Influence of constituents on the properties of self compacting repair materials

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INFLUENCE OF CONSTITUENTS ON THE PROPERTIES OF SELF COMPACTING REPAIR MATERIALS

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Abstract

The paper presents the results of laboratory tests and field application in a highway bridge of self compacting repair materials. Three commercially available repair materials and one specially designed self compacting concrete were used in the study. The properties investigated were shrinkage, creep, elastic modulus and modulus of rupture. In addition, the field investigation determined flowing characteristics, compactibility and placing procedure of the flowing materials.

The laboratory results show that the constituents of the mixtures greatly influence the basic properties of the materials. Inclusion of coarse aggregate in the mixture generally lowered the free shrinkage and modulus of rupture. Creep was highest in the material with polymer modification but creep recovery was lowest where large size aggregate was present. The elastic modulus was also influenced by the addition of coarse aggregate and copolymers The field results show that the materials can be placed and compacted satisfactorily without the aid of mechanical equipment.

1. Introduction

It is widely known that steel corrosion is caused by the ingress of carbon dioxide and chlorides to the reinforcement zone of a structural element. The resulting corrosion products induce tension in the concrete which leads to cracking and spalling if corrosion is excessive. Consequently, rehabilitation is required to restore structural integrity. This is usually accomplished by removing the deteriorated concrete and applying a new material in its place. One of the common forms of application currently used is that of self compacting materials. These are simply poured into watertight shuttering which is assembled in situ so that the geometry of the damaged element is restored upon removal. Although the method itself is economical when large volumes of repair are applied, it can only prove to be successful if the new material interacts well with the parent concrete and forms a durable barrier to guard against reinitiation of corrosion. Problems may arise since a dimensionally unstable repair material is placed against a dimensionally stable substrate concrete, as any significant drying shrinkage and creep will no longer exist in the substrate concrete due to its long term exposure to the environment and the service loading. It has been shown elsewhere [1, 2, 3, 4] that the basic properties of the repair materials (shrinkage, creep and elastic modulus) are primarily responsible for this interaction.

The basic properties of repair materials considered important for specification of concrete repair were determined for four self compacting repair materials. The results are related to the constituents of the materials and are presented in the paper. Also included is information on the field investigation comprising of flowing characteristics, compactibility and placing procedure of the flowing materials

2. Experimental Programme

2.1 Details of repair materials

Self-compacting repair materials were used to repair Sutherland Street Bridge in Sheffield, U.K. Four repair materials were used in total, three of which are commercially available repair products, whereas the fourth was a conventional self-compacting concrete.

Material S1 is a single component, pre-blended cementitious repair material containing 5mm maximum sized graded aggregate, additives and shrinkage compensating agents. The cement content is 500 kg/m^3. At the recommended water/cement ratio of 0.37, this material has a density of 2250 kg/m^3 and a compressive strength of 79 MPa at 28 days.

Material S2 is based on Portland cement and graded aggregates. The recommended water:powder ratio is 0.13 which gives a compressive strength of 65 MPa and a fresh density of 2270 kg/m^3.

Material S3 is a single component material which includes a 6mm aggregate. Typical properties are a compressive strength of 68 MPa at 28 days and a fresh density of 2250 kg/m^3.

Material S4 comprises of conventional concrete materials to produce a self compacting concrete. It consists of Portland Cement, 10mm rounded aggregate and a medium grade sand, pulverised fuel ash, superplasticiser and polypropylene fibres to control shrinkage cracks. A water:cementitious ratio of 0.45 is used, which results in a compressive strength of 39 MPa at 28 days. Mix proportions are given in Table 1.

2.2 **Casting and curing**

100 x 100 x 500mm prism specimens of repair materials were used for shrinkage, creep and modulus of rupture tests. 100mm diameter x 200mm high cylinders were used for elastic modulus tests. These are standard specimen sizes for testing concrete [5] rather than the smaller sizes allowable for testing repair materials [6] so that the properties of repair materials determined in the tests could be meaningfully used with those of the substrate concrete when analysing theoretically the structural interaction between the repair patch and concrete substrate.

Mixing was carried out in accordance with the manufacturers' instructions. A total of six prisms and two cylinders were cast for each material according to standard procedures [7]. Two prisms were used for free shrinkage and four for creep tests (two for creep measurements and two for corresponding shrinkage strains). The two prisms for free shrinkage were later tested for modulus of rupture data.

Repair materials were cast in three layers and each layer was compacted by firmly tapping the moulds with a hammer at regular frequency, similar to that used on site. After 24 hours the specimens were demoulded and demec points were attached with an adhesive to the specimens. Prisms for shrinkage tests were transferred to a controlled environment room at 20ºC and 55% RH for the duration of the tests. Prisms for creep tests were cured in a water tank at 20ºC prior to loading - the total curing period was 28 days (including one day in the mist curing room). Creep specimens were accompanied by identical shrinkage specimens so that net creep strain could be obtained by subtracting the free shrinkage strain from the gross strain measured under load.

2.3 **Shrinkage deformation**

Two sets of specimens were tested for shrinkage deformation. Datum readings for Set 1 were taken at 24 hours after casting across a gauge length of 200mm (demec gauges).

Table 1 Mix proportions for material S4

Constituent	Quantity (kg/m^3)	Type/source
Portland cement pfa	340 60	Portland Pozzalan Ltd.
coarse aggregate fine aggregate	1092 728	10mm rounded Grade M
Water	180	Yorkshire
Superplasticiser	2.25% / wt of cementitious	Melment F10
Fibres	910 g/m^3	Polypropylene

Specimens were subsequently stored in a controlled environment (20ºC and 55% RH). The shrinkage presented is the average of eight readings from all the longitudinal faces of two prisms.

Specimens in Set 2 were initially mist cured for 24 hours and cured in water at 20ºC for a further 27 days. Datum strain readings across a gauge length of 200mm (demec gauges) were taken at 28 days. Subsequently, specimens were transferred to a controlled environment (20ºC and 55% RH) for the remainder of the test period for shrinkage and creep tests. The shrinkage presented is the average of eight readings from all the longitudinal faces of two prisms. The shrinkage obtained from these prisms was also used to obtain the net creep of the repair materials under load (identical curing conditions).

2.4 **Creep deformation**

Two prisms of each material were loaded together (in series) in a standard creep rig. Creep tests were carried out in accordance with standard procedures [8]. Throughout the duration of the study, specimens were stored at 20ºC and 55% RH. Each creep deformation recorded was the average of readings of eight faces of two prisms. The net creep strain was obtained by subtracting the shrinkage strain, measured on identical specimens (shrinkage Set 2), from the gross strain measured on the specimens under load in the rig.

2.5 **Elastic modulus**

200mm long x 100mm diameter capped specimens of each repair material were tested in accordance with BS 1881:Part 121 [9]. An extensometer of gauge length 50mm was used to measure the strain. A minimum of two and a maximum of three cylinders were tested to determine the elastic modulus of each repair material.

2.6 **Modulus of rupture**

The two prisms that were initially used for the shrinkage measurements up to 100 days age, were subsequently tested at ages between 14 and 36 months for modulus of rupture data. These prisms were stored in a controlled environment throughout (20ºC and 55% RH). The specimens were tested in accordance with BS 1881: Part 118 [10] to determine the long term modulus of rupture of each repair material.

3. Results and discussion

3.1 **Free shrinkage of air/water cured specimens**

The free shrinkage of self compacting repair materials considered in this paper are given in Figure 1 and Table 2 (Sets 1 and 2). Set 1 relates to specimens stored at 20°C and 55%RH after 24 hours of mist curing. Set 2 relates to specimens stored at 20°C and 55%RH after 24 hours mist curing and 27 days immersed in water (20°C).

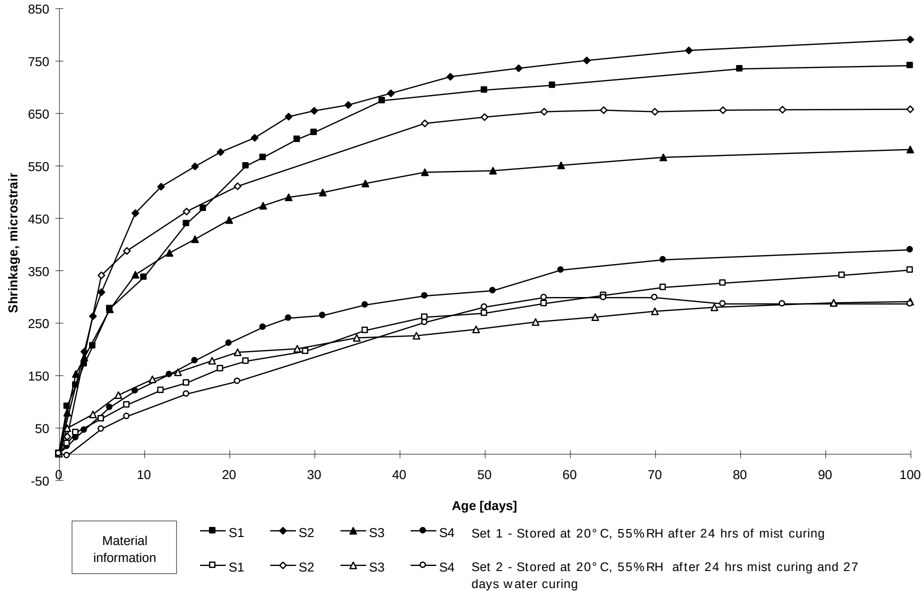

Figure 1 Shrinkage of self compacting repair materials

With regards to shrinkage of the specimens in Set 1 (stored at 20°C and 55%RH after 24 hours of mist curing), materials S1-S3 exhibit rapidly increasing rates of shrinkage in the early stages to reach 100 days shrinkage values of 580, 740 and 791 microstrain respectively. Material S4, a flowing concrete which was designed in the laboratory with conventional concrete constituents and admixtures to give a high flow material with relatively large aggregate (10mm rounded) and low cement content, displays the lowest rate of shrinkage in the early ages which contributes to the lowest shrinkage of 388 microstrain at 100 days.

Free shrinkage in normal concrete can be restricted by keeping the water:cement ratio and cement contents low [11]. The same practice applies to repair materials. Unfortunately, cement contents of repair materials are rarely given in manufacturers' literature (except material S1 - 500kg/m^3) and determination of cement contents by analysis was outside the scope of the current work. Consequently, it is not possible to comment on the free shrinkage of the materials with respect to the water:cement ratio or cement content. Repair materials which comply with the current Highways Agency standard (clause 1702 of DoT Specifications for Highway Works, Part 5) must have a minimum cement content of 400 kg/m^3. Therefore, assuming the cement contents are similar for all repair materials conforming to the standard, the variation in shrinkage of repair materials represented in Figure 1 must be due to other material constituents. The inclusion of different aggregate sizes and/or admixtures may affect the shrinkage of the

Table 2 Properties of repair materials

Mat	Aggregate	Main admixtures	Shrinkage data			Creep data				Elastic modulus	Modulus of rupture
	from suppliers' literature	from suppliers' literature	Set 1 µs	Set 2 µs	Set 1 ÷ Set 2 %	instant elastic strain µs (f_c)*	70 day creep µs	ϕ	delayed elastic strain µs (%)*	GPa	MPa (Age)*
S1	5mm graded	anti-shrinkage agents	740	350	47	818 (23.7)	445	0.54	154 (35)	24.2	6.5 (14)
S2	graded	anti-shrinkage agents, additives	791	657	83	569 (19.5)	438	0.77	100 (23)	32.2	3.3 (21)
S3	6mm graded	anti-shrinkage agents, copolymers	580	286	49	502 (20.4)	667	1.33	120 (18)	31.9	5.7 (21)
S4	10mm round	fibres	388	285	73	337 (11.7)	454	1.35	38 (8)	27.4	4.3 (21)

Set 1	free shrinkage at 100 days, stored at 20°C, 55%RH 24 hours after casting
Set 2	free shrinkage at 100 days, stored at 20°C, 55%RH, after 28 days of water curing
µs	microstrain
(f_c)*	Applied stress equivalent to 30% of 28 day cube strength (MPa)
(%)*	delayed elastic strain (creep recovery) also shown as a percentage of the creep strain
(Age)*	age in months at testing given in brackets

material. When high volume repairs are required, one of the more economical methods is to employ self compacting repair materials. Materials which belong to this category normally contain coarse aggregates (up to 10mm size) to make the material more economical. Materials used in high volume repairs are therefore expected to show less shrinkage than materials used in low volume repairs due to the fact that larger aggregates (quantity and size) are contained within the mix. Consequently, the possibility of cracking in the repair patch is decreased. Mangat and Limbachiya [12, 13], Schrader [14] and Lea [15] also reported that the type and quantity of coarse aggregate have an enormous effect on the free shrinkage of repair materials.

Regardless of the manufacturers' literature stating that their material is shrinkage free or shrinkage compensated (S1-S3 are described as such), the materials tested in this investigation showed considerable free shrinkage (see Figure 1 and Table 2). The same conclusion was also reported by Morgan [16].

With regards to the shrinkage of the specimens in Set 2 (stored at 20°C and 55%RH after 24 hours mist curing and 27 days immersed in water at 20°C - Figure 1 and Table 2), the rate of shrinkage is low in the early stages for materials S1, S3 and S4 which contributes to a lower final shrinkage value at 100 days (350, 286 and 285 microstrain respectively). These shrinkage values corresponds to 47, 49 and 73% respectively of the 100 day shrinkage for air cured specimens (Set 1). However, the rate of shrinkage for material S2 in the early stages (Figure 1) is rapid thereby giving a higher 100 day shrinkage of 657 microstrain. This corresponds to 83% of the air cured shrinkage at 100 days. Nevertheless, curing the repair materials in water for the first 28 days reduces the free shrinkage to a lesser or greater extent. Consequently, if proper curing techniques are implemented after the new repair materials are applied in the field, such as applying curing membranes and/or covering the repair patch with polythene to restrict the moisture loss from the repair patch, the free shrinkage can be drastically reduced for most repair materials. Application of curing membranes and/or polythene may not reduce shrinkage to the same level as curing in water, but nevertheless, shrinkage will be lowered. This will reduce the risk of cracking in the repair material, since the tension induced in the repair material due to the restraint to shrinkage provided by the substrate concrete will be less.

3.2 **Creep deformation of repair materials**

Information on the creep properties of the repair materials are given in Figure 2 and summarised in Table 2. A stress/strength ratio of 30% was used throughout. Referring to Figure 2 and Table 2, the instantaneous elastic strain for materials S1-S4 ranged between 818 and 337 microstrain respectively (understandably materials with a higher applied stress generally exhibited a higher instantaneous elastic strain) The total 70 day creep of the materials ranged between 438 to 667 microstrain. Material S1, S2 and S4

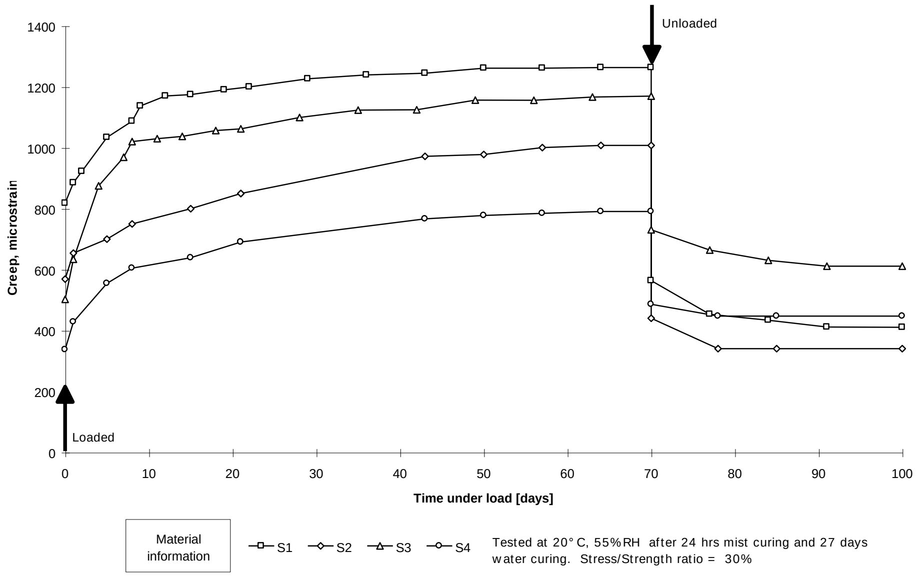

Figure 2 Compressive creep of self compacting repair materials

exhibited similar creep strains (438 to 454 microstrain) whereas material S3 had a higher creep strain of 667 microstrain.

It has been determined elsewhere that the inclusion of coarse aggregate in a mixture generally lowers the creep of the material [12, 13]. In this case, the creep of the majority of the materials was similar (materials S1, S2 and S4 - 438 to 454 microstrain). All materials contained coarse (graded) aggregate. Furthermore, it could be argued that if all materials were subjected to a constant stress and not 30% of the ultimate stress, then the creep strains presented would differ. For instance, the applied stress of material S1 is approximately twice that of material S4, but the creep strains are similar. Therefore, material S1 would behave better than material S4 in the field with regards to creep under a constant stress. Nevertheless, for comparison, a 1:3 cement:sand tested under identical conditions [17] exhibited a total creep strain of 938 microstrain at 70 days, approximately double that of materials S4. The applied stress was 13.8 MPa, only slightly greater than the applied stress of material S4. Therefore, the inclusion of course aggregate serves to reduce creep of the materials.

Material S3 exhibited a relatively high creep of 667 microstrain. This material also contained coarse aggregate and a copolymer. Hence the polymer modification has an influence on creep - compare the creep of material S3 with S2 (Table 2). Other researchers [12, 13, 18,] also reported high creep strains of polymer modified materials.

The values of ϕ, the creep coefficient, which is the ratio of creep strain to the instantaneous elastic strain upon loading are also given in Table 2 and ranges between 0.54 and 1.35. This coefficient is used to allow for the effect that creep will have on the elastic modulus of the material by calculating an effective elastic modulus, $E_{rm(eff)}$, as follows [19]:

$$E_{rm(eff)} = E_{rm} / (1+\phi) \qquad \text{Equation 1}$$

where E_{rm} is the instantaneous elastic modulus of the repair material. According to Equation 1, a high creep coefficient will result in a low effective modulus, for example, materials S3 and S4. The high creep of material S3 (polymer modified) contributes to a high creep coefficient. On the other hand, material S4 exhibits a high creep coefficient by virtue of having a low instantaneous elastic strain, even though the creep of the material was similar to materials S1 and S2. Creep will have a significant effect on the redistribution of stresses within a repair. For example, a material with an elastic modulus that was initially greater than that of the substrate concrete may in time have an effective elastic modulus less than that of the substrate concrete. As a result, the repair material may be ineffective in sharing load with the substrate concrete [2].

The delayed elastic strain, or creep recovery of the repair materials is also given in Table 2. The creep recovery is also presented as a percentage of the 70 day creep strain (shown in brackets in Table 2). Repair material S4 exhibit the lowest creep recovery strains of 38 microstrain. This corresponds to 8% of the 70 day creep strain. This repair material contains 10mm sized coarse aggregate as shown in Table 2. Neville *et al* [20] state that creep recovery has been shown to be proportional to the cement paste content of the mix (or inversely proportional to the aggregate content). Therefore, applying the conclusions found previously to repair materials [20], a repair material which contains coarse aggregate will tend to show less creep recovery as opposed to a repair material which contains fine aggregate. Material S1 showed the highest creep recovery of 35% and contained a smaller particle size coarse aggregate (5mm).

3.2 **Elastic modulus of repair materials**

Elastic modulus results obtained form 100mm diameter x 200mm long cylinders of repair material are given in Table 2. The elastic modulus ranged between 24.2 to 32.2 GPa

Referring to Table 2, it is difficult to isolate the influence that the coarse aggregate has on the elastic modulus of the repair material. Kuhlman [21] found that the elastic modulus of a repair material increased with the addition of a hard film latex. Material S3 contains a copolymer and coarse aggregate and exhibits a high elastic modulus. Material S2 also contains a graded aggregate and additives and similarly exhibited a high elastic modulus. Mangat and Limbachiya [12] observed higher elastic modulus in repair materials that contained aggregate particles. In the current test, material S1 contained the smallest coarse particle size (5mm) and showed the lowest elastic modulus.

3.4 **Modulus of rupture**

The long term modulus of rupture was obtained by testing specimens in the laboratory approximately 14-36 months after casting and is shown in Table 2. The modulus of rupture of the repair materials at 28 days varies from 3.3 N/mm^2 to 6.5 N/mm^2. A smaller particle size can broadly be attributed a higher modulus of rupture. Materials S1 and S3 contained smaller coarse particle sizes (5 and 6mm respectively) and exhibited higher modulii of rupture (6.5 and 5.7 MPa) at 14/21 months. Materials S2 and S4 which contain graded and 10mm rounded aggregate respectively shows lower modulus of rupture values of 3.3 and 4.3 MPa

3.5 **Field investigations**

Removal of deteriorated concrete at Sutherland Street Bridge was achieved by using both water jetting and mechanical means. Concrete was removed to a depth of 25mm behind the steel. All the exposed steel was grit blasted and primed using a steel reinforcement protector.

Shuttering for the self compacting repairs consisted of plywood faced timber formwork, custom made for the repairs at Sutherland Street Bridge. Preparation before application of the repair materials involved saturating the substrate concrete by filling the shuttering with water and leaving in place overnight. This was to reduce the absorption of water from the repair material into the substrate concrete.

The repair materials were mixed in accordance with the manufacturers instructions in a barrel mixer. The materials were either pumped into the shuttering or poured from a bucket. Flow characteristics of the materials are given in Table 3 and are obtained from manufacturers' literature (materials S1-S3) or field testing (material S4). All materials complied with the relevant flowing test methods [22, 23] Compaction of the flowing material was provided by firmly tapping the shuttering with a hammer at regular frequency, as the material was placed by pouring. No mechanical vibration was employed. Shuttering was left in place for at least three days after the pour to assist with curing. Overall, the repair materials were placed and compacted satisfactorily but on

Table 3 Flowing characteristics or self compacting repair materials

Material	Flow
S1	750mm in 6 secs - flow trough test [22]
S2	750mm within 10 secs - flow trough test [22]
S3	complies with standard - flow trough test [22]
S4	> 520mm - Flow table [23]

occasions, some of the materials had a poor surface finish, possibly due to the fact that shuttering deteriorated with use and was no longer waterproof. As a result, a thin coat of cementitious material was applied to the surface of all repair patches to exclude the influence of this on the performance of the repairs.

4. Conclusions

The following conclusions are based on the results of the materials tests carried out in the laboratory to determine the basic properties of the repair materials:

- Repair materials which contain coarse aggregate generally exhibit lower free shrinkage compared with repair materials which contain finer aggregate.
- All the self compacting repair materials exhibit significant free shrinkage regardless of some manufacturers' claims that their materials were shrinkage compensated or non-shrinking repair materials
- The free shrinkage of repair materials decreases when the specimens are initially cured in water for 28 days after casting as opposed to curing in air from the age of 24 hours onwards
- Polymer modified repair materials exhibit higher creep
- Repair materials with large particle size coarse aggregate show less creep recovery
- The addition of polymers and coarse aggregates generally increases the elastic modulus of a repair material.
- Repair materials which contain smaller particle size aggregates generally exhibit higher modulus of rupture than repair materials with larger particle size aggregate.
- Flowing repair materials can be placed and compacted satisfactorily in the field without the use of mechanical equipment

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