milwaukee Centre for By-products Utilization,
Second International Conference on Sustainable Construction Materials and Technologies
June 28 - June 30, 2010, Università Politecnica delle Marche, Ancona, Italy.
Main Proceedings ed. J Zachar, P Claisse, T R Naik, E Ganjian. ISBN 978-1-4507-1490-7
http://www.claisse.info/Proceedings.htm

Use of Recycled Demolition Aggregate in Precast Concrete Products

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ABSTRACT

The potential for crushing construction and demolition waste (C&DW) to produce 'recycled demolition aggregate' in order to replace quarried aggregate in the manufacture of a range of precast concrete products has been investigated. The manufacturing process of concrete building blocks and paving blocks has been replicated in the laboratory using a specially modified electric hammer mounted onto a vibrating table. The 'wet' casting technique used by industry for making concrete flags has been successfully replicated in the laboratory using an appropriately modified cube crushing machine. Replication of the industrial processes enabled the effect of recycled demolition aggregate on the mechanical properties to be carried out in a laboratory. Levels of replacement of quarried aggregate with recycled demolition aggregate were determined that did not have significant detrimental effect on their physical and mechanical properties. An increase in the cement content was therefore not required for recycled demolition aggregate products.

INTRODUCTION

In 1991 the European Commission initiated the Priority Waste Streams Programme for six waste streams. One of these was construction and demolition waste (C&DW) [Aggregates Advisory Service 1999]. The inert fraction or 'core' C&DW, which is essentially the mix of materials obtained when an item of civil engineering infrastructure is demolished, i.e. the fraction derived from concrete, bricks and tiles, is well suited to being crushed and recycled as a substitute for newly quarried (primary) aggregates for many potential uses. This core C&DW amounted to around 180 million tonnes per year in the EU, corresponding to 480 kg/person/year [Symonds Group Ltd 1999]. It was estimated that only about 28% was at the time re-used or recycled. Land filling of the other 72% would require the equivalent of landfill 10m deep and roughly 13 square km in surface area every year. It was estimated that 20 million tonnes of C&DW arose in 1980 which rose to 70 and 109 million tonnes in 1999 and 2004 respectively. Of course it is recognised that the recycling rates have increased since 1999. However, a major part of this waste stream still ends up in the landfill sites for use in temporary roads and is thus lost as a potential substitute for high value end applications which currently use quarried aggregate. An attempt to address the environmental costs associated with quarrying has been the introduction of the Aggregates Levy in April 2002 [Office of the Deputy Prime Minister 2000].

The study at the University of Liverpool, which was carried out between 2004 to 2008, investigated the use of crushed C&DW, i.e. recycled demolition aggregates, in the production of precast concrete products, e.g. concrete building blocks, paving blocks and flags. In addition to investigating the technicalities of producing concrete using recycled demolition aggregates, the economics and practicalities involved have also been studied. The project has set up a network that encompasses demolition contractors, Waste Collection Authority (WCA) and Waste Disposal Authority (WDA), councils and precast concrete product manufacturers. The project developed definitive designs and specifications for the reuse of demolition waste for high quality building products. Investigations of the extent to which a selection of high performance precast concrete products can be produced using recycled demolition aggregate in place of quarried materials is continuing.

CURRENT MARKET SITUATION

The market for precast concrete products, in the UK and elsewhere, is very competitive with large multi-national companies, that generally also own quarrying operations, dominating the sector. Aggregates are costly to transport and therefore most manufacturers have been faced with a choice between being located close to the raw materials or close to the market. It appears that in the majority of cases the decision is to have the precast factory close to or even at the quarry site. In addition to the low value grey precast concrete products, most manufacturers produce a speciality range of more expensive architectural products. These tend to be specific to the manufacturer and are sold nationally. Despite the wide variety of precast concrete products that are manufactured, the standard 'grey' products dominate sales. However, due to the much lower profit margins, the standard precast concrete products are only sold regionally; within a radius of 30 miles of the precast factory because of transportation costs. Construction statistics by the UK Department of Trade and Industry (DTI) indicated that approximately 360 million building blocks were produced annually in 2005 [Department of Trade & Industry 2003]. The estimated aggregate consumption can be based on the assumption that 90% of each block is aggregate, i.e. aggregate consumption is 3.6 million tonnes per year. A single precast factory can use up to 500 tonnes of aggregate on a single day. Based on the construction output in North West England being approximately 10% of the total output [Department of Trade & Industry 2003], it is estimated that 360,000 tonnes of aggregates are needed annually for the production of building blocks alone in North West England.

Construction aggregates are a high-volume, low-unit-value commodity, which makes the transportation cost a determining factor in competing sources. Thus the location of resources may encourage the use of C&DW derived aggregates in certain areas. For example, past surveys [British Geological Society 2001] have shown major movements of quarry materials from one region to another; e.g., West Midlands and North Wales to the North West of England. In considering future supply patterns to the North West, assumptions will need to be made about supplies from Wales, where planning policies for aggregates are now matters for the devolved administration. It cannot therefore be assumed that past supply patterns will necessarily be maintained in the future. It is not surprising therefore that the Regional Waste Strategy for the North West [Government Office for the North West 2003] aims to "promote the use of recycled construction and demolition waste in construction projects and encourage developers and contractors to specify these materials wherever possible in the construction process".

Liverpool has been selected as a realistic illustrative example. As the designated European Capital of Culture in 2008, Liverpool has seen a wide range of refurbishment and reconstruction projects over the last 18 months. 52 out of the 72 tower blocks in Liverpool were demolished between 2001 and 2006. 15,000 tonnes of construction and demolition waste resulted from the demolition of just one tower block. This ‘waste’ was transported to a nearby crushing plant where it was converted to Department of Transport ‘Type 1’ road sub-base material. Natural aggregate resources are limited in Liverpool, i.e. there are no aggregate quarries, but resource supply or feed material for a crushing plant can be guaranteed in an urban area where replacement of infrastructure is ongoing. The feed material however may change, i.e. the tower blocks were mainly constructed of in-situ concrete or precast concrete panels, while most of the local council housing expected to be demolished in the near future will be mainly masonry, low-rise buildings.

At least 4.5 million tonnes of hard C&DW is crushed and/or screened annually for use as aggregate [Soutsos et al. 1997]. Very little evidence was found of hard C&DW that could be recycled into aggregate being land filled as waste in the Merseyside region. The majority of recycled C&DW material appears to be used as a sub-base for road construction. Only very modest tonnages were identified as being used in an unprocessed form and then it was mainly for landfill engineering. However, the costs for crushing the C&DW, which is estimated to be approximately £7 per tonne [Davis et al. 2003], is not recovered when it is sold as road sub-base aggregate. The selling price depends heavily on the demand and can vary between £2 and £4 per tonne. The demolition contractors are still required to include for this difference and they are faced with paying the recycling plant operator to take away the C&DW. Operators of crushing plants would also welcome an increase in price per tonne and a guaranteed constant/regular demand for the recycled demolition aggregate. Block making factories are very interested in recycled demolition aggregates, if the price is lower than that of quarried aggregate. Indicative price ranges for quarried aggregates are £8-10 per tonne for 6mm aggregate and £3-4 for 4mm-to-dust. A conservative value of £7 per tonne for 6mm recycled demolition aggregates would satisfy both the operators of crushing plants as well as the block making factories. It was therefore concluded that there was scope for investigating a high-end value market for recycled demolition aggregate.

RECYCLED DEMOLITION AGGREGATE

If recycled demolition aggregates are to be used in precast concrete products, specific gravity, absorption, fineness, and angularity are all important physical properties that need to be taken into consideration. In the Liverpool study, aggregate gradings were obtained for limestone quarried aggregates, supplied by a block making factory, as well as recycled concrete and masonry derived aggregates supplied by local demolition companies. The concrete C&DW that was crushed to produce aggregates came from the foundations of a multi-storey reinforced concrete building while the masonry C&DW came from the demolition of low-rise council houses. It was expected that the detrimental effect of masonry-derived aggregates on compressive strength would have been higher than that of concrete-derived aggregates. It was therefore considered prudent to investigate the effects of concrete- and masonry-derived aggregates separately, with the possibility of interpolating to obtain the effects of a mixture of the two. The percentage of masonry in the mixture is likely to vary depending on what contract, whether multi-storey buildings or masonry houses, the demolition contractor has secured.

As delivered from the crushing plant, the 4mm-to-dust recycled masonry was found to be much finer than natural quarried limestone while the opposite was found to be true for the concrete-derived aggregate. In order to obtain a combined grading similar to that of natural limestone, the proportion of masonry fines needed to be reduced from 56% to 43% while that of concrete fines needed to be increased from 56% to 61%. However, the initial mixes indicated that the concrete fines could be reduced to 45% and still get the same texture on the blocks as those made with limestone aggregates. Both the concrete and the masonry-derived recycled aggregate had a very high water absorption value, as high as 18% for the 4mm-to-dust, which is similar to the behaviour of man-made lightweight aggregates in other applications. A mixing procedure adopted for making concrete using lightweight aggregates has thus been trialled and found to be successful when using recycled concrete aggregates, i.e. pre-mixing of half the mix water with the aggregate first and then adding the cement and the remaining water.

LABORATORY REPLICATION OF INDUSTRIAL CASTING PROCEDURES

Precast concrete factories are normally in operation round the clock. Stoppage in production costs a lot of money and the investigation into the effect of replacing quarried aggregate with recycled demolition aggregate had to be done in the laboratory. The first objective was to replicate the industrial casting procedures using laboratory equipment. Once this was achieved then the effect of partially replacing quarried with recycled demolition aggregates was investigated. The industrial collaborators felt that there should be no increase in the cement content if recycled demolition aggregate was to compete with quarried aggregates. The aim was to determine replacement levels that only caused small and insignificant changes to the physical and mechanical properties of the end products. The mix proportions and the physical and mechanical properties sought for concrete building and paving blocks and concrete paving flags are shown in Table 1.

Table 1. Typical mix proportions and required mechanical properties of concrete building blocks, concrete paving blocks and concrete paving flags

	Building block	Paving block	Paving flag
Mix Proportions (kg/m^3)*:*			
Cement CEM-1:42.5	100	380	320
Fine aggregate	1175 limestone	1520 sand	1022 sand
Coarse aggregate	1075 6mm limestone	380 6mm limestone	770 6mm limestone
Chemical Admixture	N/A	Superplasticiser	N/A
Physical and Mechanical Properties:			
Target density* (kg/m^3)	2350	2250~2350	2400
Compressive Strength (MPa)	> 7	> 49	N/A
Tensile Splitting Strength (MPa)	N/A	> 3.6**	N/A
Flexural Strength (MPa)	N/A	N/A	3.5***

* Fully compacted density per cubic metre of concrete
** Characteristic strength value (Target mean value of 3.9 MPa)
*** Characteristic strength value (Target mean value of 4.0 MPa)

(a) Concrete building blocks **(b) Concrete paving blocks**

Fig. 1: Alignment Compaction Rig for Making Blocks

The technique used by industry for making building and paving blocks is based on applying vibration and compaction at the same time. A heavy metal block is used to compress the concrete while it is vibrated. This procedure was replicated in the laboratory by the use of an electric hammer, see Figure 1(a). While the electric hammer was sufficient to compact the concrete building blocks and achieve the required compressive strength of > 7 MPa at 28-days, it proved not to be sufficient for paving blocks which require more compaction to achieve a denser block. Efforts concentrated on modifying the previously used frame with the electric hammer, so that the specimens could be vibrated from a source other than the electric hammer, while they were being compacted. A small metal table was modified to a vibrating table by mounting a clamp-on-vibrator, see Figure 1(b). Together with the use of a plasticizer, this improved the wet density of the paving blocks to 2390 kg/m^3 compared to 2230 kg/m^3 by using the electric hammer alone. Compressive strengths greater than the required 49 MPa and tensile splitting strengths greater than the required 3.9 MPa were achieved by this method. The texture of concrete paving blocks cast in the laboratory with the improved 'vibro-compaction' technique compared well with that of paving blocks obtained from the factory and which had similar mix proportions to the laboratory cast specimens. The similar texture and mechanical properties achieved in the laboratory confirmed that the industrial casting procedure was successfully replicated.

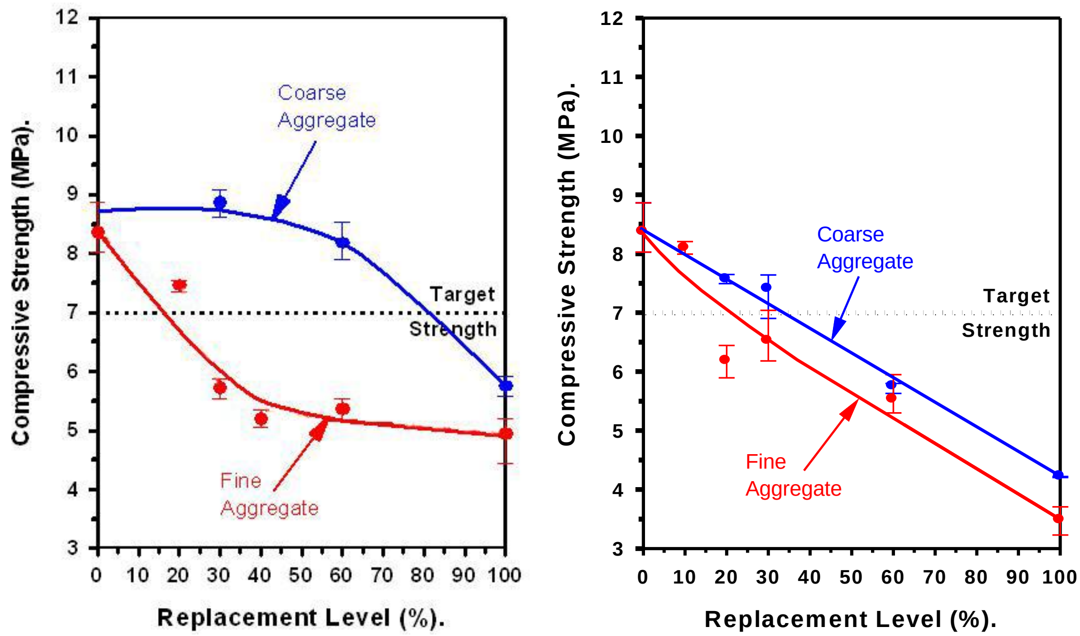
The 'wet' casting technique used by industry for making concrete flags requires a very workable mix so that the concrete flows into the mould before it is compressed. Compression squeezes water from the top as well as the bottom of the mould. The concrete flag is then vacuumed extracted. This industrial casting procedure was successfully replicated in the laboratory by using an appropriately modified cube crushing machine, see Figure 2, and a special mould typical of that used in industry (supplied by Morris Bros Ltd.). The mould could be filled outside of the cube crushing machine and then rolled onto a steel frame and into the machine for it to be compressed. The concrete was compressed at 12 MPa for 15

Fig. 2. Modified Compression Testing Machine for Making Concrete Paving Flags

seconds. A similar compressive stress (10~12 MPa) is used by precast concrete factories but the duration of the flag being pressed is only 12 seconds. The additional 3 seconds were to account for the time it took the compression machine to reach 12 MPa. Vacuum suction of the water at the top of the mould was achieved through the use of a compressed air supply and appropriate devices supplied by Morris Bros Ltd. These devices were the same as used by the precast concrete industry. The mould was then rolled out of the compression machine and a jack was used to push the bottom steel plate of the mould, together with the concrete flag, upwards and out of the mould. The concrete flag was lifted off the steel plate, using vacuum suction again. Concrete paving flags were then air-cured for 24-hours before being placed in water at a temperature of 20±5^{o}C until they were tested.

RESULTS AND DISCUSSION

After having successfully replicated the industrial block- and flag-making procedures in the laboratory, the replacement of quarried limestone with concrete-derived aggregate was investigated.



(a) Concrete-derived aggregate **(b) Masonry-derived aggregate**

Fig. 3. Compressive Strength Versus Replacement Level (%) with Recycled Demolition Aggregate for Building Blocks

Concrete building blocks

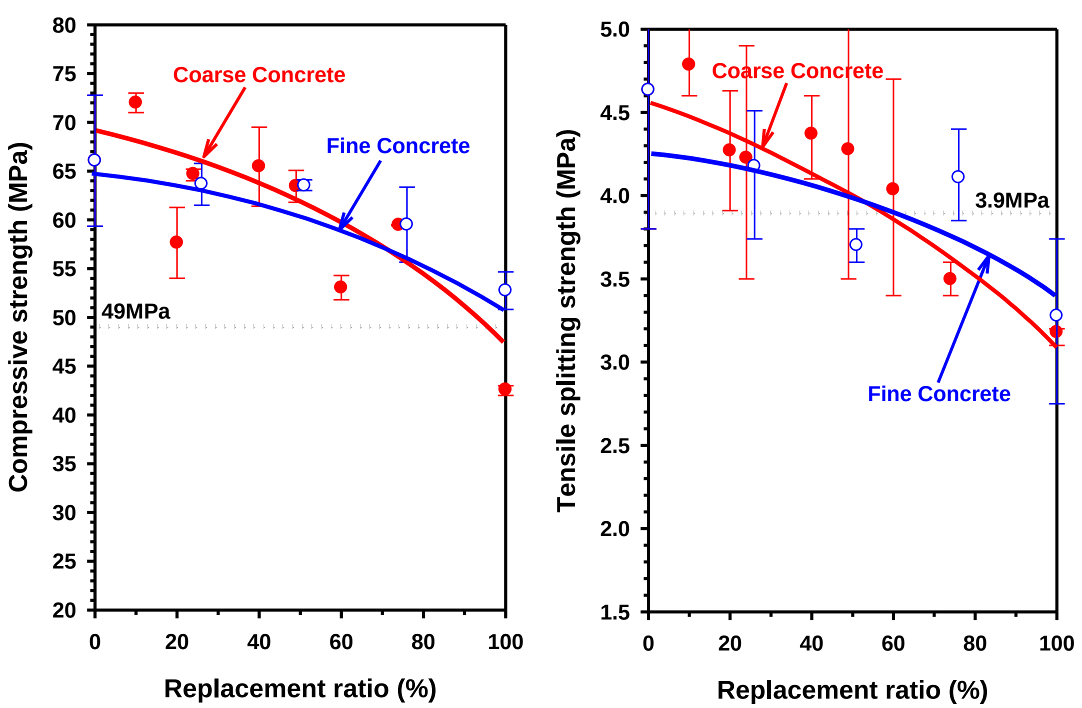
The mix proportions of natural limestone aggregate used by a block making factory, shown in Table 1, had to be converted to equivalent volumes, replaced by an equal volume of recycled demolition aggregate, and then converted back into weight. This ensured that the replacement was on a volumetric basis, which was required in order to take into account the different densities of the recycled aggregates compared with quarried limestone aggregates. Blocks made with recycled concrete aggregates therefore had marginally lower wet densities than quarried limestone blocks, e.g., 1890 kg/m^3 for a block using 100% replacement of both 6 mm and 4 mm-to-dust limestone aggregates with concrete-derived aggregates compared to 2125 kg/m^3 for a block using only limestone aggregates.

Each series of mixes started with an initial cement content of 100 kg/m^3. Experience has shown that if the concrete mix held together after it is squeezed tightly in the hand, then the mix will have sufficient workability to be compacted into the moulds. A handful of the concrete mix was taken after mixing for three minutes. If it did not hold together then additional water was added. Two or three blocks were then cast. An increment of additional cement was then added, the concrete was re-mixed for another two minutes, and again a visual inspection determined whether it had sufficient workability to be compacted into the moulds. Incremental increase of the cement content in this manner resulted in blocks with various cement contents, water-cement ratios, and therefore compressive strengths. Early age strengths, i.e. 1-day, were sufficient to allow moving and stacking of blocks as required in the manufacturing process. All blocks were tested at 7-days using fibreboard end packing and, following factory procedure, a conversion factor of 1.06 was used to convert this strength to the equivalent 28-day strength. The values shown in Figure 3 are the equivalent 28-day strengths. Studies were then carried out with the objective of replacing either the coarse fraction or the fines fraction, but not both, in order to quantify the relative effects of each fraction. Promising results were obtained for a 60% replacement of the coarse fraction with concrete-derived aggregate, i.e. the detrimental effect on the compressive strength was small and the target mean strength was still exceeded. Replacement of the fine aggregate fraction only with concrete-derived aggregate had a bigger detrimental effect on strength than the coarse aggregate replacement. Higher than 30% replacement level of fine aggregate is not recommended because the target strength was not achieved. It was concluded that reasonable replacement levels would be 60% for the coarse fraction and not more than 30% for the fine fraction.

The effect of replacing newly quarried limestone with recycled masonry-derived aggregate is also shown in Figure 3 and the detrimental effect was found to vary almost linearly with the percentage replacement level. 20% replacement level of coarse and fine aggregate was selected as it still produced blocks with compressive strengths above 7 MPa.

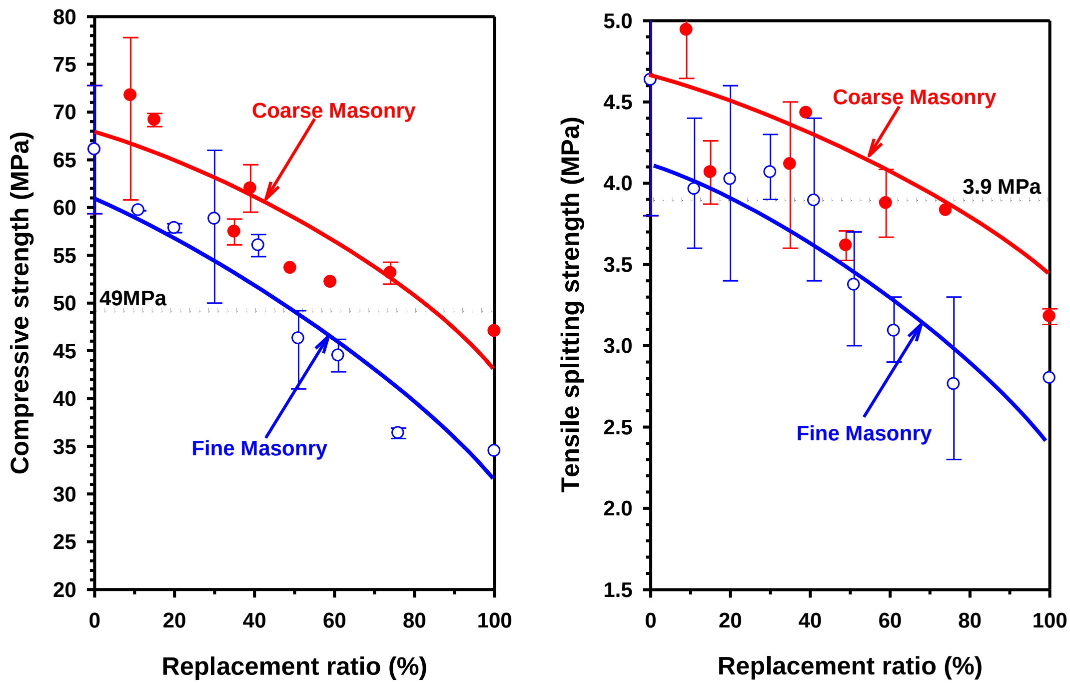
Concrete paving blocks

Paving blocks are required to have 28-day compressive and tensile strengths of 49 MPa and 3.9 MPa respectively, see Table 1. It is therefore not surprising that the cement content normally used is considerably higher than the one used for building blocks, i.e. 380 kg/m^3 compared to 100 kg/m^3.



(a) Compressive strength **(b) Tensile splitting strength**

Fig. 4: 28-day Strength Versus Replacement Level (%) with Concrete-derived Aggregates for Paving Blocks



(a) Compressive strength **(b) Tensile splitting strength**

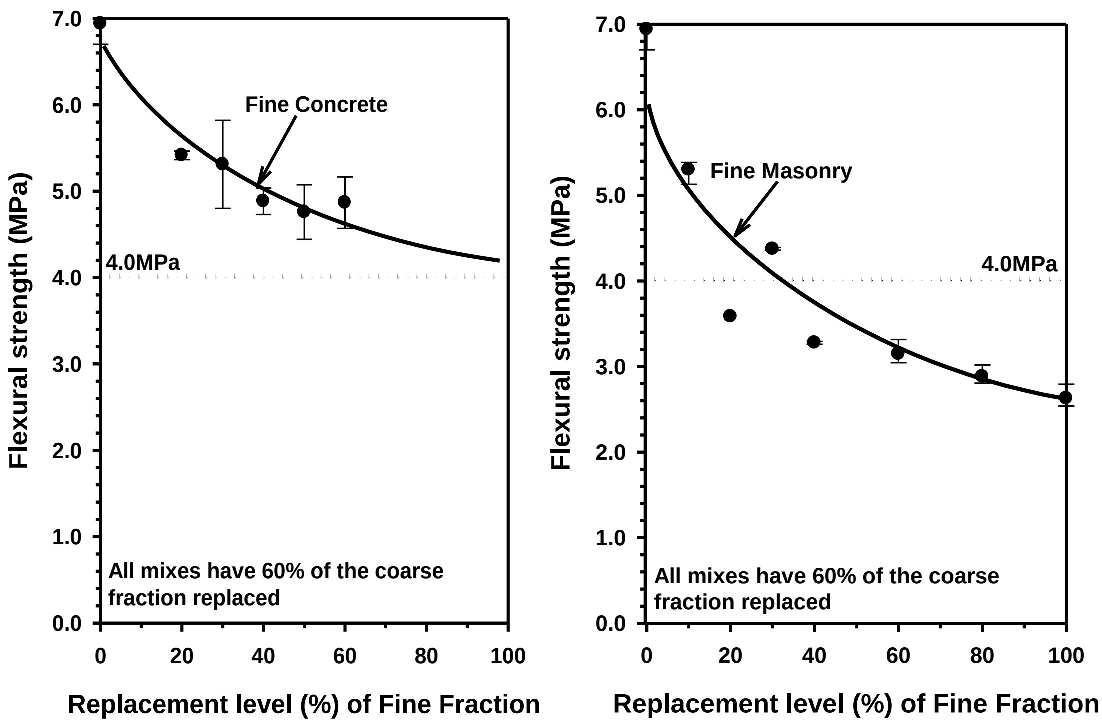
Fig. 5: 28-day strength Versus Replacement Level (%) with Masonry-derived Aggregates for Paving Blocks

Concrete paving blocks, unlike concrete building blocks, use a much higher fine/coarse aggregate ratio 4:1, compared to about 1:1 for the building blocks, in order to get a better surface finish. Initially this was worrying since the fine fraction was shown to have a bigger detrimental effect on the compressive strength of concrete building blocks than the coarse aggregate. Figure 4(a) and 4(b) show that although there was some detrimental effect this was similar to the coarse fraction. It can be concluded that reasonable replacement levels would be up to 60% for the coarse and similarly 60% for the fine fraction for concrete-derived aggregate. Upon reflection, it is not surprising that a high percentage replacement only causes a small detrimental effect on strength; the coarse aggregate proportion is only 20% of the total aggregate.

The replacement of newly quarried limestone aggregate with masonry-derived aggregate has been investigated separately from concrete-derived aggregates for paving blocks in parallel to the building blocks study. Figure 5(a) and 5(b) show that reasonable replacement levels with masonry derived aggregates would be 60% for the coarse fraction and 40% for the fine fraction. However, further studies with combined coarse and fine replacements indicated that it would be prudent to recommend that only 20% of the fine fraction be replaced with masonry-derived aggregates, in order to guarantee that the target strength is still achieved at the age of 28 days.

Concrete flags

Only a combination effect, i.e. replacing both coarse and fine fraction with concrete-derived aggregates, was examined for concrete flags. BS EN 1339:2003 requires the characteristic



(a) Concrete-derived aggregate **(b) Masonry-derived aggregate**

Fig. 6: Flexural Strength Versus Replacement Level (%) with recycled demolition aggregates for paving flags

splitting strength to be greater than 3.5 MPa. A target mean flexural strength of 4.0 MPa has been set for this project after consultation with industrial collaborators. With up to 60% of the coarse and 60% of the fine fractions replaced with concrete-derived aggregates (keeping recommended replacement values on the conservative side), the target flexural strength of 4.0 MPa was still achieved at the age of 28 days, see Figure 6(a).

Fine masonry-derived aggregate appears to adversely affect the flexural strength (or tensile splitting strength in the case of paving blocks), more than it does to the compressive strength. Therefore a replacement level of 60/20% of coarse and fine fraction is suggested as the maximum replacement level with masonry-derived aggregates, see Figure 6(b).

CONCLUSIONS

The location of aggregate resources may encourage the use of C&DW derived aggregates in certain areas. It is believed that Liverpool, whose regeneration calls for demolition and major reconstruction, can benefit from a high value end use of C&DW derived aggregates. The market research carried out showed that most of the 4.5 million tonnes of annual C&DW material is crushed and/or screened for use as aggregate, mainly for low value road sub-base use. However, the costs associated with crushing the C&DW are not recovered and there was therefore scope for investigating a high-end value market, such as their use in precast concrete products. The technical aspects of the use of recycled demolition aggregates in the production of concrete building and paving blocks and concrete paving flags indicated that the replacement levels of quarried aggregate need to be determined such that the mechanical properties are maintained without the need to increase the cement content. For the concrete building blocks, the recommended levels of replacement of quarried aggregates with:

- Concrete derived aggregate were 60% for the coarse fraction, i.e. 6mm, and 30% for the fine fraction, i.e. 4 mm-to-dust.
- Masonry-derived aggregate were 20% for the coarse fraction, i.e. 6mm, and 20% for the fine fraction, i.e. 4 mm-to-dust.

ACKOWLEDGEMENTS

The authors are grateful to the Veolia Environmental Trust and the Flintshire Community Trust Ltd (AD Waste Ltd) for funding this project. The authors would also like to thank the following industrial collaborators for their assistance with the project: Clean Merseyside Centre, Marshalls Ltd, Forticrete Ltd, Charcon Ltd., Cemex Readymix Ltd., RPC Ltd., Liverpool City Council, Liverpool Housing Action Trust (LHAT), WF Doyle & Co. Ltd, Lafarge Aggregates Ltd., Hanson Aggregates Ltd., Aggregate Industries Ltd., Appleby Group Ltd., UKQAA, Tarmac Ltd., and Morris Brothers Ltd.. The contribution of J. Gradwell of Enviros Ltd. to the work on the concrete building blocks is particularly acknowledged. However, the views given in this discussion are those of the authors and do not necessarily represent those of the funders, regulatory bodies or commercial interests.

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