Performance Of Concrete With Recycled Aggregates

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ABSTRACT

In the Netherlands, as well as some other European countries, recycled aggregates are applied increasingly. Recycled aggregates are obtained from the processing of stony building and demolition waste. Concrete, containing up to 100% fine and coarse aggregates may be utilised successfully. Significant savings on primary aggregates may be obtained, thereby contributing to closing the concrete life cycle. It is estimated that in Europe alone, about 200-300 million tonnes of building and demolition waste is currently landfilled or applied in road construction. However, recycled aggregates may also be applied very well as coarse aggregate in concrete, thereby upgrading its application.
In this paper, the practical experiences gained with the application of recycled aggregates in concrete in the Netherlands will be highlighted, starting with a brief historical overview of relevant actions taken in the past, and ending with a discussion of future trends.
Introduction of “new” raw materials in the building industry is only possible when there is no discussion on aspects such as the product quality and the ratio between price and performance. Therefore, this paper will give attention to results obtained in the mix-design, strength, durability as well as environmental performance and concrete with recycled aggregates. It will be shown that for the most common ordinary concrete, durability is not a topic for much concern, based on results of tests on chloride-ion ingress and freeze-thaw resistance.

Keywords: chloride ingress, concrete, freeze-thaw, recycled aggregates, specifications, quality control.

1. INTRODUCTION

For millennia, construction and the demolishing of constructions go hand-in-hand. Especially in densely populated countries or regions, an example being the Netherlands, the possibility to recycle stony “waste” materials derived during the process of building, renovation and demolition of structures, has been drawing particular attention since about two decades.
In the Netherlands, almost 15 million tonnes of building and demolition waste’is produced annually; this is equivalent to about 1 tonne per capita. A conservative estimate is thus, that within the EC countries alone approximately 200-300 Mtonnes of this particular kind of waste is produced annually. And just in order to visualise: this is roughly equivalent to an area of 400km^2, with a total height of 1 meter, given an average volumic mass of 1.500 kg/m^3.
The major part of building and demolition waste consists of stony components. These components are, upon recycling, generally referred to as recycled aggregates. According to the definition provided in reference [6], a recycled aggregate is a granular material, resulting from an industrial process involving the processing of inorganic materials, previously exclusively used for construction, applied again for construction purposes.
In the Netherlands, the major marked for recycled aggregates is found in relatively low-tech applications such as embankments, road foundations, etcetera. These low-tech applications are faced with an ever-increasing competition with other secondary raw materials, while at the same time demand is decreasing. However, it is very well possible to upgrade the application of recycled aggregates. It then becomes a potential raw material for the large market of “common concrete”, i.e. concrete which does not have to meet the highest standards with respect to workability, flowability, strength and/or durability. In the Netherlands, roughly 80% of the annual concrete production of about 16 million m^3 is used for ordinary concrete in the strength class up to 25MPa, i.e. almost 13 million m^3. The demand for stones and gravel (4 - 32 mm) and sand (0 – 4 mm) for this concrete is respectively about 14 million and 9.5 million tonnes. And although the production rate of this concrete far exceeds the production of recycled aggregate, the application of this material into concrete is - as a concept - interesting, since it contributes to closing the concrete life cycle, thereby contributing to a sustainable society.
So far however, in only few EC-countries a well functioning building and demolition waste recycling industry, actually producing recycled aggregates of sufficient quality, is present. Within Europe, this is particularly the case in the Netherlands.
In the following chapters a historic overview is presented, starting with a discussion of the meaning of the term “sustainable”, the basis of Dutch environmental policy, followed by an overview of Dutch- and EC-policy on recycled aggregates, legislation, standardisation and quality control, resources and types of aggregates produced, processing, practical experiences, ending with a discussion on future trends.

2. SUSTAINABILITY

“Sustainability” is the fundamental topic behind terms like energy conservation, recycling, efficiency improvement, etcetera. Many definitions exist. The Brundtland report of 1987 “Our Common Future”, published by the World Commission on Environmental Development, describes this term by formulating three aims, the first being an economical development, within the prior condition of ecological criteria.
The outlook for next generations (say in about 50 years) is that world population will approximately double, that this world population will have an average level of prosperity which is about 4-8 times higher than the current one, and that at the same time the pressure on the environment should be reduced with a factor of 2-4. For the building industry as a whole, this means that in 50 years we will have to able to build about 15 to 50 times more efficient.

In order to fulfil our common needs for building (housing, infrastructure, etc.), the building industry should contribute by increasing its overall efficiency in terms of raw materials and energy consumption, low emissions into the environment, ease of adaptability of constructions, an optimised durability (design for durability) and, last but not least, the recyclability of constructions (ease of demounting or demolition and recycling, preferably back into its own product chain). It is particularly this latter aspect which is addressed in this paper.

3. DUTCH- AND EC-ENVIRONMENTAL POLICY

As one of the reactions on the Brundtland report the Dutch National Environmental Policy Plan (NMP) was published in 1989. In this document, as well as the later published update of this plan, and in the "National package" on "Sustainable Building - Investigation into the future", intentions and guidelines were formulated with the aim to anchor the concept of sustainability into, amongst others, the Dutch building industry. A few years back this resulted in an "Implementation Plan on Building and Demolition Waste", with the aim to apply 90% of this kind of waste by the year 2000. In this plan, and its subsequent updates, no particular preference for any particular application was formulated.
Integral chain management is considered to be one of the central themes needed in order to reach a "sustainable" way of building. Integral chain management may be considered as the closing of a product or material life-cycle is such a way that only a minimised amount of material needs to be landfilled or cornbusted, at the same time maximising product and materials reuse and recycling. Preferably, reuse and recycling should take place into the same application. The effect of integral chain management is considered twofold:

1. Materials recycling. This results in a decrease of emissions into air, water and soil (which would take place as a result of landfilling or combustion), as well as a reduction of the environmental impact related to land filling; and
2. Limited use of primary raw materials. This results in a reduced intervention into (scenic) landscapes and extended exploitation of -essentially finite - natural resources.

Within the Netherlands, a National Council for the Construction Industry has been established in order to provide for a discussion platform between building industry and government bodies.
On a much smaller scale, also an EC-building council has been operating. Both councils merely serve to provide a basis for formulating realistic goals, as well as performance related quality criteria.

4. LEGISLATION, STANDARDIZATION AND QUALITY CONTROL

In order to establish a normally operating market for recycled materials in the building industry, one of the major aspects was the formulation of appropriate guidelines. Since the early eighties several Rilem committees have been working in the field of recycling and reuse of secondary raw materials. Results have been presented at the conference proceedings of Rotterdam (1985), Tokyo (1989) and Odense (1993; 4). As a result, a Rilem recommendation was prepared with respect to the applications of recycled aggregates in concrete. This Rilem specification was based on experience obtained since the early eighties in The Netherlands, Denmark and Belgium. Since only few countries have substantial practical experience with the use of recycled aggregates in concrete, only few EC countries developed standards and regulations in this field.
At the same time, two CEN committees were already active in fields which could influence the use of recycled aggregates: CEN/ TC 154 "Aggregates for unbound and hydraulically bound materials for Civil engineering work and road construction" and several task groups within CEN/TC 227, focussing on materials for road construction.
A related, but important discussion was taking place within CEN/TC 229 "Characterisation of Waste".

In 1994 the CEN/TC 154 “ad-hoc group on recycled aggregates” was founded; prime task of this group was to advice TC 154 and its subcommittees on specification requirements and any additional tests required for recycled aggregates. The British Building Research Establishment handles the secretary tasks of this ad-hoc group. This resulted among others to a draft proposal for materials specification for unbound, hydraulically bound and bituminous bound recycled aggregates in 1996 [6].

On a national scale a division should be made between standardisation on the one hand, and legislation on the other hand. The process of national standardisation has been stimulated by the publication of the already mentioned Rilem recommendation. Since a couple of years, Dutch national standards (valid up to concrete with a compressive strength of about 65 MPa) allow for a replacement of 20% (m/m) of natural primary aggregates by either mixed recycled aggregate or concrete recycled aggregates, without the need for additional performance based tests. Mixed recycled aggregates are aggregates which have to contain at least 50% (m/m) of recycled concrete aggregate (and less than 50% (m/m) of recycled masonry aggregate); they should also fulfil other criteria, adressed later. In the recently published “National package for sustainable building in the Netherlands” the suggested standard for concrete was indeed to replace 20% of the primary coarse aggregates (4 – 32 mm), by secondary ones. Currently, there is debate on this 20% limit, since the majority of concrete produced may contain significantly higher amounts [1].

Natural aggregate replacement is allowed, provided legislative requirements are fulfilled. In the Netherlands, diffusion-leaching tests are considered appropriate to monitor this. By January 1999, concrete containing secondary materials, applied outdoors, will have to fulfil to limit values regarding the imission of specific elements into the soil and surface water (which differs from the emission from a building product), specified in the Dutch Building Products Directive. Starting point is the concept that only an increase of specified (an)organic elements by 1% over a period of 100 years is considered to be acceptable. This imission is calculated by taking into account the leaching characteristics of a variety of elements as well as the specific application. For indoor applications, legislation addressing radon emanation is currently in study [l].

Key quality control criteria for recycled aggregates used in concrete include of course grain size distribution, grain shape, the fines content, specific mass, chloride and sulphate content, alkali-silica reactive material (glass), organic components influencing setting and hardening time and “soft’ components, such as plastics and wood. Essentially, specifications do not differ much from the specifications for natural aggregates. A summary is provided in table 1.

In the Netherlands, the producers of recycled aggregate carry out quality control; both recycled concrete- as well as recycled mixed aggregates are sold with quality certificates. Periodically, certification institutes carry out audits, thereby providing an external quality control assurance.

5. RESOURCES AND AVAILABLE TYPES OF AGGREGATES

In the Netherlands, each year about 120 Mtonnes of raw materials are used in the building industry; 85% of this quantity is actually produced in the Netherlands. As already stated, the amount of building and demolition waste is currently estimated at about 15 Mtonnes per year. Of these 15 Mtonne, 11 Mtonne is recycled, of which a majority of about 80% in “on the ground” applications; only 20% is applied in “above ground” applications.

In 1996 the total installed recycling capacity was about 16.3 Mtonnes. Total production in 1996 was less: 10.9 Mtonnes. 10.4 Mtonnes were actually applied. About 68 percent of it originated from demolishing operations, other sources being waste produced at large infrastructural projects, such as road construction (15 %) and building waste sorting installations (5%). Approximately 9% of it was produced at building sites, the remaining 3% from other sources.

Several qualities of recycled aggregates are currently available in the Netherlands. They are summarised in table 2.

Table 1. Specifications for recycled aggregates.

description	specification			standard
grain size distribution	sieve	percentage on sieve (v/v)		NEN 5916
		4/16	**4/32**	
	C63			
	C45		0	
	c31.5		o-5	
	C22.4	0		
	CI6	O-IO	**30-70**	
	C11.2			
	C8	**30-70**		
	C5.6			
	c4	85-I 00	85-100	
	2mm	**95-100**	95-I 00	
grain shape	max. 35% (m/m)			NEN 5935
very **fine** materials	max. 3% (m/m) **<** 63 **µm**			NEN 5917
composition	Specific mass: recycled concrete aggregate: min. 90% (m/m) **>** 2100 **g/m^3** recycled mixed aggregate: min. 50% (m/m) LA-value: recycled concrete aggregate: **<** 50 (% m/m) recycled mixed aggregate: **<** 40 (% m/m) Non-stony components: max. 1.0 % (m/m)			NEN 5942 ASTM Cl31 NEN 5933 NEN 5942
chloride content	Recycled concrete aggregate: max. 0.015 % (m/m) recycled mixed aggregate: max. 0.05% (m/m)			NEN 5921 (method "A")
sulphate content	acid dissolved sulphate (as **SO_3):** max. 1.0 % (m/m) total sulphur compounds (as **SO_3):** max. 1 .O % (m/m)			NEN 5930 NEN 5936
alkali-silica reactive material	may not be present according to standard			NEN 5925
organic components	no significant darkening according to standard			NEN 5919
setting time	no deviation **> +/-** 25% of standard without recycled aggregates			NEN-EN **196-3**
soft components	less than 0.5 % (m/m) may be crushed by hand			NEN 5918

Table 2. Types of recycled aggregates produced in the Netherlands (1996; [I])

type of recycled aggregate	Mtonne/year (1996)
recycled concrete aggregate	1 **.0** (+ 0.07 applied in concrete)
recycled masonry aggregate	0.9
recycled mixed aggregates	5.3 (+ 0.11 applied in concrete)
hydraulic aggregates (Korrelmix **®)**	0.9
total	**8,1** (+ 0.18 applied in concrete)

As can be seen from table 2, about 98% of these recycled aggregates are not applied as secondary raw material in concrete. However, the potential is clearly very high, even when it is considered that recycled masonry aggregates and hydraulic granulates as such can not be applied because of their too low specific mass and friable nature.

New developments include the production of secondary sand **(0/4** mm) of various sources. Such sources include sand which comes available at the concrete crushing plant, sand which comes available from sieving operations at crushing plants, sand which originates from cleaned sandy soils and sand which comes available during river dredging operations. The current amounts produced are however small compared to recycled aggregates. Potentially, some 2 Mtonne may be produced of sufficient quality.

6. PROCESSING

Essentially, the processing of building and demolition waste does not differ from the processing of natural aggregates. In order to be economically feasible, plant size ranges typically between 100 and 250 ktonne. Important is that the demolition waste is separated as early as possible in the recycling chain; this should be achieved preferably at the demolition site, but it may also take place in so-called sorting centres.

Separation generally starts with a crushing action. Further sorting may be carried out by sieving, windsifting to separate light materials, a magnetic sorting to separate iron-parts and sieving. Especially when high quality granulates are needed, the material is subjected to a washing step. Disadvantage of washing operation is that in the end usually a polluted sludge remains, which has to be disposed of, at relatively high costs. Debate is currently going on to reduce these costs significantly, since it poses a significant burden on potential high quality applications, such as concrete.

7. PRACTICAL EXPERIENCES

7.1 Availability and price

Although in principle capacity should be sufficient, the market for low quality applications is still very large. Generally, recycled aggregates for concrete are produced on demand. Recycled concrete aggregate is rather difficult to obtain; because of the difficult applicability of recycled masonry aggregates, recycled mixed aggregate is the main product. Prices are similar to natural aggregates.

7.2 Replacement level of recycled aggregates in concrete

For over 15 years demonstration projects have been carried out in the Netherlands. Concretes with varying levels and types of recycled aggregates have been produced. A recent survey confirms that a replacement level of 20% (v/v) of recycled concrete- or mixed aggregates, for common strength classes such as B15 or B25, and likely up to B35, is very well possible without any performance loss [3;4].

Concretes containing significantly higher amounts of recycled aggregates (up to 100% replacement) may also be produced. Currently, in a housing project near Delft 100% mixed aggregates are applied in almost all precast concrete elements used (walls, floors, and foundations). A compressive strength of about 45 MPa was generally reached, exceeding specifications. Furthermore, an increase in noise reduction compared with traditional concrete was noted, apparently due to the use of the more porous mixed recycled aggregate.

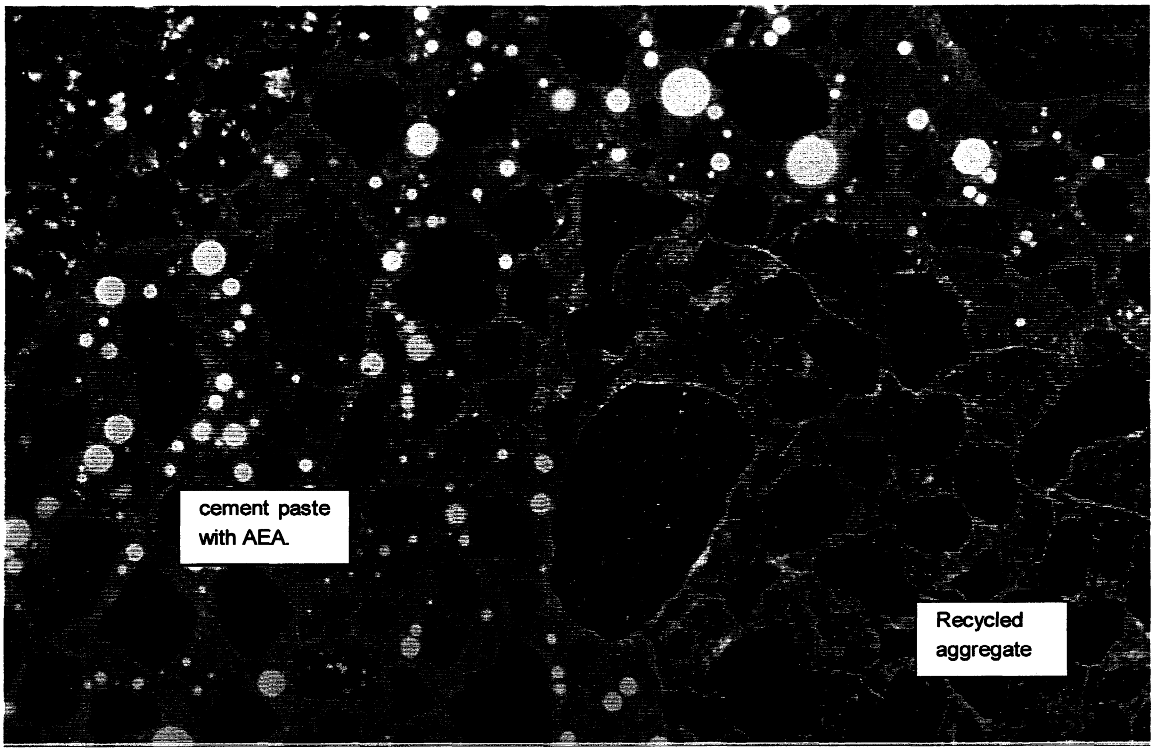
7.3 Mixdesign

In cases of high aggregate replacement levels, care should be taken to analyse the moisture content and adsorption potential of the recycled aggregates, since water demand is usually higher. This is particularly so for aggregates containing masonry or lime-sandstone brick. Three options to overcome this problem exist: the first consist of wetting the recycled aggregates prior to mixing, the second by simply adding more water during mixing, the third by addition of a superplasticiser and/or air entraining agents. Especially this last option is applied successfully in practise. Experiences with replacement of secondary sand 0/4 are still in an embryonic stage. One of the major problems may be, apart from increased water demand plus quality variations within one lot, the hydraulic behaviour, which may cause handling problems in storage bunkers (caking).

7.4 Strength development

Generally, concretes containing up to 20% recycled aggregates do not show a significant strength loss. Higher replacement levels of recycled concrete aggregates also do not seem to be problematic. Due to the hydraulic behaviour of recycled aggregates, as well as their comparatively high surface roughness, good bonds between cement pastes and aggregates exist. An example is shown in figure 1. This micrograph were taken from a (fluorescent) epoxy impregnated thin section.

Figure 1. Microstructure of concrete with recycled mixed aggregate (fluorescent light; 1 cm = 0.3 mm)



7.5 Durability

So far, no damage cases have been reported were the use of recycled aggregates itself was the likely explanation. In practice, no problems with frost-thaw action have occurred, although the porous nature of some recycled aggregates may be a problem in countries with more severe climates, compared to the Netherlands. Air entraining agents may be applied in such cases. In figure 2, some examples of the freeze thaw resistance of concrete with recycled aggregates are shown, based on the RILEM 4 CDC test [2]. Results from chloride penetration tests, according to APM 302, are shown in figure 3. In this test concrete is subjected to a highly saturated chloride solution; after 35 days the relative chloride ingress is analysed. It is an accelerated test. The composition of the concrete used in these tests is summarised in table 3. The water-cement ratio was 0.45. In all cases a superplasticiser was applied, within the allowed specifications. The recycled sand- and aggregates were all pre-wetted; the recycled concrete aggregate contained an additional 16 litres (1.45%), the recycled mixed aggregate 4/16 40 litres (3.6%) and the recycled mixed aggregate 4/32 75 litres (6.8%).
From figure 1 it can be seen that the recycled (concrete) aggregate displays a strong bond with the cement paste, as evidenced by a lack of defects at the interface. Generally, concrete aggregates

display micro-cracks, the significance of which is presumed to be little, as there is not interconnected three-dimensional network present.
The freeze-thaw results from figure 2 demonstrate that the saturation percentage above which "damage" may occur starts at a saturation level of about 77% (critical saturation level). Concrete displaying a critical saturation level over 85-90% may generally be considered to be fully frost-thaw resistant, since such high saturation only occur in special applications. Note that no air-entraining agent was present. The concrete with recycled concrete aggregate performed markedly better than the concretes with recycled mixed aggregates. However, all concretes displayed a performance at least equivalent to the reference concrete with natural aggregates.
From figure 3 it is clear that up to a depth of 12 mm the concretes containing recycled aggregates display a somewhat increased level of chloride ingress; thereafter no difference with reference concrete could be noted. The well-known fact that concrete based on blast furnace slag cement performs better in such tests is also demonstrated.

Table 3. Concrete compositions (all values in kg/m^3)

sample	cement (+ type)	coarse aggregate (+ type)	secondary sand	natural sand
PC	350; CEM I 42.5	1100; Dutch river gravel (4/32)	-	710; riversand
BFSC	350; CEM III 42.5 HL L	1100; Dutch river gravel (4/32)	-	710; riversand
CON32P	350; CEM I 42.5	1100; concrete aggregate (4/32)	248; sieve sand	364; riversand
MIX32B	350; CEM III 42.5 HL L	1100; mixed aggregate (4/32)	248; sieve sand	364; riversand
MIX32P	350; CEM I 42.5	1100; mixed aggregate (4/32)	248; sieve sand	364; riversand
MIX16P	350; CEM I 42.5	1100; mixed aggregate (4/16)	248; sieve sand	364; riversand

Figure 2. Freeze-thaw resistance of several concretes (indicated is the saturation level above which the dynamic E-modulus drops upon 6 frost-thaw cycles)

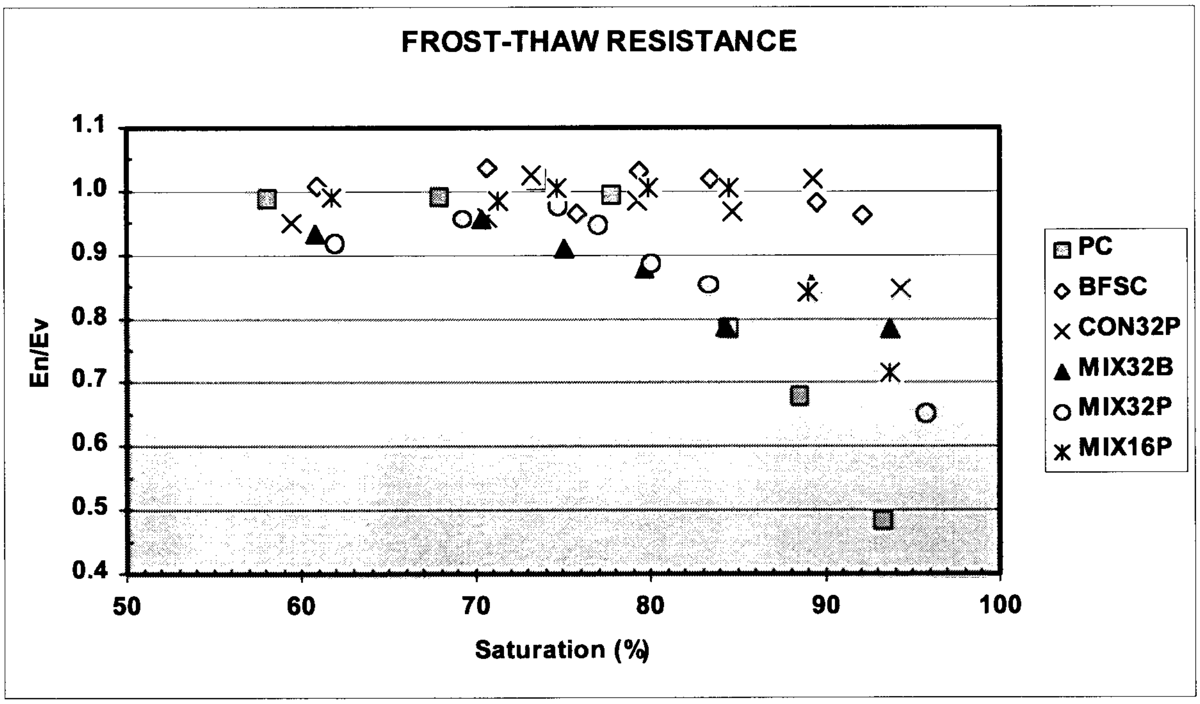
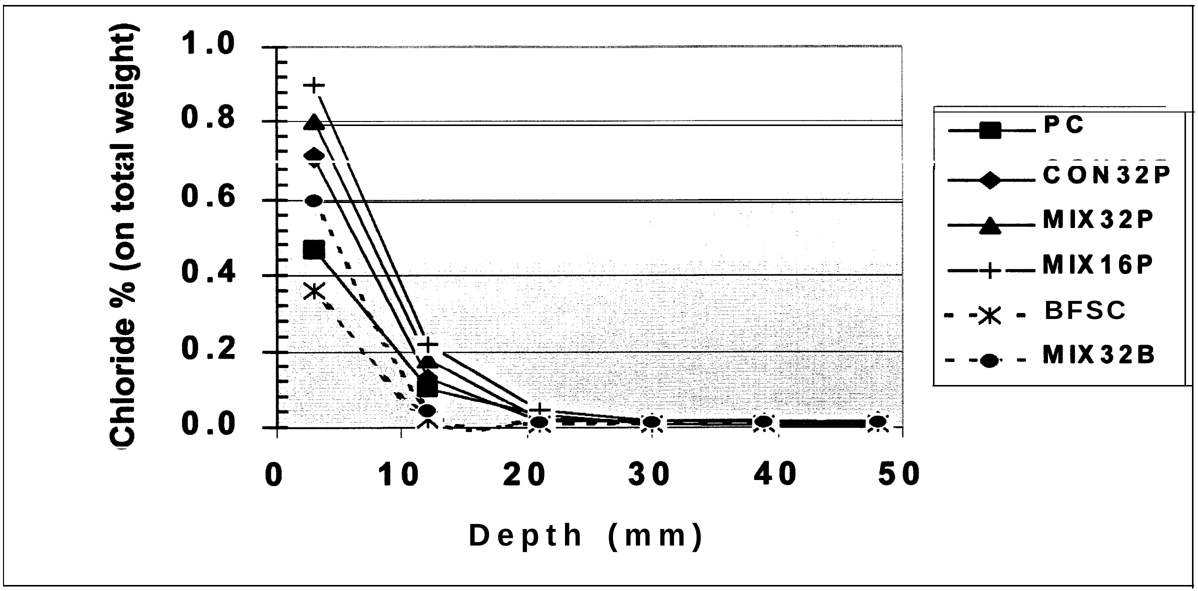


Figure 3. Chloride ingress.



8. CONCLUSIONS AND FUTURE OUTLOOK

Application of recycled aggregates in concrete contributes to closing the concrete life cycle, and reduces the impact on the landscape due to the exploitation and quarrying of natural aggregates.

Recycled aggregates may be applied successfully in concrete. This is especially true for the majority of the concrete market, which consists of relatively low-demanding products. Coarse aggregate replacement levels of 20% to 100% are very well feasible, especially in case of recycled concrete aggregates. The durability of concretes with up to 100% recycled aggregates is, given the concrete quality tested, within range of concrete without recycled aggregates. Both frost-thaw resistance and chloride ingress levels are acceptable for normal use (in the Netherlands). Mix-design should be done with care and experience, since the water demand of notably mixed aggregates is rather high. Pre-wetting is one of the more practical precautions to be taken.

In order to obtain an effective building and demolition recycling industry, the technical- and possible legally required specifications should be made absolutely clear. The best way to obtain good quality aggregates is to work with strict acceptance criteria "at the gate" of a recycling plant. The better the quality and homogeneity of the input, the more easy it is to produce recycled aggregate of high and constant quality. External quality control has proven to be a key element towards a successful market introduction in the Netherlands. The same applies for a clear government commitment.

One of the current discussions in order to stimulate the application of recycled aggregates is to introduce a gate-fee for recycled aggregate, which should counterbalance the residue-dumping costs, which are unavoidable, when the recycled aggregates need to be washed. Currently, the costs of recycled mixed aggregates are approximately 20% less than natural ones, also depending on the building location. Other stimulating actions may consist of prescribing the use of recycled aggegates in buidling specifications. A clear insight in supply and demand of building materials is also needed in order to evaluate results of the stimulating actions taken.

On the long term, it is foreseen that the amount of building and demolition waste will decrease, as a result of renovation, a trend towards more flexible building and an extension of the service life of buildings and structures. From the point of view of integral chain management, application of recycled masonry aggregates in concrete is something that may be of importance when recycling for a second, third or fourth time. The authors are currently addressing this topic [l].

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