Modified Reactive Powder Concrete with Artificial Aggregates

by S. Monosi, G. Pignoloni, S. Collepardi, R. Troli, and M. Collepardi

Synopsis: Reactive Powder Concretes (*RPC*) - in form of superplasticized cement mixtures with silica fume, steel fibers, quartz fine sand (100-400 μm) and/or limestone coarse aggregate (0.1-8 μm) - were studied in comparison with modified *RPC* where artificial aggregates substituted for natural aggregates.

Artificial aggregates were obtained by grinding portland clinker coarsely so that fine and coarse aggregate were obtained with approximately the same particle size distribution of natural fine quartz (100-400 μm) and limestone gravel (0.1-8 mm) respectively.

The source of clinker-aggregate was the same as that used for portland cement as binder of *RPC*. The idea was to improve the bond strength between cement paste and aggregate due to some hydration of the clinker-aggregate surface.

RPC specimens were cured at room temperature (20°C) or steam-cured at low or high pressure at 90°C or 160°C respectively. Compressive strengths were measured as a function of time at 1-28 days. The 28-day compressive strength level was as high as 200 MPa.

Regardless of the curing temperature, compressive strength of *RPC* was increased by about 20 MPa when clinker-aggregate was used instead of natural aggregates. These results indicate that the bond strength of the interface between cement paste and aggregate is improved when clinker particles are used instead of natural stones. Scanning electron microscope observations of the microstructure confirmed this hypothesis and indicated that the interface between cement paste and natural aggregate is the weak point in *RPC*.

Keywords: aggregate; concrete (fiber-reinforced); silica fume; superplasticizer

Saveria Monosi is Assistant Professor of Materials Technology in the University of Ancona. She is author or co-author of numerous papers in the area of concrete durability and chemical admixtures.

Gioacchino Pignoloni is a PhD student working in the area of cementitious materials, University of Ancona, Italy.

Silvia Collepardi is a research civil engineer of Enco, Spresiano, Italy. She is working in the field of superplasticized concrete mixtures and has published several papers in this area.

Roberto Troli is a research civil engineer and Director of the Enco laboratory. He is author of several papers in the field of concrete technology, particularly in the area of chemical and mineral admixtures.

Mario Collepardi is Professor of Materials Science and Technology at the Ancona University, Italy. He is author or co-author of numerous papers on concrete technology and cement chemistry. He is also the recipient of several awards for his contributions to the fundamental knowledge of superplasticizers and their use in concrete.

INTRODUCTION

Reactive Powder Concrete (*RPC*) is a cement-based material which performs like a low-porosity ceramic material with compressive strength of about 200 MPa. However, *RPC* can be placed by casting techniques and curing conditions as those usually adopted for *in situ* placed or precast concrete structures. This material is expected to be used more in the area of machine parts (moulds for metallic parts of cars) or environmental applications (watertight containers of hazardous fluids or nuclear waste) rather than in the field of infrastructural or building engineering.

According to Richard and Cheyrezy (1), *RPC* consists of a fiber-reinforced, superplasticized, silica fume-cement mixture with very low water-cement ratio (*w/c*) and only fine aggregate (max size: 0.4 mm) instead of both course and fine aggregate. Therefore, in reality, it is not a concrete because there is no coarse aggregate in the cement mixture. The absence of coarse aggregate was considered by the inventors to be a key-aspect for the microstructure and the performance of the *RPC* in order to reduce the heterogeneity between the cement matrix and the aggregate.

However, Collepardi et al. (2) studied a modified *RPC*, where a well graded natural aggregate (max. size 8 mm) replaced the very fine quartz, and they did not find any decrease in the compressive strength (200 MPa). The purpose of this study was to investigate the effect of using crushed Portland cement clinker particles as a fine and coarse aggregate in *RPC*.

EXPERIMENTAL

Materials

Cementitious materials: A C_3A-free ASTM Type V portland cement (Blaine fineness 340 m^2/Kg) and an un-densified silica fume were used as cementitious binders. Chemical composition of these materials is shown in Table 1; other properties were also given in previous papers (2-4).

Natural aggregates: Fine ground quartz sand (max. size: 0.4 mm), with a specific gravity of 2.75 g/cm^3, was used for manufacturing the *RPC* mixture according to the original composition given by Richard an Cheyrezy (1). For modified *RPC* mixtures (2), well graded natural aggregate (maximum size: 8 mm, and specific gravity 2.75 to replace the whole volume of the fine ground quartz. Figure 1 shows the particle size distribution of the ground fine sand in agreement with the original *RPC* and that of the natural aggregate — a limestone based rock — used to replace the fine quartz and manufacture the modified *RPC*.

Artificial aggregates: The same portland clinker, as that used for the portland cement shown in Table 1, was crushed to obtain about the same particle size distribution as the natural aggregates (Fig. 1). The specific gravity was 3.13 g/cm^3 for the fine aggregate, and 2.95 g/cm^3 for the graded aggregate (0.1-8 mm).

Fibers: Steel fibers — 13 mm long with a diameter of 0.18 and an aspect ratio of 72 — were used.

Superplasticizer: An acrylic polymer (*AP*), in the form of a 30% aqueous solution from Mapei, Milan (Italy), was used as superplasticizer. Details on the performance of this superplasticizer, with respect to other superplasticizers, are given elsewhere (5, 6).

Concrete Mixtures

Two *RPC* with natural aggregates – quartz or limestone – were manufactured by keeping the same mass proportion in the dry mixture as that of the "original" *RPC* (1):

- cement 100 parts
- silica fume 25 parts
- superplasticizer dry polymer 1.36 parts
- steel fibers 20 parts
- aggregate 110 parts

In other two *RPC*, with artificial aggregates, fine or graded clinker particles replaced the whole volume of quartz or limestone respectively.

For each concrete mixture, a proper amount of mixing water – including that of the superplasticizer aqueous solution – was used to attain to the same workability level corresponding to a plastic-fluid consistency: about 185 mm according to a modified flow table test described in previous papers (3, 4).

Table 2 shows the composition of mixtures No. 1 and No. 2 with natural and artificial fine aggregate, respectively. Table 3 indicates the composition of mixtures No. 3 and 4 with natural and artificial graded aggregate respectively.

All concrete specimens were consolidated by vibration and measurements were carried out after an adequate curing time.

Curing

Concrete specimens were moist cured in three different conditions:

- *room temperature* (always at 20°C)
- *steam curing*: at 90°C after a preliminary curing at 20°C for 6 hours;
- *high-pressure steam curing* (autoclave process) at 160°C after a preliminary curing at 20°C for 24 hours.

Diagrammatic presentation of these curing processes is shown in Fig. 2.

Testing

Compressive strength of hardened concrete was tested on cube specimens (40mm). Some visual observations of the microstructure were also recorded by scanning electron microscopy (*SEM*).

RESULTS

Figure 3 shows the compressive strength as a function of curing time at 20°C of the "original" *RPC* with fine quartz (Mix No. 1, Table 2) versus the modified *RPC* with clinker as fine aggregate (Mix No. 2, Table 2). The substitution of the clinker aggregate (0.1-0.4 mm) for the fine quartz caused a slight increase of the order of about 10%.

Similar results, with a strength increase of about 20%, were obtained when the artificial graded aggregate (0.1-8 mm) replaced the natural one in *RPC* cured at 20°C (Fig. 4).

Steam curing at 90°C causes a strength increase at early ages with respect to the *RPC* cured at room temperature. Figures 5 and 6 show the compressive strength of steam-cured *RPC* with fine and graded aggregate respectively: again *RPC* with artificial aggregate performed better (about 20-30% more strength) than the corresponding *RPC* with natural aggregates.

High-pressure steam curing at 160°C causes a further strength increase with respect to the *RPC* steam-cured at 90°C. Again the *RPC* with artificial aggregates (clinker) performed better than the corresponding natural aggregates

(Fig. 7-8). In particular, the strength difference is remarkable (20%) with graded aggregates (Fig. 8), and negligible (5%) with fine aggregates (Fig. 7).

All the above results would indicate that, due to chemical reaction with the the clinker phase, the interfacial bond between the cement matrix and the artificial aggregate was stronger than the corresponding bond in *RPC* with natural aggregate. Only when fine siliceous aggregate (quartz) and high-pressure steam curing (160°C) were used the difference with respect to the corresponding *RPC* with the fine clinker aggregate became negligible (Fig. 7). This is due to the thermal activation of the finely ground quartz which, at 160°C, can react with calcium hydroxide (7).

If the increase in the bond strength between the artificial aggregate and the cement matrix is responsible for the increase in the compressive strength (Fig. 3-8), then this means that the weak link of the chain in the compressive strength of *RPC* with natural aggregates is the interface between the cement paste and aggregate. Visual observations by *SEM* seem to be in agreement with this hypothesis. Figures 9 and 10 show the micrographs of the aggregate-cement paste interface in the *RPC* with natural (limestone) and artificial (clinker) aggregate, respectively. In the micrograph of *RPC* with natural aggregate (Fig. 9) there are visible voids at the interface between the cement matrix and the limestone particles. On the other hand, in the microstructure of the *RPC* with the artificial aggregate (Fig. 10), the clinker phase can be distinguished (on left-above of the micrograph) from the cement matrix only for its inherent morphological feature characterized by the presence of irregular voids in the coarse particles of un-ground clinker (Fig. 11). One cannot see any discontinuity at the interface between the cement matrix and the clinker phase acting as artificial aggregate (Fig. 10).

CONCLUSIONS

The substitution of artificial aggregate in forms of clinker grains for the natural aggregate, at equal particle size distribution increased the compressive strength of *RPC* by about 20%.

The increase was only 5% when the natural aggregate was a fine siliceous powder and the mortar mixture was cured at high-pressure (160°C).

The increase in the compressive strength of *RPC* containing clinker as coarse aggregate is attributable to a stronger bond between the cement matrix and the clinker coarse aggregate particles as a result of interfacial chemical reaction.

ACKNOWLEDGEMENT

Financial support from the National Council of Research (CNR) of Italy is thankfully acknowledged.

The assistance of Isabella Capogna in preparing the text and the Figures is also acknowledged.

REFERENCES

1. Richard. P. and Cheyrezy, M.H. "Reactive Powder Concretes with High Ductility and 200-800 MPa Compressive Strength", *Concrete Technology: Past, Present, and Future, Proceedings of the V. Mohan Malhotra Symposium*, ACI SP-144, S. Francisco 1994, pp.507-518, Editor: P.K. Mehta.
2. Collepardi, S., Coppola, L., Troli, R., and Collepardi, M., "Mechanical Properties of Modified Reactive Powder Concrete", *Procedings of the International Conference on Superplasticizers and Other Chemical Admixtures*, ACI SP-173-1, 1997, pp 1-21, Editor V.M.Malhotra.
3. Coppola, L., Troli, R., Collepardi, S., Borsoi, A., Cerulli, T., and Collepardi, M. "Innovative Cementitious Materials. From HPC to RPC. Part II. The Effect of Cement and Silica Fume Type on the Compressive Strength of Reactive Powder Concrete", *L'Industria Italiana del Cemento*, 707, 1996, pp. 112.125.
4. Coppola, L., Cerulli, T., Troli, R., and Collepardi, M. "The Influence of Raw Materials on Performance of Reactive Powder Concrete", *International Conference on High-Performance Concrete, and Performance and Quality of Concrete Structures*, Florianopolis, Brazil, 1996, pp. 502-513.
5. Cerulli, T., Collepardi, M., Coppola, L., Ferrari, G., Pistolesi, C., Quek, F. and Zaffaroni, P. "Zero Slump-Loss Superplasticized Concrete", 18th *Conference on Our World in Concrete & Structures*, Singapore, 1993, pp 73-79.
6. Collepardi, M. "Superplasticizers and Air Entraining Agents: State-of-the-Art and Future Needs", *Concrete Technology: Past, Present, and Future, Proceedings of the V. Mohan Malhotra Symposium*, ACI SP-144, San Francisco 1994, Editor: P.K. Mehta, pp 399-416.
7. Taylor, H.F.W., "*Cement Chemistry*", 2nd Edition, Thomas Telford, London, 1997, pp. 459.

Table 1. Composition and properties of silica fume and portland cement (type V ASTM or CE I 42.5R according to ENV 197/1)

Composition (%) - Property	Portland Cement	Silica Fume
SiO_2	20.59	98.87
Al_2O_3	3.66	0.01
Fe_2O_3	6.10	0.01
CaO	63.78	0.23
MgO	0.95	0.01
K_2O	0.48	0.08
Na_2O	0.26	0.00
SO_3	2.50	0.23
C_3A	0.00	—
Blaine fineness (m^2/kg)	340	—
Mean particle size (μm): without superplasticizer with superplasticizer	 — —	 13.87 0.76

Table 2. Composition of RPC with fine aggregate

Materials	Batch composition (Kg/m^3)	
	Mix No.1	Mix No.2
Portland cement	930.0	933.0
Silica fume	232.5	233.3
Superplasticizer	12.6	12.7
Steel fibers	186.0	186.6
Natural quartz (0.1-0.4 mm)	1023.0	-
Portland clinker (0-0.4 mm)	-	1186.0
Water	232.5	251.9
w/c	0.25	0.27
w/cm	0.20	0.22
Flow table (mm)	190	194

Table 3. Composition of RPC with coarse aggregate

Materials	Batch composition (Kg/m^3)	
	Mix No.3	Mix No.4
Portland cement	928.7	932.2
Silica fume	232.0	232.8
Superplasticizer	12.6	12.7
Steel fibers	185.7	186.2
Natural limestone (0.1-8 mm)	1021.6	-
Portland clinker (0.1-8 mm)	-	1098.8
Water	241.4	242.1
w/c	0.26	0.26
w/cm	0.21	0.21
Flow table (mm)	180	175

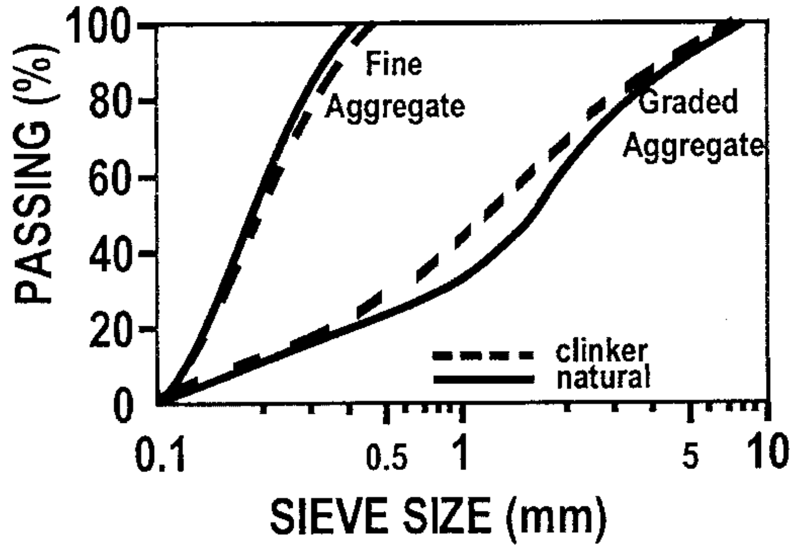

Fig. 1 - Particle size distribution of the natural and artificial (clinker) aggregates used in RPC

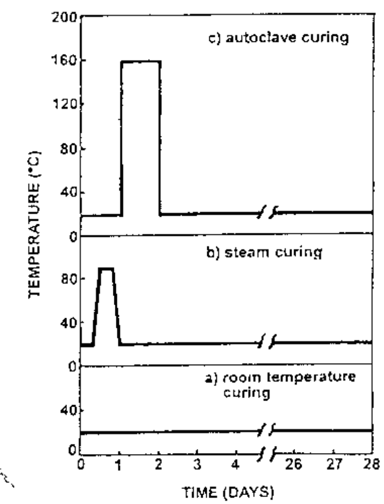

Fig. 2 - Temperature versus time for the three curing conditions

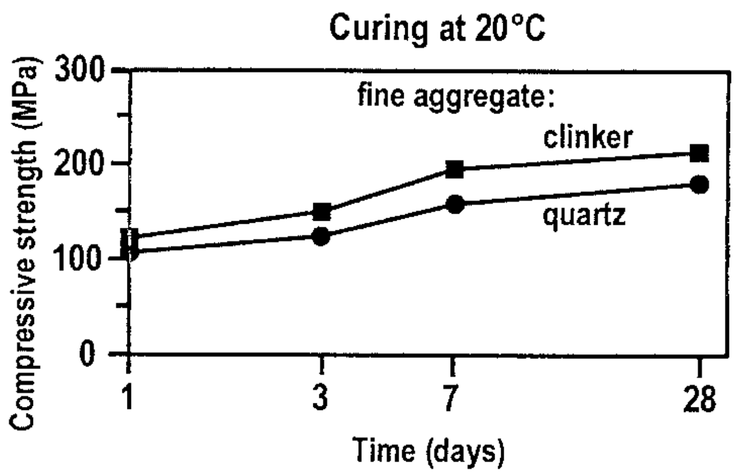

Fig. 3 - Compressive strength of RPC with natural (quartz) or artificial (clinker) fine aggregate at 20°C.

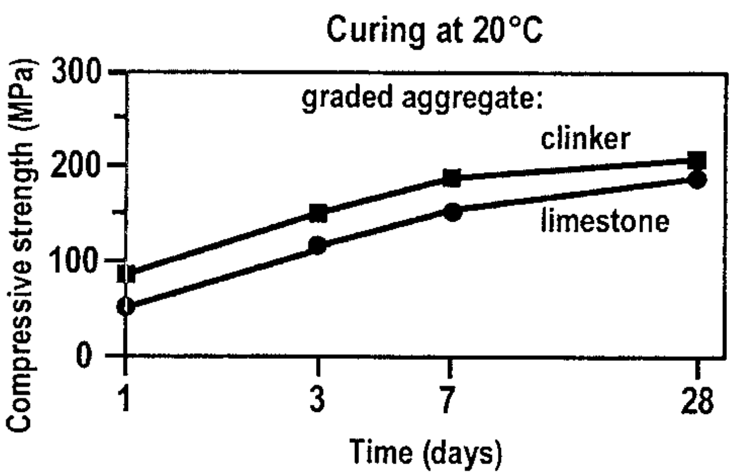

Fig. 4 - Compressive strength of RPC with natural (limestone) or artificial (clinker) graded aggregate (0.1 - 8 mm) at 20°C.

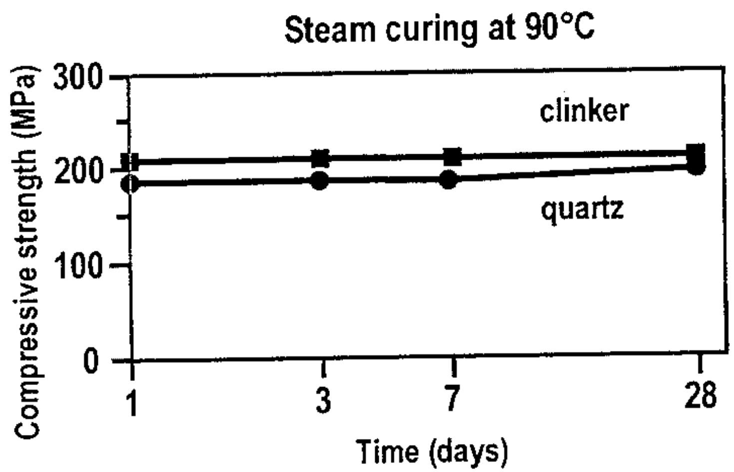

Fig. 5 - Compressive strength of steam-cured (90°C) RPC with natural (quartz) or artificial (clinker) fine aggregate.

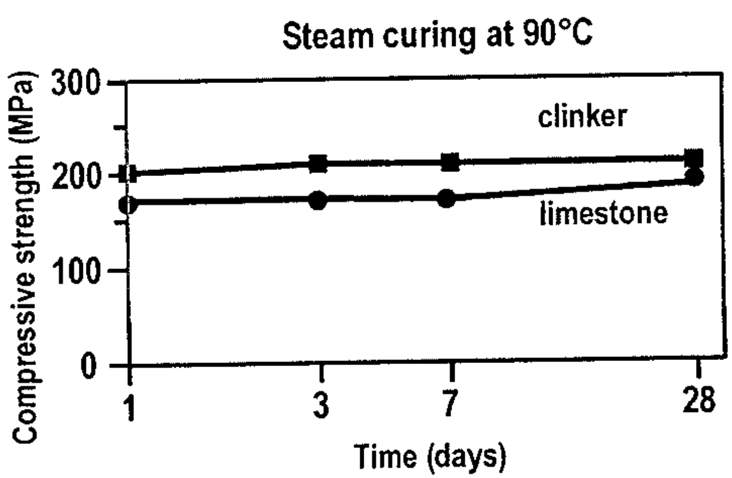

Fig. 6 - Compressive strength of steam-cured (90°C) RPC with natural (limestone) or artificial (clinker) graded aggregate (0.1 - 8 mm).

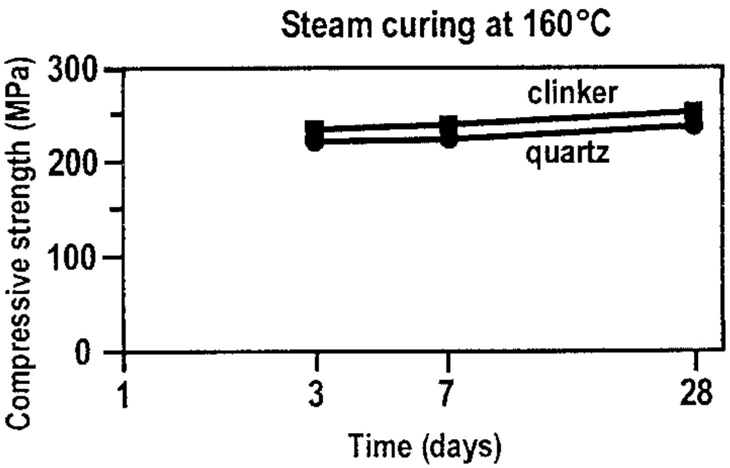

Fig. 7 - Compressive strength of high-pressure steam-cured (160°C) RPC with natural (quartz) or artificial (clinker) fine aggregate.

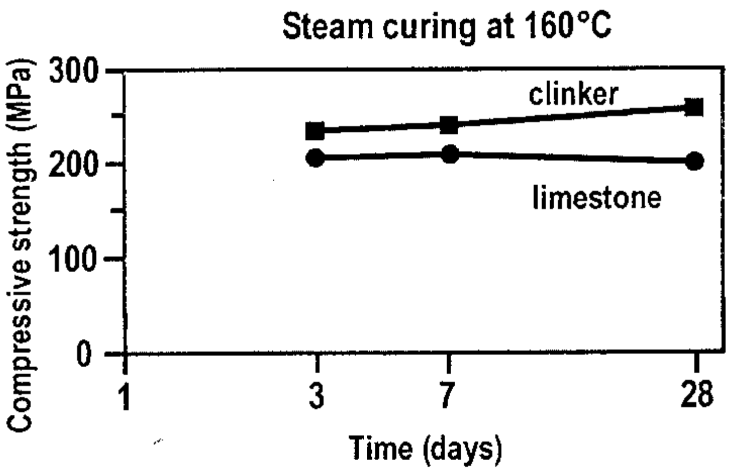

Fig. 8 - Compressive strength of high-pressure steam-cured (160°C) RPC with natural (limestone) or artificial (clinker) graded aggregate (0.1 - 8 mm).

Fig. 9 - SEM micrograph of RPC with limestone aggregate (above).

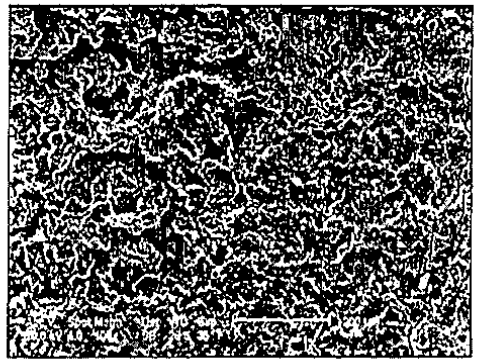

Fig. 10 - SEM micrograph of RPC with coarse clinker aggregate (left/above).

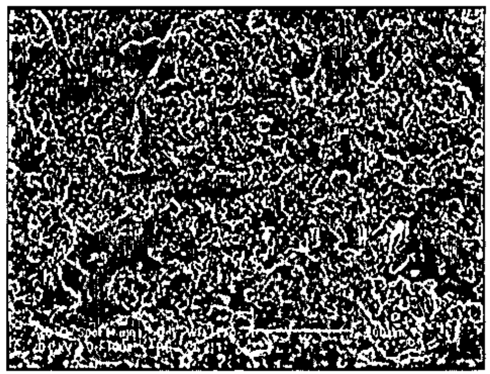

Fig. 11 - SEM micrograph of a single clinker aggregate.