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The use of recycled demolition aggregate in precast concrete products – Phase III: Concrete pavement flags

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HIGHLIGHTS

► Development of a "mini-press" technique for casting concrete flags in the lab.
► Investigation of partial replacement of newly quarried with recycled demolition aggregate.
► Flexural strength was the mechanical property investigated for concrete flags.
► Replacement levels were determined that had only very small effect on the mechanical properties.

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ABSTRACT

A study undertaken at the University of Liverpool has investigated the potential for using construction and demolition waste (C&DW) derived aggregate in the manufacture of a range of precast concrete products, i.e. building and paving blocks and pavement flags. Phase III, which is reported here, investigated concrete pavement flags. This was subsequent to studies on building and paving blocks. Recycled demolition aggregate can be used to replace newly quarried limestone aggregate, usually used in coarse (6 mm) and fine (4 mm-to-dust) gradings. The first objective was, as was the case with concrete building and paving blocks, to replicate the process used by industry in fabricating concrete pavement flags in the laboratory. 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 out water from the top as well as the bottom of the mould. This industrial casting procedure was successfully replicated in the laboratory by using an appropriately modified cube crushing machine and a special mould typical of what is used by industry. 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 texture and mechanical properties of the laboratory concrete flags were found to be similar to the factory ones. The experimental work involved two main series of tests, i.e. concrete flags made with concrete- and masonry-derived aggregate. Investigation of flexural strength was required for concrete paving flags. This is different from building blocks and paving blocks which required compressive and tensile splitting strength respectively. Upper levels of replacement with recycled demolition aggregate were determined that produced similar flexural strength to paving flags made with newly quarried aggregates, without requiring an increase in the cement content. With up to 60% of the coarse or 40% of the fine fractions replaced with concrete-derived aggregates, the target mean flexural strength of 5.0 N/mm² was still achieved at the age of 28 days. There was similar detrimental effect by incorporating the fine masonry-derived aggregate. A replacement level of 70% for coarse was found to be satisfactory and also conservative. However, the fine fraction replacement could only be up to 30% and even reduced to 15% when used for mixes where 60% of the coarse fraction was also masonry-derived aggregate.

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1. Introduction

Successful outcome of Phase I and II which investigated the use of recycled demolition aggregate in the manufacture of concrete building [1] and paving blocks [2] relied on replicating the industrial processes for casting them in the laboratory. The same approach was adopted for Phase III which required the industrial process for casting concrete pavement flags to be replicated in the laboratory. Recycled demolition aggregate can be used to replace newly quarried limestone aggregate, usually used in coarse
mix proportions are different from those of concrete paving blocks immediately after pressing and stacked on wooden pallets. The flags can be removed from the mould, using vacuum suction, top surface. The casting process is very efficient in that concrete of water from the bottom but vacuum suction is required from the forated steel plates. Gravity forces are sufficient for the extraction and removed from both the top and bottom surfaces through per-
poured into a mould and then compressed. Water is squeezed out. A good surface finish is still achieved as the ce-
ment paste and fine aggregate is transported by the water to the surface and retained there by the filter paper.

Possible contamination from C&DW directly affecting reinforce-
ment is not an issue as pavement flags are unreinforced.

Unlike construction projects, paving flags fabrication is essentially a manufacturing process where supply of input materials and storage of output are more easily mananged.

There may be local circumstances that would make the use of secondary and recycled materials for high-grade use cost effective. Merseyside and more specifically Liverpool has been selected as a realistic illustrative example of a major UK conurbation undergoing regeneration [3].

Resource supply or feed material can be guaranteed in an urban area like Liverpool where replacement of infrastructure is occurring, natural aggregate resources are limited, disposal costs are high, and environmental regulations encourage recycling.

Precast concrete paving flags have been used for nearly a cen-
tury and the first national specification was published in 1929 [4]. As the ‘chunky boys’ [5] in the segmental pavement family, concrete paving flags are normally bigger than concrete paving blocks, with a standard size ranging from 300 × 300 mm to 600 × 900 mm [6]. They offer an attractive surface and are suitable for paving areas such as footways, driveways and gardens. The approximate price for one square metre of concrete flags is about 10–20% less than that of concrete paving blocks [5]. In spite of all these advantages, there is a noticeable decline in the sale of flags in the UK. Lilley [4] attributed this to the change in demand. Concrete flags were used for carriageways and car parks but flag fail-
ures meant that their use is nowadays restricted to pedestrian areas. Laboratory tests indicated that thicker flags would be required to carry frequent load from commercial vehicles but this would have increased handling difficulties. Reducing the plan size of flags may reduce the bending moment imposed on the flag and therefore reduce the risk of cracking from loading by vehicles.

The industry uses two casting methods, i.e. “wet” and “dry”. The “dry” method is not much dissimilar to that used for concrete paving blocks [7]. The “wet” method is the one most favoured and this requires a very workable/self levelling mix which can be poured into a mould and then compressed. Water is squeezed and removed from both the top and bottom surfaces through perforated steel plates. Gravity forces are sufficient for the extraction of water from the bottom but vacuum suction is required from the top surface. The casting process is very efficient in that concrete flags can be removed from the mould, using vacuum suction, immediately after pressing and stacked on wooden pallets. The mix proportions are different from those of concrete paving blocks (6 mm) and fine (4 mm-to-dust) gradings. Partial replacement of limestone aggregate with recycled demolition aggregate could only be investigated extensively once the industrial procedure had been replicated in the laboratory.

Pavement flags were selected as a promising precast concrete product where large quantities of recycled demolition aggregate could be used but also because:

- Possible contamination from C&DW directly affecting reinforce-
ment is not an issue as pavement flags are unreinforced.
- Unlike construction projects, paving flags fabrication is essentially a manufacturing process where supply of input materials and storage of output are more easily managed.
- There may be local circumstances that would make the use of secondary and recycled materials for high-grade use cost effective. Merseyside and more specifically Liverpool has been selected as a realistic illustrative example of a major UK conurbation undergoing regeneration [3].
- Resource supply or feed material can be guaranteed in an urban area like Liverpool where replacement of infrastructure is occurring, natural aggregate resources are limited, disposal costs are high, and environmental regulations encourage recycling.

in that the percentage of coarse aggregate is higher, i.e. 40% of the total aggregate for flags compared to only 20% for paving blocks, see Table 1. The higher proportion of coarse fraction is beneficial for the “wet” casting process. The water can be more easily squeezed out [7]. A good surface finish is still achieved as the cement paste and fine aggregate is transported by the water to the surface and retained there by the filter paper.

Performance requirements for concrete paving flags are given in BS EN 1339: Concrete Paving Flags – Requirements and Test Meth-
ods [6] which classifies paving flags in three classes, see Table 2, according to the following mechanical properties:

- Minimum flexural strength.
- Minimum weathering resistance (water absorption or freezing/ thawing resistance).
- Minimum abrasion resistance.
- Minimum slip/skid resistance.

2. Aims and objectives

The first aim was the development of the “mini-press” tech-
nique needed to replicate the industrial casting procedure in the lab. Once this was achieved satisfactorily, i.e. paving flags cast in the lab with the same materials and mix proportions as used by the industry had the same mechanical properties, then the partial replacement of newly quarried aggregates with recycled demolition aggregate was investigated. The effect of concrete and ma-
sonry derived aggregates on the mechanical properties was investigated separately. Flexural strength, rather than tensile splitting strength as used for paving blocks, was investigated for concrete flags. The Industrial Collaborators required that there should be no increase in the cement content if recycled demolition aggregate was to compete with quarried aggregates. The aim therefore was to determine replacement levels that only caused

<table>
<thead>
<tr>
<th>Property</th>
<th>Recommended values</th>
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<tr>
<td>Dimension tolerance (Class 3)</td>
<td>±2</td>
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<td>Strength performance</td>
<td>±2</td>
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<tr>
<td>Minimum characteristic bending strength</td>
<td>±2</td>
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<tr>
<td>Weathering resistance</td>
<td>±2</td>
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<tr>
<td>Abrasion resistance</td>
<td>±2</td>
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<tr>
<td>Abrasion resistance</td>
<td>±2</td>
</tr>
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</table>

| Target density (kg/m³) | 2250–350 | 2400 | 2400 |
| Cement (kg/m³) | CEM-1:42.5 | CEM-1:42.5 | CEM-1:42.5 |
| Fine aggregate (kg/m³) | M grade sand 1520 | M grade sand 1022 | M grade sand 773 |
| Coarse aggregate (kg/m³) | 6 mm single sized limestone 380 | 6 mm single sized Limestone 770 | 10 mm single sized Limestone 773 |
| Admixture | Superplasticiser 0.6% of cement content | N/A | Concrete water reducer 0.25% of cement content |

<p>| Performance requirements for concrete paving flags [6]. |
|---------------------------------|-------------------|</p>
<table>
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<th>Property</th>
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<td>±2</td>
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<tr>
<td>Weathering resistance</td>
<td>±2</td>
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<tr>
<td>Maximum water absorption (%) by mass</td>
<td>±2</td>
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<tr>
<td>Maximum mass loss after freeze/thaw test</td>
<td>±2</td>
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<tr>
<td>Abrasion resistance</td>
<td>±2</td>
</tr>
<tr>
<td>Maximum groove</td>
<td>±2</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>±2</td>
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<tr>
<td>Maximum slip/skid resistance</td>
<td>±2</td>
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</table>

<table>
<thead>
<tr>
<th>Admixture</th>
<th>N/A</th>
<th>Concrete water reducer 0.25% of cement content</th>
</tr>
</thead>
</table>
3. Materials and experimental methods

3.1. Materials

Specific gravity, water absorption, fineness, and angularity are all important physical properties that need to be taken into consideration if recycled demolition aggregate are to be used in precast concrete products. The aggregate gradings for limestone quarried aggregates, supplied by a block making factory, as well as recycled concrete aggregate (RCA) and recycled masonry aggregate (RMA) supplied by local demolition companies are shown in Fig. 1. The concrete construction and demolition waste (C&DW) that was crushed to produce aggregate 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 RMA on compressive strength, because of its lower density, would be higher than that of RCA. It was therefore considered prudent to investigate the effects of RCA and RMA separately.

The grading of 6 mm recycled aggregate, both RCA and RMA, were found to be very similar to the quarried limestone, as Fig. 1 shows. However, the 4 mm-to-dust grade of RCA was found to be finer than natural medium grading sand while the opposite was found to be true for the RCA. Both RCA and RMA had very high water absorption values, see Table 3, which are similar to the behaviour of man-made lightweight aggregate. A mixing procedure adopted for making concrete using lightweight aggregate was trialled and found to be successful when using recycled demolition aggregate, i.e. pre-mixing of half the mix water with the aggregate first and then adding the cement and the remaining water.

3.2. Laboratory casting procedure for concrete flags

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 out water from the top as well as the bottom of the mould as was described earlier. This industrial casting procedure was successfully replicated in the laboratory by using an appropriately modified cube crushing machine, see Fig. 2, and a special mould typical of what is used by industry. 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 N/mm² for 15 s. A similar compressive stress (10–12 N/mm²) is used by precast concrete factories but the duration of the flag being pressed is only 12 s. The use of a compression machine for this enabled the maximum load to be applied but this could only be applied at a slower rate than in industry. The additional 3 s were to account for the time it took for the compression machine to reach 12 N/mm². Vacuum suction of the water at the top of the mould was achieved through the use of a compressed air supply and appropriate ancillary devices similar to those used in 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 again vacuum suction. Concrete paving flags were then air-cured for 24-h before placed in water at a temperature of 20 ± 5 °C until they were tested.

Mix proportions used by two concrete pavement flag making factories are shown in Table 1. It was planned that a full scale factory trial would be carried out at Factory no. 01. Hence, mix proportions used at this factory were also used in the preliminary trials of this project. However, the fine aggregate percentage of 57% of the total aggregate was not resulting in a good surface finish. This was increased to 60% to get the same finish as that of concrete flags produced by the industry.

Increased duration of the compressive force, and its effect on flexural strength, was also investigated. The prolonged pressing time was found not to have a big effect on the flexural strength of newly quarried aggregate flags. However, it did have an effect on recycled demolition aggregate flags and this is believed to be due to the higher water content of the mixes used for these. It was decided that 15 s was sufficient to replicate the industrial procedure. The 28-day flexural strength of industry supplied concrete pavement flags was 6.9 N/mm² and this was achieved in the laboratory with one that had a density of 2,400 kg/m³.

3.3. Flexural testing of concrete flags

The British European standard BS EN 1339 [6], Concrete paving flags – requirements and test methods, has superseded the British Standard, BS 7263–1, in the requirements and test methods of concrete paving flags. The physical performance

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**Table 3**

<table>
<thead>
<tr>
<th>Water absorption and densities of aggregates.</th>
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</thead>
<tbody>
<tr>
<td>Fine aggregate (graded medium-fine sand)</td>
</tr>
<tr>
<td>Coarse aggregate (5 mm single size aggregate)</td>
</tr>
<tr>
<td>Sand</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Particle density (SSD)² (kg/m³)</td>
</tr>
<tr>
<td>Particle density (oven-dry) (kg/m³)</td>
</tr>
<tr>
<td>Water absorption (% by mass)</td>
</tr>
</tbody>
</table>

* Saturated and surface dry condition.
as well as mechanical requirements are used BS EN 1339 [6] to classify concrete flags into different classes, allowing a cost-effective solution to customers based on the area where they are to be used. The actual mean flexural strength of industry supplied concrete pavement flags was found to be 6.9 N/mm². The requirement for Class 3, as shown in Table 2, is a characteristic flexural strength of at least 5.0 N/mm² at 28 days. The mean flexural strength of 6.9 N/mm² allows a margin for converting characteristic to target mean strength. These concrete flags were 50 mm thick and they are usually used for “pedestrian areas only with very occasional vehicles” [6]. Such application only requires a Class 2 concrete flag. Applications such as footways, crossings, car parks and lightly trafficked roads require a minimum thickness of 60 mm [6].

Flexural strength is the mechanical property required for concrete flags, unlike paving blocks where it was tensile splitting strength [2]. Flexural strength is a more appropriate property for estimating the load bearing capacity of concrete paving flags where the principal action is bending [8]. Concrete paving flags are placed on two bearing supports (radius of 20 ± 1 mm) and the load is applied at the centre steadily until failure occurs, see Fig. 3. The failure load must be reached within 45 ± 15 s [6]. All the results shown on Figs. 4–6 are the mean values obtained from three specimens.

3.4. Durability characteristics of concrete flags

In addition to flexural strength, with which concrete pavement flags need to comply, there are some other requirements: (a) slip resistance, (b) abrasion resistance, and (c) water absorption.

Concrete flags need to show a satisfactory slip/skid resistance during the design life of a pavement. The measure of unpolished slip resistance value (USRV) is required by BS EN 1339 [6]. The pendulum friction test rig incorporates a spring loaded slider made of a standard rubber attached to the end of the pendulum. On swinging the pendulum the frictional force between the slider and test surface is measured by the reduction in length of the swing using a calibrated scale. A USRV value of at least 63 is considered to be ‘acceptable for good skid resistance’ [6]. Time constraints meant that this test was not conducted in the laboratory but it is going to be used for specimens cast during factory trials in the near future.

The weathering resistance of concrete paving flags is related to the water absorption. BS EN 1339 [6] requires concrete flags to have less than 6% water absorption. The weathering resistance can also be determined by the freeze–thaw resistance test according to BS EN 1339 [6]. This requires soaking of concrete flags in a 3% NaCl solution for 28 freeze/thaw cycles from -20 to 20°C. Concrete flags are classified based on their mass loss. This test was not conducted in this project because such a low temperature cyclic freezer was also not readily available in the laboratory. It is anticipated that this as well as slip/skid and abrasion resistance tests will be carried out on factory cast specimens by the factory’s quality control laboratory.

4. Results and discussion

It was believed that the fines fraction, i.e. 4 mm-to-dust, is the one that would have the biggest detrimental effect on the strength. Studies therefore aimed to replace either the coarse or the fine fraction only but not both in order to quantify the relative effects of each.
RCA. Fig. 4a shows the effect of the coarse fraction replacement on the flexural strength of concrete flags. It is not clear how much of the detrimental effect is due to the increasing replacement of the coarse fraction alone as all of the mixes had 20% replacement of the fine fraction as well. The flexural strength reduction seems to be similar to that reported by Dhir et al. [9], i.e. a 19% concrete compressive strength reduction when 100% coarse RCA was used. This is believed to have had a considerable effect which can be seen by comparison with Fig. 4b. The fine RCA has considerable detrimental effect on the flexural strength. Nonetheless, even with up to 60% of the coarse or 40% of the fine fractions replaced with RCA aggregate, the mean flexural strengths were well above the required 5.0 N/mm² characteristic flexural strength at the age of 28 days for Class 2 concrete flags. These are the most commonly used type of concrete flag, i.e. for pedestrian areas with only occasional vehicles. Recommended values were based on a target mean flexural strength of 5.0 N/mm² to allow a reasonable margin from the required characteristic flexural strength of 4.0 N/mm² given in Table 2.

4.1.2. Series II – RMA

The replacement of newly quarried limestone aggregate with RMA has been investigated separately from RCA. The lower density of fine RMA (4 mm-to-dust) was expected to be problematic. Poon and Chan [10] reported a 10% reduction in density of paving blocks when 75% crushed clay was used. The results from the mixes with coarse fraction replaced with RMA have been plotted as flexural strength versus replacement level, see Fig. 5a. There is some detrimental effect which increases with increasing levels of RMA. Approximately 30% reduction is expected with 100% coarse RCA. This is comparable to that reported by Dhir et al. [9], i.e. 35% compressive strength reduction in concretes with 100% coarse RMA. It can be concluded that reasonable replacement level would only be up to 70% for the coarse fraction in order to allow a sufficient margin above the required flexural characteristic strength. The effect of fine RMA on flexural strength is shown in Fig. 5b. The fine fraction, i.e. 4 mm-to-dust, was expected to have an even greater detrimental effect than RCA fines and it was found to be so as can be seen from Fig. 5b. It can be recommended that a reasonable replacement level should be 30% for the fine fraction with RMA. This recommendation was believed to be conservative as the industrial casting procedure will be more efficient than the laboratory technique for compacting specimens, as it was shown in Phase I for concrete building blocks [2].

In order to maximise the recycling, an investigation of the combined effect, i.e. replacement of both coarse (set conservatively at 60%) and varying fine fraction with RMA, was conducted in the laboratory. Fig. 6 shows that the effect of increasing percentage replacement of fine fraction has a considerable detrimental effect on the 60% coarse RMA mix as the 3-day and 28-day flexural strengths drop significantly. Therefore a replacement level of 60 for the coarse and 15% for the fine fraction are suggested to be the maximum replacement levels with RMA.

4.2. Water absorption of concrete pavement flags

In addition to flexural strength, which pavement flags need to comply with, there is a requirement for the concrete weathering resistance which can be measured by conducting a water absorption test [6]. 28-day old specimens were cured in a water tank until they reached constant mass. The time required for this was usually not longer than 3 days. They were then oven dried to constant mass. The loss in mass was expressed as a percentage of the mass of the dry specimen.

The high water absorption of recycled aggregate appears to influence adversely the concrete water absorption (see Figs. 7.
and 8). Similar and even higher values of water absorption have been reported by Poon and Chan [10]. BS EN 1339 [6] requires pavement flags to have less than 6% water absorption and this can only be achieved with the replacement levels indicated in Table 4. Industry cast limestone aggregate specimens had, on aver-

<table>
<thead>
<tr>
<th>Aggregate type</th>
<th>Flexural strength &gt;5 (N/mm²) (%)</th>
<th>Water absorption &lt;6%</th>
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</thead>
<tbody>
<tr>
<td>RCA aggregate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>60</td>
<td>N/A</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>40</td>
<td>0%</td>
</tr>
<tr>
<td>RMA aggregate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>70</td>
<td>40%</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>30</td>
<td>30%</td>
</tr>
</tbody>
</table>

* All mixes with coarse RCA also contained 20% fine RCA.

Fig. 7. Effect of replacing fine fraction (inc. 60% coarse aggregate replacement) and coarse fraction (inc. 20% fine aggregate replacement) with RCA aggregates on (a) the concrete water absorption, and (b) the oven-dried density of concrete paving flags. (a) Water absorption (%). (b) Oven-dried density (kg/m³).

Fig. 8. Effect of replacing coarse or fine fraction with RMA aggregates on the (a) water absorption, and (b) the oven-dry density. (a) Water absorption (%) and (b) Oven-dried density (kg/m³).

Age, a water absorption of 5%. The critical or deciding factor for the level of replacement of newly quarried limestone aggregates with recycled demolition aggregate may have to be the water absorption rather than the strength. For example, the recommended 70% replacement level for the coarse fraction with RMA based on the flexural strength, may have to be reduced to 40% to comply with the maximum water absorption requirement. The replacement of fine fraction with RMA should also be limited to 30% replacement based on the water absorption values. The water absorption values appear to be related to the reduction of the density of concretes made with RMA. Densities less than 2,100 kg/m³ resulted in water absorptions of more than 6%. All combinations of 60% coarse RMA with fine RMA resulted in water absorptions higher than 6%. All the RCA mixes had high water absorptions, see Fig. 7, and this was because even the coarse RCA mixes had 20% fine RCA replacement. Tests are planned for factory cast specimens to confirm these findings. It is also believed that, because of the high water absorption of the recycled demolition aggregate, the water absorption by the blocks may not be indicative of their durability. This will be confirmed with freeze–thaw tests to be carried out on factory cast specimens.
5. Conclusions

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. The industrial casting procedure squeezes out water from the top as well as the bottom of the mould and this was successfully replicated in the laboratory by using an appropriately modified cube crushing machine and a special mould typical of what is used by industry. 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 N/mm² for 15 s. A similar compressive stress (10–12 N/mm²) is used by precast concrete factories but the duration of the flag being pressed is only 12 s. The industrial casting procedure was successfully replicated in the laboratory, i.e. paving flags cast in the lab with the same materials and mix proportions as used by the industry had the same mechanical properties. The partial replacement of newly quarried aggregates with recycled demolition aggregate was then investigated.

Only the combination effect, i.e. replacement of both coarse and fine fraction with RCA, was investigated in the laboratory. With up to 60% of the coarse or 40% of the fine fractions replaced with RCA, the target mean flexural strength of 5.0 N/mm² was still achieved at the age of 28 days.

The replacement of newly quarried aggregate with RMA has been more extensively investigated. Acceptable replacement levels with coarse RMA were found to be up to 70%, giving the required flexural strength. There was significant detrimental effect on flexural strength by incorporating the fine RMA and therefore lower replacement levels, i.e. up to 30%, can be recommended. This needed to be reduced even further when both coarse and fine fractions of RMA were used, i.e. a replacement level of 60% for the coarse and 15% for the fine fraction are suggested to be maximum replacement levels of the RMA, giving the required flexural strength.

The higher water absorption of recycled demolition aggregate resulted in high water absorption values for the concrete pavement flags. As for paving flags, this may not however be a good indicator for durability; the freeze–thaw resistance of concrete flags needs therefore to be investigated in order to determine whether this will be the determining factor on the replacement level with recycled demolition aggregate.

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