

## **Mechanical Properties of Modified Reactive Powder Concrete**

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Synopsis: Original Reactive Powder Concrete (*RPC*) - in form of a superplasticized cement mixture with silica fume, steel fibers and ground fine quartz (150-400  $\mu\text{m}$ ) - was studied in comparison with a modified *RPC* where a graded natural aggregate (max size 8 mm) was used to replace the fine sand and/or part of the cementitious binder.

Original and modified *RPC* were manufactured at a plastic-fluid consistency, cast by vibration and cured at three different conditions: *a*) room temperature; *b*) steam-curing at 90°C; *c*) high pressure steam-curing at 160°C.

The addition of the graded aggregate does not reduce the compressive strength provided that the quality of the cement matrix, in terms of its water-cement ratio, is not changed. This result is in contrast with the model proposed to relate the high compressive strength level of *RPC* (200 MPa) to the absence of coarse aggregate.

Both the original and modified *RPC* (with the coarse aggregate addition) perform better - in terms of higher strength and lower drying shrinkage or creep strain - when they are steam cured rather than cured at room temperature. This improvement was related to a more dense microstructure of the cement matrix, particularly in the *RPC* specimens steam cured at 160°C.

Keywords: Creep properties; flexural strength; high-strength concrete; shrinkage; silica fume; steels; superplasticizers; toughness.

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## INTRODUCTION

The term Reactive Powder Concrete (*RPC*) has been used to describe a fiber-reinforced, superplasticized, silica fume-cement mixture with very low water-cement ratio (*w/c*) characterized by the presence of very fine quartz sand (0.15-0.40 mm) instead of ordinary aggregate (1, 2). In fact, 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* (1, 2) in order to reduce the heterogeneity between the cement matrix and the aggregate. However, due to the use of very fine sand instead of ordinary aggregate, the cement factor of the *RPC* is as high as 900-1000 kg/m<sup>3</sup>. This unusual cement factor could increase drying-shrinkage and creep strain of the *RPC* with respect to ordinary concrete with cement factor usually in the range of 300-500 kg/m<sup>3</sup>.

The main purpose of the present investigation was to modify *RPC* including some coarse aggregate in the mixture and to study the influence of the coarse aggregate on the properties of cement mixtures in terms of required mixing water, compressive and flexural strength, shrinkage, swelling and creep.

Moreover, with respect to the original manufacturing process (1) - where additional sophisticated treatments are also used to remove the excess of mixing water through compacting pressure of the mixture in the moulds before and during setting, or to prolong the heating process at 90-400°C to dry the hardened material - traditional casting by vibration of fresh mixtures and conventional curing processes were adopted in the present investigation.

## EXPERIMENTAL

### Materials

A C<sub>3</sub>A-free portland cement (Blaine fineness 340m<sup>2</sup>/kg), combined with a grey-coloured un-densified silica fume, was used as cementitious binder (Table 1). Details on chemical composition and properties of these materials were also given in previous papers (2, 3).

Fine ground quartz sand (0.15-0.40 mm) with a specific gravity of 2.75 g/cm<sup>3</sup> was used for manufacturing the *RPC* mixture according to the original composition given by Richard and Cheyrezy (1). For modified *RPC* mixtures, well graded natural aggregate (maximum size: 8 mm, and specific gravity 2.75 g/cm<sup>3</sup>) was used to replace a part or the whole volume of the fine sand and/or a part of the cementitious binder. 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 in the present investigation to replace the fine sand and manufacture the *RPC*.

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

An acrylic polymer (*AP*), in form of a 30% aqueous solution, was used as superplasticizer. Details on the performance of this superplasticizer, with respect to other superplasticizers, are given elsewhere (4, 5).

### Concrete Mixtures

Three sets of concrete mixtures were manufactured with respect to the original *RPC* composition without coarse aggregate:

- i)* a set where the amount of ground fine quartz sand (0.15-0.40 mm) of the original *RPC* composition was partially or totally replaced by the natural graded aggregate (0-8 mm) without changing the cement factor (Table 2);
- ii)* a set where part of the cementitious binder (cement + silica fume) was replaced by the graded aggregate (0-8 mm) without changing the amount of fine sand (Table 3);
- iii)* a set where part of the cementitious binder and the whole of fine sand was replaced by the graded aggregate (Table 4).

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: 150-155 mm according to a modified flow table test described in other papers (2, 3).

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:

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

Details of these curing process are shown in Fig. 2.

### **Measurements**

The following properties were measured on hardened concrete specimens:

- compressive strength on cube specimens (40 mm);
- observation of the microstructure by scanning electron microscopy;
- flexural strength and stress-strain curves by symmetrical two point loading test on beam specimens (150x150x600 mm);
- flexural strength by one central loading test on prism specimens (40x40x160 mm);
- steel-concrete bond measured through pull-out test on deformed steel bars (diameter 20 mm) embedded for 100 mm in a 200-mm cube specimens;
- shrinkage (65% R.H.) and swelling (under water) of prism specimens (50x50x250 mm);
- modulus of elasticity and creep strain on cylinder specimens (diameter of 60 or 120 mm with height/diameter of 2) under stress of 13.3 or 53.0 MPa.

## RESULTS

The data of the present work will be examined in two separate sections: preliminary tests on compressive strength of the mixtures shown in Tables 2 to 4, and the additional tests on some specific mixtures.

## Compressive Strength

Figure 3 shows the compressive strength of the “original” *RPC* with ground quartz sand only (Mixture No. 1 on Table 2) versus modified *RPC* where this fine sand was partly or totally replaced by the graded aggregate with a maximum size of 8 mm. (Mixture No. 2 or 3 respectively). A small strength increase was recorded when the fine quartz sand (Mixture No. 1 in Fig. 3) was replaced by the coarser natural graded aggregate (Mixtures No. 2 and 3 in Fig. 3) due to the small reduction in the  $w/c$  (Table 2). The 28-day compressive strength was in the range of 160-180 MPa for the specimens cured at room temperature or steam-cured at 90°C, and in the range of 190-210 MPa for the autoclaved specimens cured at 160°C. Therefore, the compressive strength results of the present work do not confirm the beneficial role played by the very fine sand with respect to a coarser aggregate, as claimed by Richard and Cheyrezy (1, 2).

Figure 4 shows the effect of the graded natural aggregate, substituted for a part of portland cement and silica fume, on the compressive strength: due to reduction in the cementitious material, the  $w/c$  and  $w/(c+sf)$  increased a little by using the graded aggregate (Table 3) and consequently the compressive strength of the modified *RPC* (Mixture No. 5 and 6 in Fig. 4) was a little lower with respect to the original one (Mixture No. 4 in Fig. 4).

Figure 5 shows the compressive strength of the modified *RPC* mixtures, all without very fine ground sand, and with reduced amounts of cement and silica fume (Mixtures 7, 8 and 9 of Table 4) with respect to that of the original *RPC* (Mixture No. 1, Table 2). Again, due to the increase in the water-cement and water-binder ratios (Tables 2 and 4), the compressive strength decreased by increasing the aggregate to cement ratio from 1.10 (original *RPC*) to 1.35-2.08 (modified *RPC*). However, the reduction in the compressive strength of the autoclaved specimens at 160°C was negligible with respect to that recorded for the specimens cured at lower temperatures (20°C or 90°C).

## Additional Tests

*Scanning electron micrographs.* In order to understand the role played by the curing process in determining the performance of the material, the microstructure of *RPC* was studied by SEM. To facilitate the observation of the cement matrix, specimens without steel fibers were manufactured. Figure 6 shows typical fracture surfaces of *RPC* cured at 20°C, steam-cured at 90°C or autoclaved at 160°C. All specimens were observed at 7 days. The microstructure of the autoclaved specimen (Fig. 6C) was much more dense than that of the *RPC* steam-cured at 90°C (Fig. 6B) and this appeared a little less porous than the material cured at 20°C (Fig. 6A).

*Flexural strength.* Table 5 shows the influence of the graded natural aggregate on the flexural strength with respect to the original *RPC* (Mixture No. 1); when all the fine ground sand was replaced by the coarser aggregate (Mixture No. 3) there was a reduction in strength and the effect was more significant when part of the cementitious binder and all the fine sand were replaced by the graded aggregate (Mixture No. 8).

Flexural strength, measured on larger specimen beams (150 mm thick) test through symmetrical two-point loading, were significantly lower than the values measured on smaller specimens (40-mm thick) by central point loading test. This agrees with the published data from technical literature (6). The flexural strength data (25-60 MPa) on *RPC* according to Richard and Cheyrezy (1) - obtained through central point loading test and relatively small specimens (40-70 mm) - are in good agreement with those of the present investigation of similar thickness (40 mm).

*Bending stress-strain curves.* Figure 7 shows the deflection of beams under bending stress for the original (Mixture No. 1) and modified *RPC* (Mixtures No. 3 and 8). A small change in the deflection curve is caused by replacing the fine ground sand of the original *RPC* (Mixture No. 1) with the graded aggregate (Mixture No. 3). A further reduction in the cementitious material (Mixture No. 8) reduced the area under the stress-deflection curve and therefore the toughness of the material.

*Strength-bond.* Table 5 shows that the steel-concrete bond, measured at 28 days on the specimens cured at 20°C, was much higher in modified *RPC* with coarse aggregate than in the original one. This could be ascribed to the interlocking between coarse aggregate and steel reinforcement which increases the stress required to pull the bar out.

*Shrinkage-swelling behaviour.* Original and modified *RPC* mixtures, after a 7 day curing time, were exposed to a 65% R.H. air for 30 days and then submerged under water (Fig. 8). In contrast with what happens for ordinary concretes, there was no significant change in the shrinkage-swelling behaviour as a function of the aggregate-cement ratio of the examined *RPC*. This can be ascribed to the very dense microstructure of the cement matrix of these materials. Moreover, both shrinkage and swelling, regardless of the mixture composition, were lower in steam-cured and specially in autoclaved specimens with respect to those cured at room temperature.

The shrinkage of original or modified *RPC* cured 7 days at room temperature was about  $600 \cdot 10^{-6}$  after 1 month of air-exposure (65% R.H.). The change in dimensions of the autoclaved mixture was significantly lower - about 10 times less - than the corresponding material cured at room temperature. This is an agreement with both the microstructural densification produced by the autoclave curing at 160°C (Fig. 6) and the published data (6). On the other hand, the shrinkage reduction of the steam-cured (90°C) *RPC* with respect to that of the corresponding material cured at room temperature - less than 50% - is supported by the SEM observation of the present paper (Fig. 6), but it is not

confirmed by other published data (6). Nevertheless, some preliminary water absorption measurements - not shown in the present paper - indicated that steam-cured *RPC* at 90°C were less porous than the corresponding materials cured at room temperature and this could justify the differences in shrinkage and swelling as well between *RPC* cured at room temperature and that steam cured at 90°C.

*Modulus of elasticity and creep behaviour.* Figure 9 shows creep strains under permanent compressive stress of 13.3 or 53 MPa of the original *RPC* (Mixture No. 1) and modified *RPC* with the graded gravel replacing all the ground fine sand (Mixture No. 3) or substituting for part of the cementitious binder and all the fine sand (Mixture No. 8). All the specimens were steam-cured at 90°C and subjected to compressive loading at 7 days in the air (RH=65%), i.e. at a time when the compressive strength ranged from 150 to 160 MPa.

From the immediate strain of the specimens a modulus of elasticity of about 40 GPa was calculated for all the three mixtures and this value appeared to be lower than that recorded by Richard and Cheyrezy (56-60 GPa) for *RPC* with a compressive strength of 200 MPa (1).

The creep strain after loading of the *RPC* steam-cured specimens under the stress of 13.3 MPa (and therefore with a stress-strength ratio of about 0.09) was much lower than that of ordinary strength concrete with compressive strength of 30-40 MPa (6). The creep strain of the *RPC* specimens under the stress of 53 MPa (therefore with a stress-strength ratio of 1/3 at the loading time) was of course higher. However, the ultimate specific creep including the elastic strain was about  $35 \cdot 10^{-6} \text{ MPa}^{-1}$  regardless of the stress-strength ratio and of the aggregate/cement ratio of the original or modified *RPC*, and then about one third of the specific creep of ordinary strength concrete (6).

Other creep tests indicated that the specific creep of autoclaved *RPC* was even lower, whereas that of *RPC* cured at room temperature was of the same order of magnitude as that of ordinary strength concretes.

## CONCLUSIONS

The replacement of the fine ground quartz sand (0.15-0.40 mm) by an equal volume of well graded natural aggregate (maximum size: 8 mm) did not change the compressive strength of the *RPC* at the same water-cement ratio. These results are not in agreement with the model proposed by Richard and Cheyrezy since they attributed the high compressive strength level of *RPC* to a better homogeneity of the mixture in the absence of coarse aggregate.

When the graded aggregate replaced all the fine sand and part of the cementitious binder (cement and silica fume), at a given workability level, there was an increase in the water-cement ratio, due to the reduction in the cement factor, and hence a corresponding decrease in the compressive strength.

Flexural strength was lower when graded coarse aggregate replaced all the very fine sand. This effect could be explained in terms of a better homogeneity when only very fine sand is present and then to a more effective bond-strength between cement matrix and aggregate under shear stress produced in bending tests.

In the presence of coarse aggregate the steel-concrete bond was increased with respect of the original *RPC* and this effect could be ascribed to the interlock developing between coarse aggregate and deformed reinforcing bar.

Steam-curing at 90°C and specially high pressure steam-curing at 160°C gave a better performance of *RPC* - in terms of higher strength, lower drying shrinkage and creep strain - than the curing at room temperature. This improvement in the performance was related with a more densified microstructure of the cement matrix.

#### ACKNOWLEDGEMENT

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#### 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. 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.
3. 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, 1996, pp.502-513.
4. 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.

5. 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.
6. Neville, A.M. "Properties of Concrete", Fourth Edition, 1995, Editor: Longman Group Limited, Essex, England, p. 844.

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

<b>Composition (%) - Property</b>	<b>Portland Cement</b>	<b>Silica Fume</b>
SiO <sub>2</sub>	20.59	98.87
Al <sub>2</sub> O <sub>3</sub>	3.66	0.01
Fe <sub>2</sub> O <sub>3</sub>	6.10	0.01
CaO	63.78	0.23
MgO	0.95	0.01
K <sub>2</sub> O	0.48	0.08
Na <sub>2</sub> O	0.26	0.00
SO <sub>3</sub>	250	0.23
C <sub>3</sub> A	0	-
Blaine fineness (m <sup>2</sup> /kg)	340	-
Mean particle size (μm): without superplasticizer	-	13.87
with superplasticizer	-	0.76

**Table 2 - Composition of RPC mixtures with graded aggregate (max size = 8 mm) replacing fine sand (0.15-0.40 mm).**

<b>Mixture No.</b>	<b>1 (Original RPC)</b>	<b>2 (Modified RPC)</b>	<b>3 (Modified RPC)</b>
Portland cement ( <i>c</i> )	934 kg/m <sup>3</sup>	933 kg/m <sup>3</sup>	937 kg/m <sup>3</sup>
Silica fume ( <i>sf</i> )	234 kg/m <sup>3</sup>	234 kg/m <sup>3</sup>	235 kg/m <sup>3</sup>
Fine sand ( <i>fs</i> )	1030 kg/m <sup>3</sup>	539 kg/m <sup>3</sup>	--
Graded aggregate ( <i>ga</i> )	--	489 kg/m <sup>3</sup>	1031 kg/m <sup>3</sup>
Superplasticizer (dry)	12.7 kg/m <sup>3</sup>	12.7 kg/m <sup>3</sup>	12.7 kg/m <sup>3</sup>
Steel fibers	187 kg/m <sup>3</sup>	187 kg/m <sup>3</sup>	187 kg/m <sup>3</sup>
Water ( <i>w</i> )	215 kg/m <sup>3</sup>	205 kg/m <sup>3</sup>	200 kg/m <sup>3</sup>
<i>w/c</i>	0.23	0.22	0.21
<i>w/(c + sf)</i>	0.18	0.17	0.17
<i>fs/(fs + a)</i>	1.00	0.52	0.00
<i>a*/c</i>	1.10	1.10	1.10
Flow table (mm)	150	150	155

\* *a* = total aggregate = *fs* + *ga*

**Table 3 - Composition of RPC mixtures with graded aggregate replacing part of the cementitious binder (cement + silica fume).**

Mixture No.	4 (Original RPC)	5 (Modified RPC)	6 (Modified RPC)
Portland cement ( <i>c</i> )	934 kg/m <sup>3</sup>	843 kg/m <sup>3</sup>	754 kg/m <sup>3</sup>
Silica fume ( <i>sf</i> )	234 kg/m <sup>3</sup>	211 kg/m <sup>3</sup>	189 kg/m <sup>3</sup>
Fine sand ( <i>fs</i> )	1030 kg/m <sup>3</sup>	1029 kg/m <sup>3</sup>	1035 kg/m <sup>3</sup>
Graded aggregate ( <i>ga</i> )	--	109 kg/m <sup>3</sup>	217 kg/m <sup>3</sup>
Superplasticizer (dry)	12.7 kg/m <sup>3</sup>	12.7 kg/m <sup>3</sup>	12.8 kg/m <sup>3</sup>
Steel fibers	187 kg/m <sup>3</sup>	187 kg/m <sup>3</sup>	188 kg/m <sup>3</sup>
water ( <i>w</i> )	215 kg/m <sup>3</sup>	202 kg/m <sup>3</sup>	204 kg/m <sup>3</sup>
<i>w/c</i>	0.23	0.24	0.27
<i>w/(c + sf)</i>	0.18	0.19	0.22
<i>fs/(fs + a)</i>	1.00	0.90	0.82
<i>a*/c</i>	1.10	1.47	1.66
Flow table (mm)	150	150	155

\* *a* = total aggregate = *fs* + *ga*

**Table 4 - Composition of RPC mixtures with graded aggregate replacing all fine sand and part of the cementitious material.**

Mixture No.	7 (Modified RPC)	8 (Modified RPC)	9 (Modified RPC)
Portland cement ( <i>c</i> )	847 kg/m <sup>3</sup>	758 kg/m <sup>3</sup>	665 kg/m <sup>3</sup>
Silica fume ( <i>sf</i> )	212 kg/m <sup>3</sup>	190 kg/m <sup>3</sup>	166 kg/m <sup>3</sup>
Graded aggregate ( <i>ga</i> )	1146 kg/m <sup>3</sup>	1259 kg/m <sup>3</sup>	1383 kg/m <sup>3</sup>
Steel fibers	188 kg/m <sup>3</sup>	189 kg/m <sup>3</sup>	189 kg/m <sup>3</sup>
Superplasticizer (dry)	12.8 kg/m <sup>3</sup>	12.9 kg/m <sup>3</sup>	12.9 kg/m <sup>3</sup>
water ( <i>w</i> )	195 kg/m <sup>3</sup>	192 kg/m <sup>3</sup>	193 kg/m <sup>3</sup>
<i>w/c</i>	0.23	0.25	0.29
<i>w/(c + sf)</i>	0.18	0.20	0.23
<i>a*/c</i>	1.35	1.66	2.08
Flow table (mm)	150	150	150

\* *a* = total aggregate = *ga*

TABLE 5 – FLEXURAL STRENGTH: EFFECT OF REPLACEMENT OF THE CEMENTITIOUS BINDER (CEMENT + SILICA FUME AND FINE SAND BY THE GRADED AGGREGATE

Mixture No.	1			3			8		
Portland cement (kg/m <sup>3</sup> )	930			937			758		
Silica fume (kg/m <sup>3</sup> )	232			235			190		
Fine sand (kg/m <sup>3</sup> )	1024			-			-		
Graded aggregate (kg/m <sup>3</sup> )	-			1031			1259		
w/c	0.22			0.21			0.25		
<b>Curing (max temperature)</b>	20°C	90°C	160°C	20°C	90°C	160°C	20°C	90°C	160°C
<b>Flexural strength (MPa) at</b>	Two point loading tests on 150x150x600 mm beams								
- 3 days	16.7	23.9	22.5	17.8	16.6	20.6	10.9	18.2	18.4
- 7 days	19.6	18.5	19.1	21.9	18.1	19.0	13.8	18.1	18.6
- 28 days	20.5	20.2	20.1	20.1	21.0	21.6	16.1	18.0	17.9
<b>Flexural strength at</b>	Central point loading tests on 40x40x160 mm specimens								
- 3 days	39.6	42.4	59.7	30.7	37.4	40.1	30.2	35.6	38.5
- 7 days	43.8	43.1	57.7	34.9	38.9	41.1	36.8	36.7	38.6
- 28 days	45.7	48.3	60.1	35.5	40.6	40.7	38.7	38.3	39.6
<b>Steel-bond at 20°C (28 days)</b>	28.4			37.9*			32.2*		

\* failure of the steel bar by tensile stress

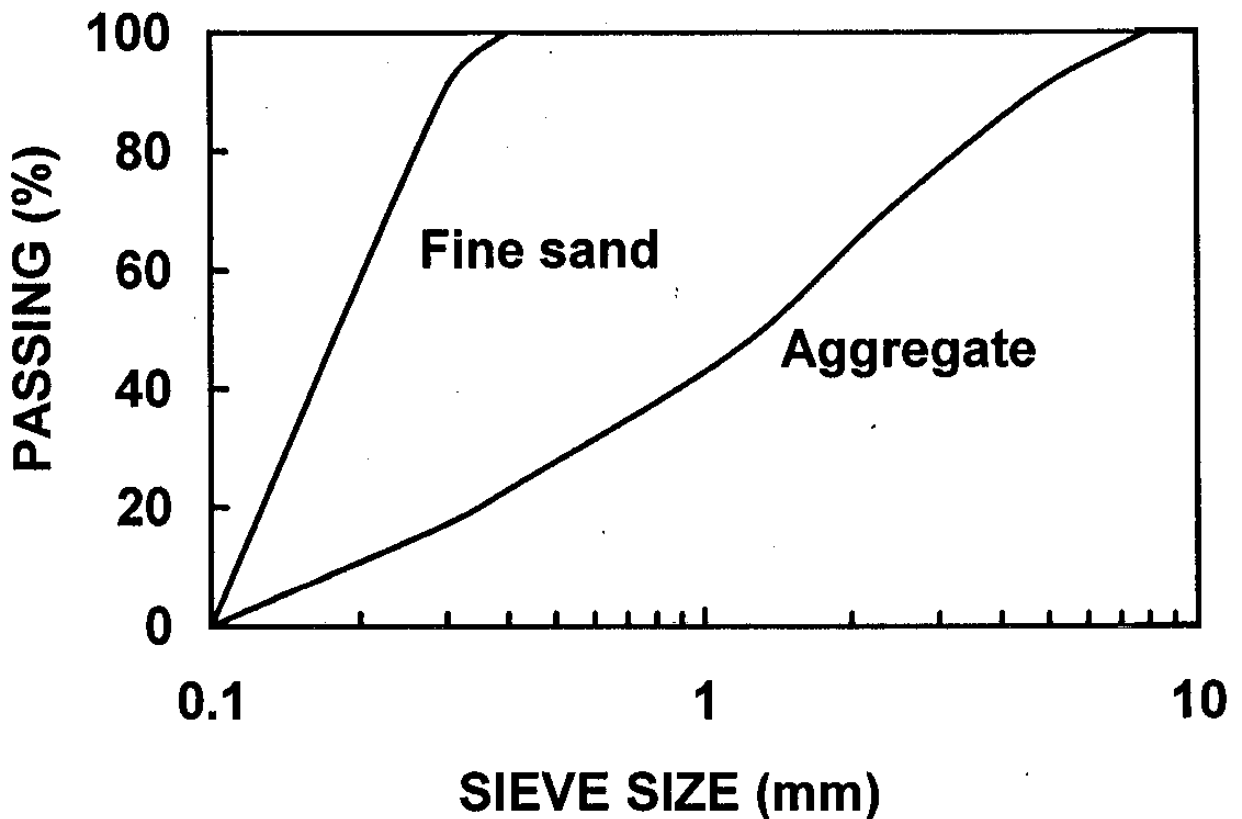


Fig. 1—Particle size distribution of the fine sand used in the original RPC and the aggregate used to replace it

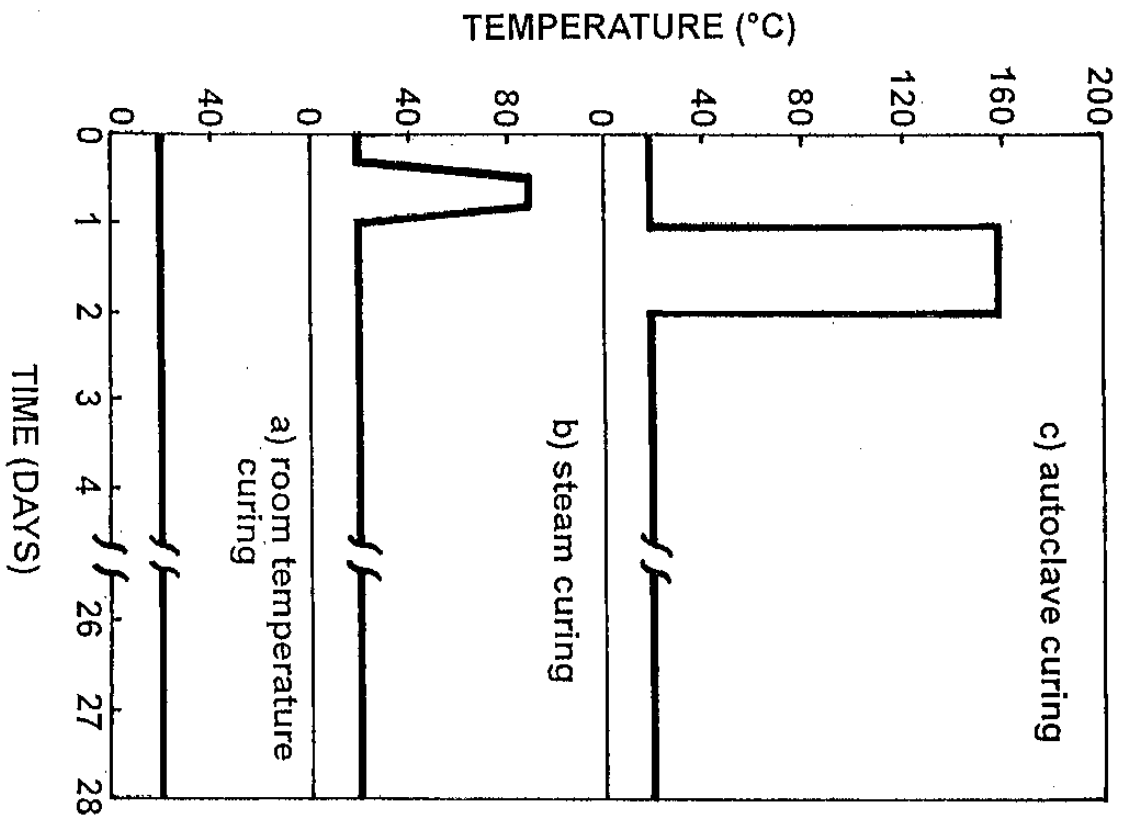


Fig. 2—Temperature versus time for the three curing conditions

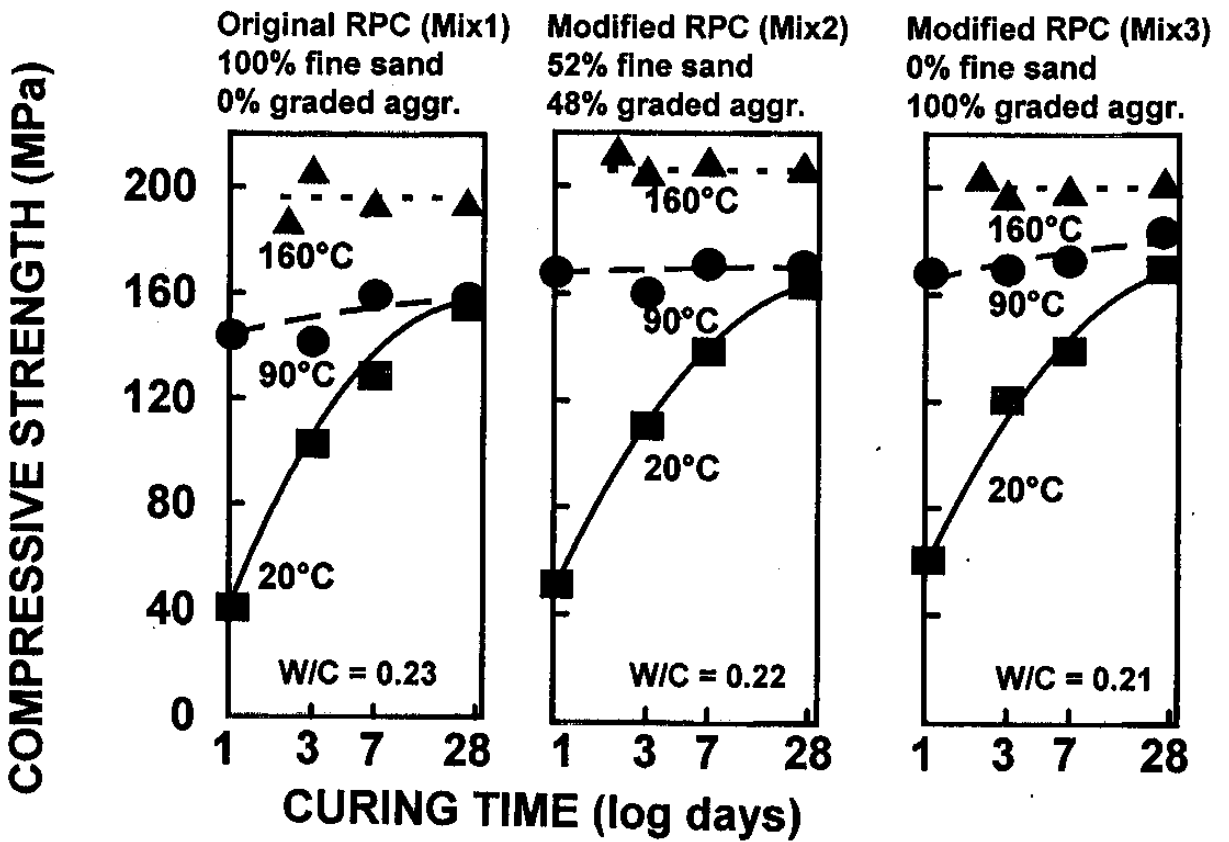


Fig. 3— Compressive strength versus curing time of mixtures 1, 2 and 3 (Table 2): effect of replacement of fine sand by graded aggregate (0-8mm).

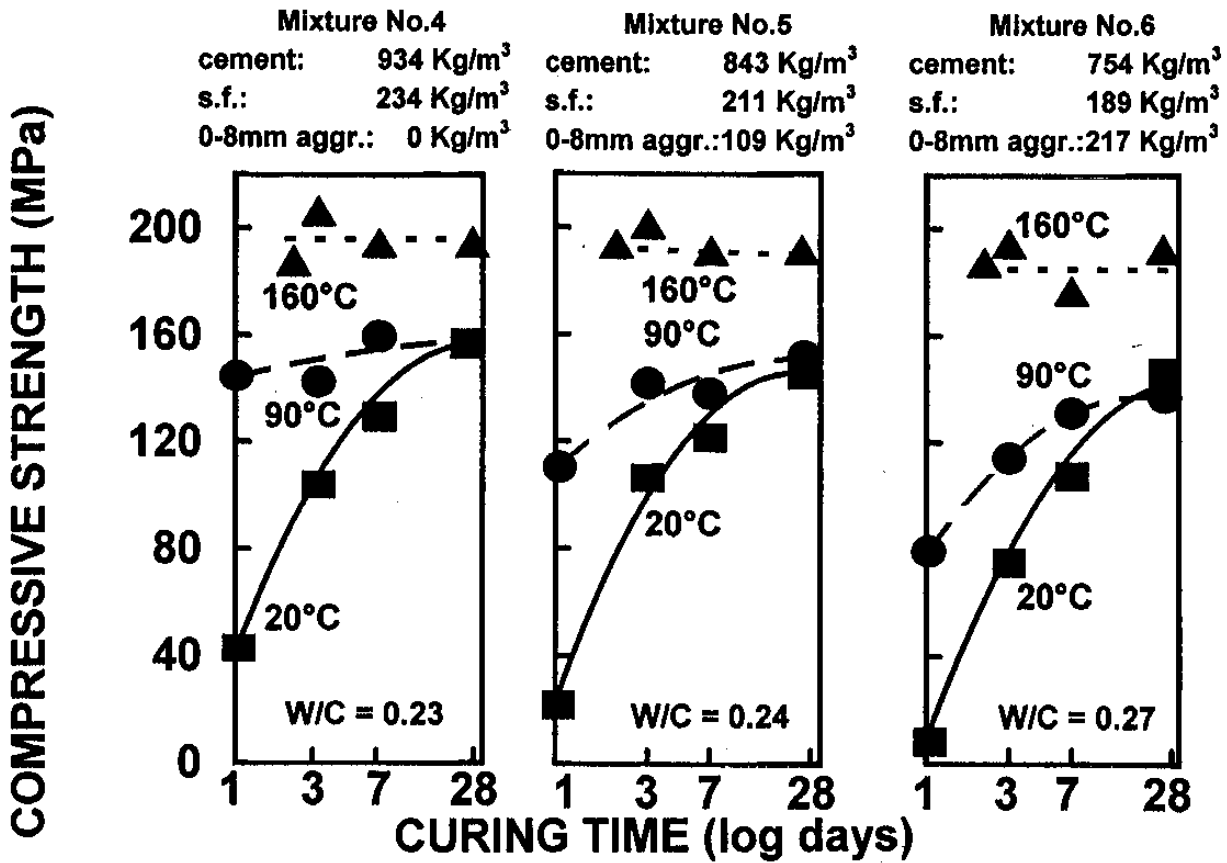


Fig. 4—Compressive strength versus curing time of mixtures 4,5 and 6 (Table 3): effect of replacement of cement, silica fume and fine sand by graded aggregate (0-8mm)

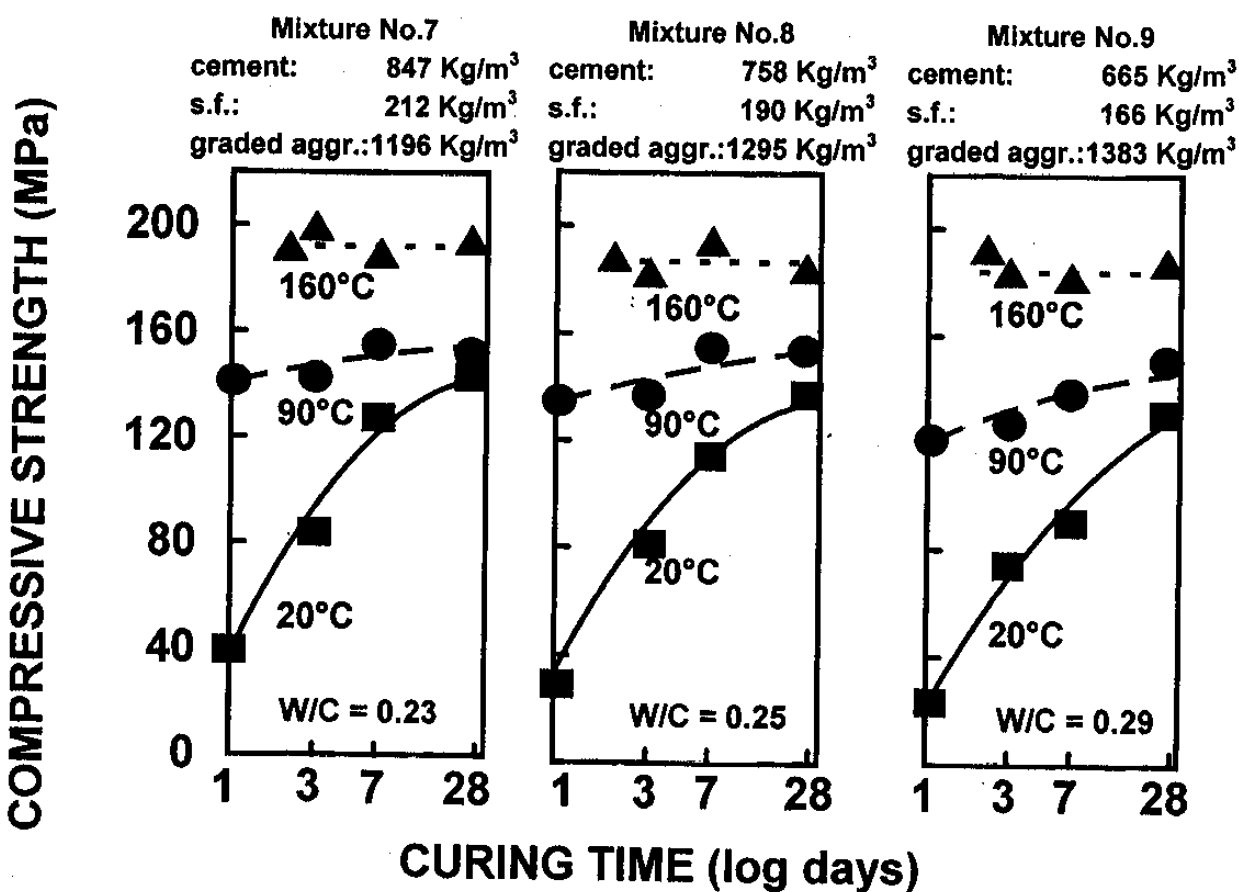


Fig. 5—Compressive strength versus curing time of mixtures 7,8 and 9 (Table 4): replacement of cementitious binder by the graded natural aggregate in the absence of fine-ground sand.

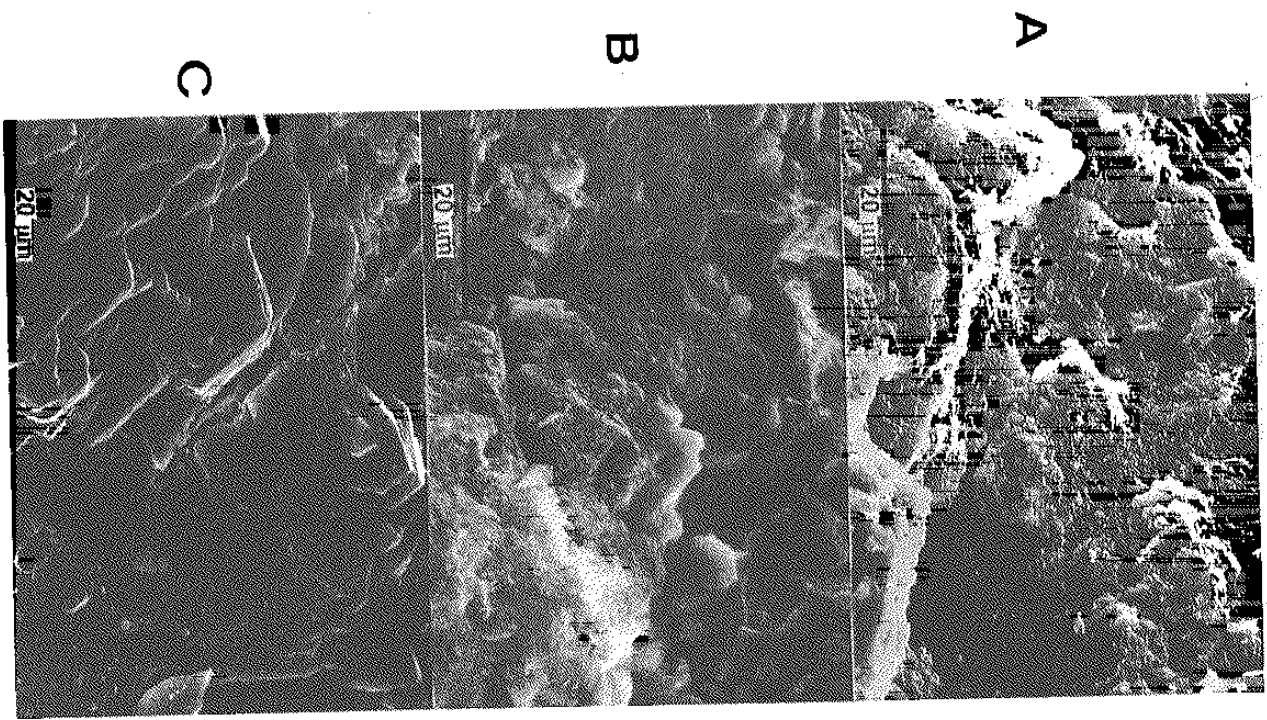


Fig. 6—Scanning electron micrographs of 7-day cured specimens in the absence of steel fibers. A: curing at 20°C; B: steam-curing at 90°C; C: autoclave curing at 160°C

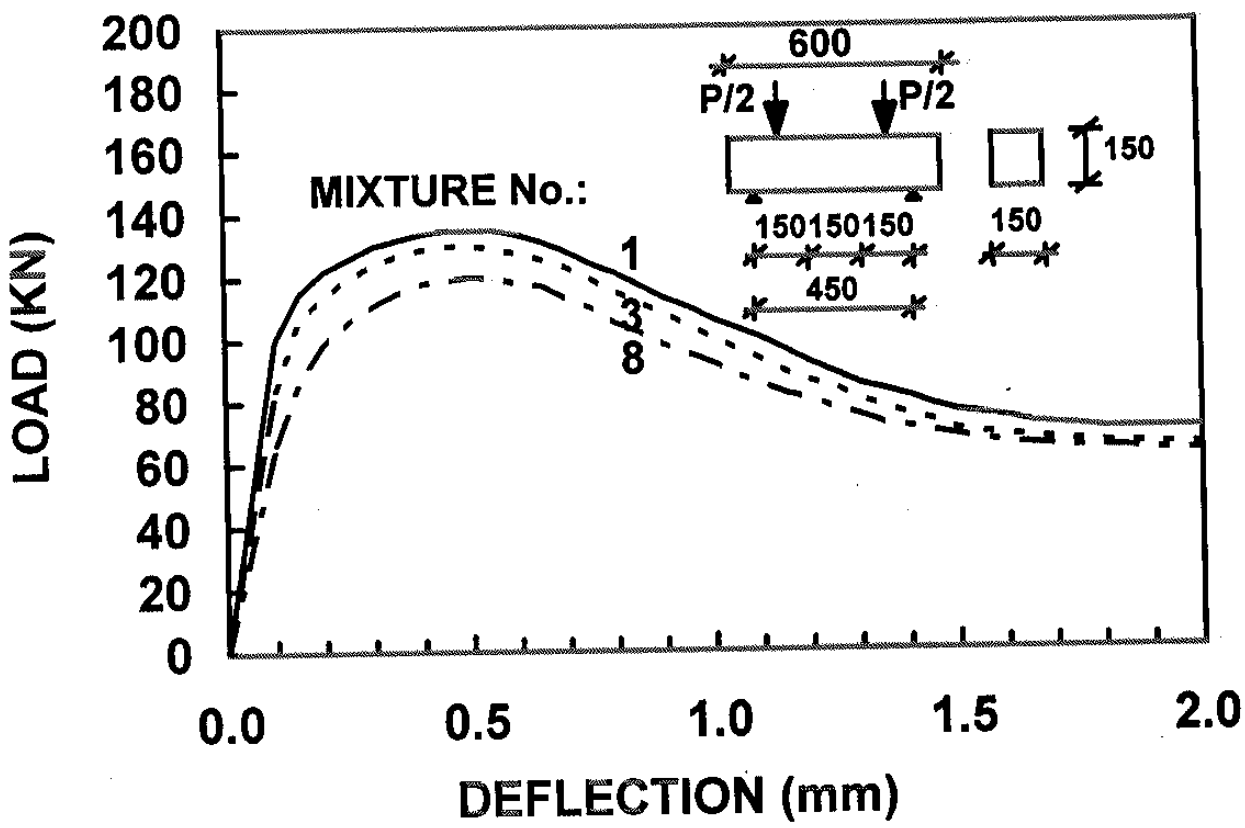


Fig. 7—Strain under flexural loading of steam-cured mixtures 1, 3 and 8 (Tables 1 and 3) at 7 days

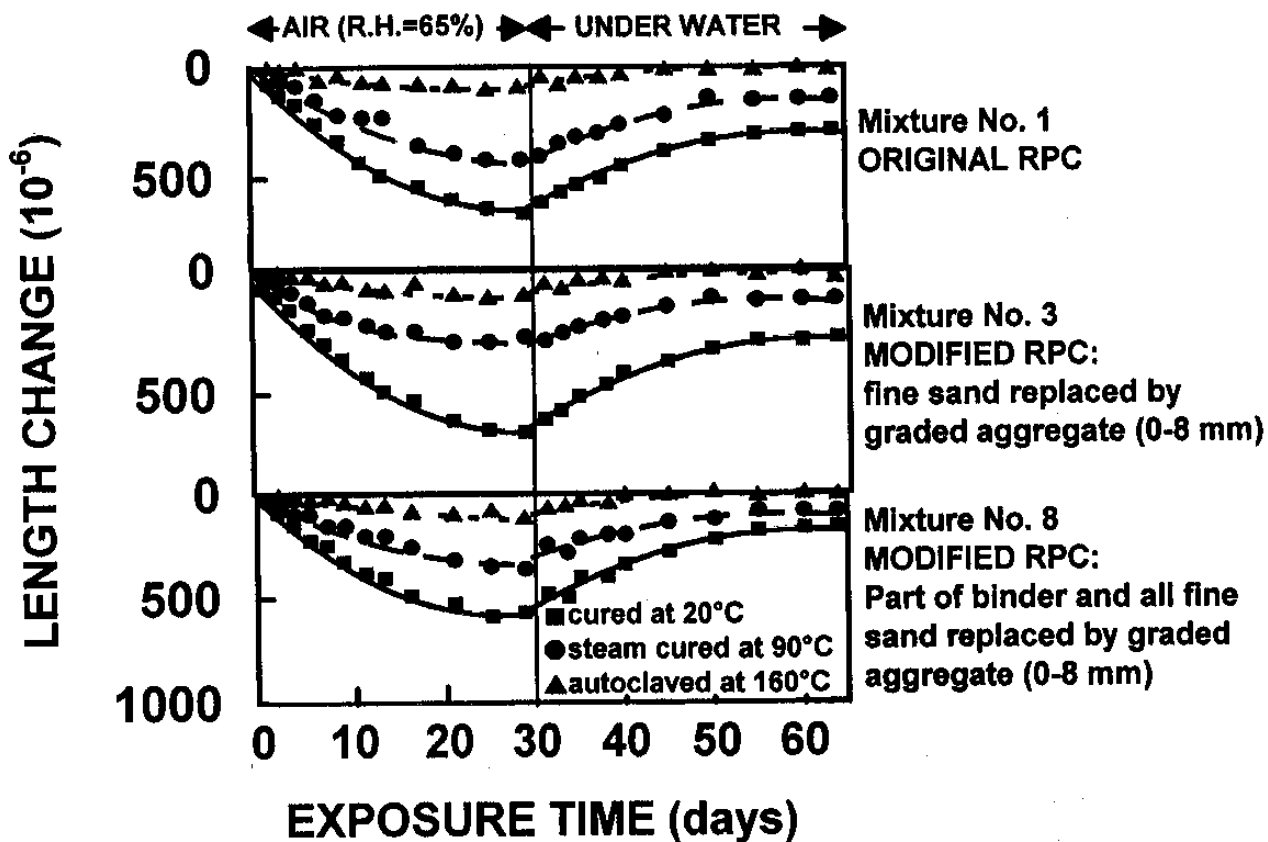


Fig. 8—Length change of specimens exposed to air and then to water after 7 days of curing

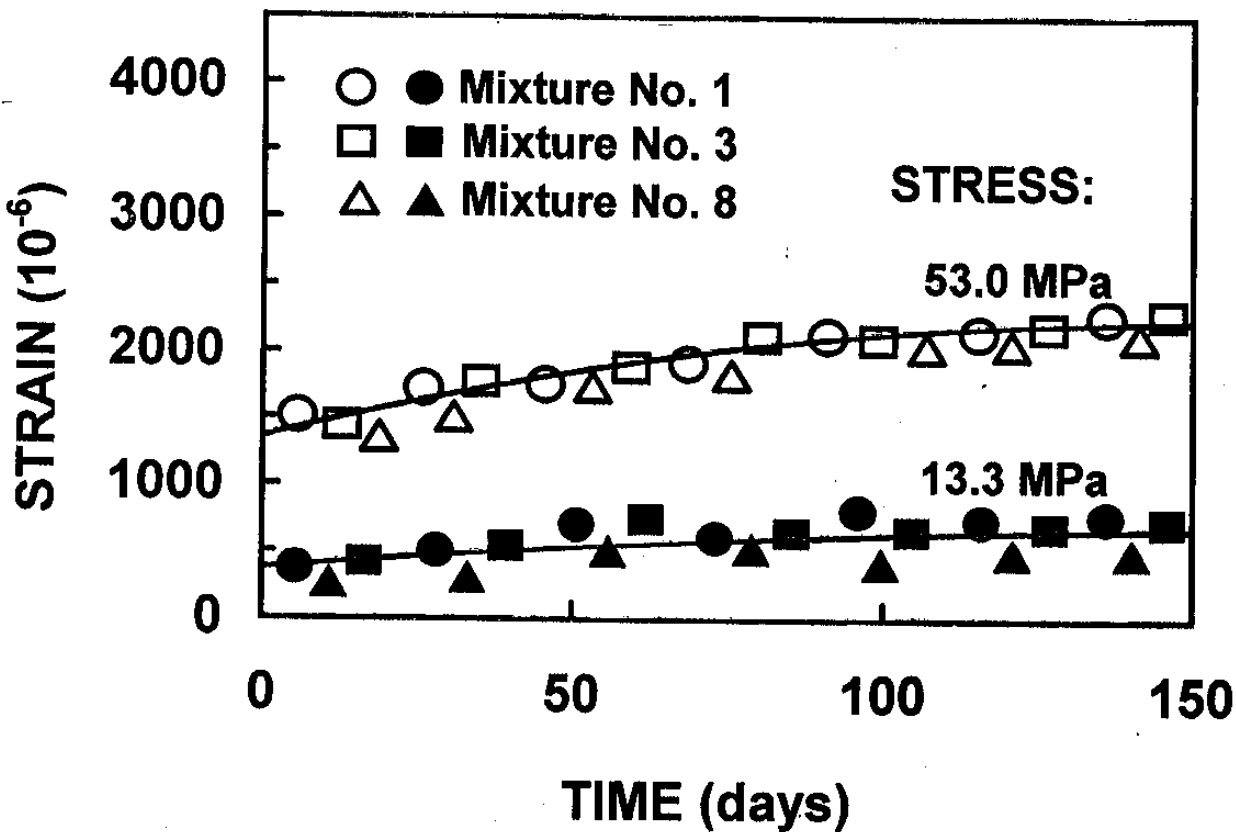


Fig. 9—Creep strain of concrete specimens steam-cured at 90°C and loaded at 7 days