$D_{min}$ and $D_{max}$ over from the selected materials. The used distribution modulus amounts to 0.23. For the purpose of comparison the PSDs of all contained materials are given too.

### 3.3. Experimental Results

Using both the new design concept based on the particle grading and the information given by the determination of the water demands, various SCC mixes have been produced and tested for their fresh and hardened concrete properties. The analysis of this information shows a promising way of designing new kinds of SCC with improved qualities in regard to their workability, mechanical properties and durability. A profound further increase of the cement efficiency to values of 0.19 - 0.22 MPa per kg/m$^3$ (16 – 19 psi per lb/yd$^3$) was obtained.

Another basic observation concerns the application of the water/cement ratio. Up to now the strength was given as a function of the water/cement ratio, the cement content and type of cement (it must be understood that there are also other influences). In applying the new design tool, unconventionally low cement contents [250 to 280 kg/m$^3$ (420 to 470 lb/yd$^3$)] were selected, the water/cement ratio therefore sometimes considerably exceeded the mark of 0.60. Considering the limits given for different exposure classes in the standards, this might be a handicap. Note that with these high water/cement ratios, no high total water contents are obtained. In evaluating the data gathered in the framework of these test series no distinct correlation between water/cement ratio and strength properties could be derived.

Creating different states of packing with equal water/cement ratios, a broad margin of strength values was obtained and contrary equal strength was achieved with different water/cement ratios. Relating, however, strength to water/powder ratios (w/p) a clear linear correlation could be found (all particles smaller than 125 μm ($4.92 \times 10^{-3}$ in.) are counted as powder). The data in Fig. 8 show that for a certain amount of powder in a mix, the lowest possible water content should be found by means of grading optimization (with compliance of requested workability).

Focusing on the achieved compressive strength data, it can be noticed that the general level is high, knowing that a SCC was produced using a cement type CEM III/B 42,5N and aggregate sizes up to 32 mm (1.25 in.) (for most of the mixes). As filler material limestone powder, fly ash and stone waste powders (granite) were employed. The majority of strength measurements amounted to values in the range of 50 up to 60 MPa (7000-8400 psi) which is remarkable considering the fact that for most mixes only 270 kg (595 lb) of cement or even less was used. Another interesting aspect is the application of these bigger aggregates in SCC. Normally, maximum aggregate sizes of 16 mm (0.63 in.) or sometimes 22 mm (0.87 in.) are applied for SCC.

Given that with increasing aggregate size especially the durability properties are affected, a loss of durability qualities was expected for these kinds of concrete. But the packing influence by the *"particle size engineering"* showed a much stronger effect. Finally, SCC mixes have been produced with q = 0.22 having a better durability performance than

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SCCs designed with $D_{max}$= 16 mm (0.63 in.). As an example in Fig. 9 the capillary water absorption as a simple indirect durability parameter of these SCCs is given compared with the improved mixes containing 32 mm (1.25 in.) aggregates. Concretes with $D_{max}$= 32 mm (1.25 in.) and with good workability, durability and medium strength seem to be feasible with cement contents of only 150 kg/m$^3$ (250 lb/yd$^3$) or even less. The used method is based on the particle packing and internal specific surface of all solids in the mix.

This method offers an enormous potential for cement reduction and is one emphasis of ongoing research. Future research will concern the widening of the particle size ratio by lowering the smallest particle size from 400 nm ($1.57 \times 10^{-5}$ in.) down to 10 nm ($3.94 \times 10^{-7}$ in.), adding natural stone aggregate and filler (to produce aesthetic SCC), and developing inorganic coatings that will bond photo-catalytic powders to the concrete surface (so the surface becomes self-cleaning and degrades $NO_x$).

## 4. EARTH-MOIST CONCRETE

As stated in the introduction, in the precast concrete products industry (such as pavement stones, kerbstones and concrete pipes), earth-moist (or "zero-slump") concrete is applied for the mass production of these products. These concrete mixes are dry with a very stiff consistency, so they are rammed in the rigid mould, and after dense compaction, demoulding can take place almost immediately so that short processing times with high quantities can be achieved. In the past, relatively little attention has been paid to these concretes; a recent thorough study was made by Bornemann [24].

Capillary forces between the finer particles combined with the inner friction of the mix then provide the required so-called green strength. In soil mechanics this phenomenon is also called apparent cohesion, which can only be activated in partially saturated sands or sandy soils. Here, the content of fines as well as the fineness of the smaller particles and the degree of saturation influences the capillary forces. Caused by their dry consistency associated with low water content, earth moist concrete mixes show a low degree of hydration after production and a high potential for reactions afterwards during weathering which renders the products durable [25]. For that reason, and caused by the short processing times, earth-moist concrete mixes are the ideal starting substance for the mass production of concrete products.

Although earth-moist concrete mixes are used on a big scale for the mass production of the aforementioned earth-moist concrete products, the applied methods for designing mixes are strongly geared to procedures and standards for standard concrete. Nevertheless, the regulations that apply to these products allow innovations such as cement reduction, introduction of nanoparticles, application of stone sludge waste, a higher and tailor-made aggregate content etc. In particular, the reduction and substitution of expensive primary filler materials (cement) by secondary stone waste materials is of vital importance for the cost reduction. Here, this will be demonstrated by the results of first preliminary tests on earth-moist concrete.

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### 4.1. Preliminary Tests on Earth-Moist Concrete

First tests on earth-moist concrete were executed in order to confirm the fundamental idea of the newly developed mix design which was already applied for the mix proportioning of self-compacting concrete mixes (see above). Improved densest possible packing is the philosophy of this new approach. With an improved and optimised packing of all aggregates, considering all particles from the coarsest to the finest particle size, the properties of concrete in hardened as well as fresh state can be affected in a positive way. This was already observed and recommended by Féret [15] and Fuller and Thompson [19].

To determine the usability of the newly developed mix design tool for earth-moist concrete, several mixtures with different mix proportioning were investigated. Based on the distribution function for continuously graded particle mixtures based on Eq. (3), different distribution moduli q were examined. The range of investigated distribution moduli ranged from 0.25 to 0.40 in combination with different w/c ratios. For the mix proportioning different kinds of Rhine sands (sizes 0/1, 0/2, 0/4), natural gravel (sizes 2/8, 4/16, 8/16), as well as crushed granite (size 2/8) were used. A CEM III/B 42.5N LH/HS or a mix of CEM III/B 42.5N LH/HS and CEM I 52.5N were applied as binder. Fig. 10 shows the PSDs for some of the tested earth-moist concrete mixes.

These designed mixes were evaluated regarding:

- Degree of compactibility using defined and constant compaction effort;
- Packing density;
- Density of fresh concrete according to DIN-EN 12350-6:2000;
- Density of hardened concrete according to DIN-EN 12390-7:2001;
- Compressive strength according to DIN-EN 12390-3:2002;
- Tensile splitting strength according to DIN-EN 12390-6:2001.

Furthermore, the water demand of the used powders was determined according to the applied test procedures described for SCC. Fig. 11 depicts the improvement of the mechanical properties of hardened concrete considering the relation between packing density and compressive strength.

The line pertaining to 310 kg (520 lb/yd$^3$) cement per m$^3$ concerned CEM III/B 42.5N LH/HS, the line pertaining to 325 kg (550 lb/yd$^3$) cement per m$^3$ concerned a mix of CEM III/B 42.5N LH/HS and CEM I 52.5N. Both lines clarify that an improved packing with higher packing density results in a stronger concrete while maintaining constant cement content. The applied cement contents of 310 kg and 325 kg (520 and 550 lb/yd$^3$) per m$^3$ concrete are necessary to follow the given target function for the grading as close as possible. Cement contents between 350 kg and 375 kg (590 and 630 lb/yd$^3$) per m$^3$ concrete are usually used in current line productions. But this amount can be reduced by selecting the right distribution modulus q for the target function. In doing so, the reduction of cement content from 375 kg to 325 kg (630 to 550 lb/yd$^3$) per m$^3$ leads to a

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cost reduction of 13.3%, considering the actual prices for aggregates and cement in the Netherlands.

Note that the fitted trend lines in Fig. 11 extrapolate to compressive strengths of 118 and 183 MPa (17 and 27 ksi) for 310 kg and 325 kg/m$^3$ (520 and 550 lb/yd$^3$) cement per m$^3$, respectively, if 100% would be achieved, implying maximum theoretical cement efficiencies of 0.38 and even 0.56 MPa per kg/m$^3$ (33 and 49 psi per lb/yd$^3$). The latter value reveals that adding a finer cement (CEM I 52.5N to CEM III/B 42.5N LH/HS) substantially improves the cement efficiency, most likely by the improved packing and the larger specific surface. From Fig. 11 one can see that at a packing fraction of 85%, actual cement efficiencies of 0.20 to 0.30 MPa per kg/m$^3$ (17 to 26 psi per lb/yd$^3$) are achieved, which can be further enhanced by improved packing, e.g. by applying nanometre particles. Considering the high compressive strength, as well as tensile splitting values for mixes with 325 kg/m$^3$ (550 lb/yd$^3$), the design method also allows reducing the cement content further. The achieved compressive strength of about 100 MPa (14.5 ksi) at 85% packing is namely far in excess of the requirements given by the Dutch standards.

Also, the tensile splitting strength for mixes with 325 kg (550 lb/yd$^3$) cement per m$^3$ is with 4.9 MPa to 5.0 MPa (710 to 725 psi) higher than required by the Dutch standard NEN-EN 1338. For tensile splitting strength, the NEN-EN 1338 prescribes a characteristic value higher than 3.6 MPa and an individual value higher than 2.9 MPa (420 psi) for pavement stones. A further reduction of the cement content is therefore possible if a suitable material for replacement is available. For this purpose, the grading of the mineral additive should follow the grading of the replaceable part of cement as close as possible or should have even a higher fineness (lower mean particle diameter). A suitable mineral additive can be found in stone waste powders generated during the processing of natural stone. These powders will be applied in future tests on earth-moist concrete regarding their positive effects on mechanical as well as durability properties.

Based on the results obtained from tests on concrete in fresh as well as hardened state, the following standard values for the proportioning of earth-moist concrete are advisable:

| | |
|---|---|
| Distribution modulus q: | 0.325 – 0.375 (mean 0.35) |
| Paste content [< 125 μm (4.92 × 10$^{-3}$ in.)]: | 0.225 – 0.25 m$^3$ per m$^3$ (yd$^3$ per yd$^3$) |
| Water/powder ratio (w/p): | 0.30 – 0.39 |
| Water/cement ratio: | 0.35 – 0.40 |

The use of lower distribution moduli than 0.30 is not advisable for earth-moist concrete mixes as the content of fines is strongly increasing with distribution moduli smaller than 0.30 (Fig. 12) and the mixes are not workable without using high compaction efforts or big amounts of admixtures. The use of distribution moduli higher than 0.40 is also not suitable for earth moist concrete mixes as the better workability/compactibility of these mixes without plasticizers is resulting in a worse packing caused by a missing content of powders [particles smaller than 125 μm (4.92 × 10$^{-3}$ in.)].

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The best results regarding packing density and compressive strength could be achieved for the preliminary mixes using the above mentioned values. Based on the first results presented here, future research will focus on the role of basic parameters such as the internal specific surface, packing density, water/air content (saturation) etc on compactability, green strength, production speed and properties in hardened state. The objective is to design mixes that are cheaper and environmentally friendly, and that also meet all practical requirements.

## 5. SUMMARY AND CONCLUSIONS

New European regulations allow more and more the performance design of materials and structures, which offers opportunities to introduce nanoparticles in a cost effective way in concrete mixes. For properties that can relatively easily be evaluated, such as mechanical (compressive strength etc), it enables cost effective solutions, also in regard to the materials choice. In this paper, which focuses on calcium oxide-based products (cement, lime, sulphates), examples are given of concrete that outperform in regard to technical properties, sustainability and costs. These products are obtained by the consequent and systematic use of *mineral oxide engineering* and *particle size engineering*.

This *particle size engineering* approach is based on the packing and internal specific surface area of all solids in a concrete mix. Up to now, already 13 binders (cements, lime, calcium sulphates), 11 fillers (natural stone waste, fly ashes, granulated slag, $TiO_2$ powders etc), 7 sands and 6 gravels (primary, recycled) have been characterized in regard to their PSD [from 10 nm to 32 mm ($3.94 \times 10^{-7}$ to 1.25 in.)] and specific surface area, and this number is steadily growing. They can all be combined in the newly developed mix design software tool. This mix design method renders the common material cement a high-tech material when the obtained specific strength (*cement efficiency*) is considered: from 0.22 MPa (SCC) to 0.30 MPa (earth-moist concrete) per kg/m$^3$ (19 to 26 psi per lb/yd$^3$). For example, considering a steel density of 7900 kg/m$^3$ (13,300 lb/yd$^3$), this material would need a compressive strength of 1738 MPa to 2370 MPa (252 to 344 ksi) to match these cement efficiencies. Though the comparison is not completely fair, as full hydration of 1 kg (2.2 lb) of the cement requires about 0.4 kg (0.9 lb) of water, the required steel strength is not so easy to achieve.

Based on *mineral oxide engineering*, slag reactivity and hydration can be simulated, allowing the optimum substitution of clinker by granulated slag. The model also permits the development of new binders/additions, such as shrinkage-compensating cement. These additions add to the size stability and to the tightness (durability) of concrete. Another result is recipes that speed up the ripening process of dredging sludge, and that render highly contaminated dredging sludge into an applicable building material[4] [26]. Furthermore, the 3-D simulation of the prevailing cement packing and subsequent chemical reactions has proven to be a useful design tool. The results show that by

[4] The fruitful application of *mineral oxide engineering* for the development of recipes for soil and dredging sludge, that both also mainly consist of mineral oxides, has not been discussed in the present paper.

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combining coarser and finer (nano-) cements, the cement efficiency can be improved, i.e. this offers opportunities for increasing the added value of cement.

From this study it also appears that the water/powder ratio [w/p, whereby powders are defined as all particles in the mix < 125 μm (4.92 × $10^{-3}$ in.)] is an important design parameter. The w/p is perhaps a better parameter for assessing the mechanical and physical properties of concrete than the conventional w/c. In this respect it could also be recommended to use the w/p as reference for the maximum water content of a concrete mix, or alternatively, to simply maximize the water content as such, e.g. 150 l/$m^3$ (423 gal/$ft^3$), as is also the case already with the air content in concrete (commonly maximized to 30 l/$m^3$ (85 gal/$ft^3$)). Summarizing, the recent "functional demand" approach, as well as the combined particle size engineering and mineral oxide engineering presented here, enable a cost effective and more sustainable development of civil and residential concrete structures. Applied in a smart way, using advanced mix design tools, nanoparticles can play an important role in this development.

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Table 1. Mix proportions of the mix from Fig. 7.

| Material | Volume (*l*) | Mass (kg) |
|---|---|---|
| CEM III/B 42,5N NW/HS/NA | 103.8 | 300.0 |
| Limestone Powder | 35.0 | 91.5 |
| Marble Powder | 63.5 | 174.1 |
| Sand 0-1 | 38.4 | 101.3 |
| Sand 0-4 | 259.7 | 686.2 |
| Gravel 2-8 | 122.9 | 321.9 |
| Gravel 4-16 | 214.7 | 559.2 |
| Water | 150.0 | 150.0 |
| Air | 12.0 | - |
| Total | 1,000.0 | 2,384.3 |

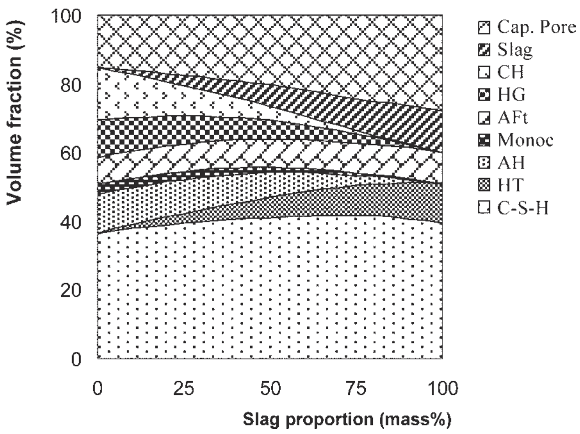


Fig. 1—Predicted and measured C/S ratio in C-S-H versus slag proportions in blended cement (experimental data from [12], ratio of the slag/clinker hydration degrees is 0.7, *w*/*b* = 0.4).

For figure and table conversions, please see the conversion factors table on p. 157-158.

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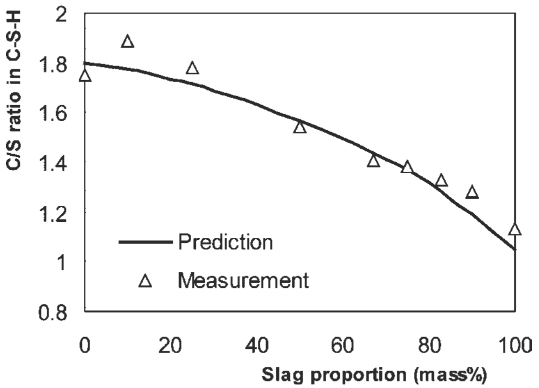


Fig. 2—Volume fraction of products in hydrating slag cement paste vs. slag proportions ($w/b$ = 0.4, assuming all clinker and 70 percent of slag has reacted).

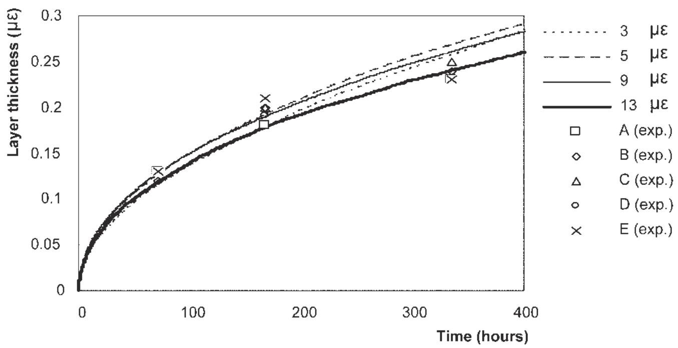


Fig. 3—Effect of particle size on the hydrated layer thickness of slag particles (experimental data from [13]).

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