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Development of Combined Cure Type for Rigid Pavement with Reactive Powder Concrete

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***Abstract*—** In this study, fiberless reactive powder concrete (RPC) was produced with high pressure and flexural strength. C30/37 concrete was chosen as the control sample. In this study, 9 different cure types were applied to fiberless RPC. the most suitable combined cure type was selected according to the pressure and flexure strength. Pressure and flexural strength tests were applied to these samples after curing. As a result of the study, the combined cure type with the highest pressure resistance was obtained. The highest pressure resistance was achieved with consecutive standard water cure at 20 °C for 7 days – hot water cure at 90 °C for 2 days - drying oven cure at 180 °C for 2 days. As a result of the study, the highest pressure resistance of fiberless RPC was found as 123 MPa with water cure at 20 °C for 7 days - hot water cure at 90 °C for 2 days - drying oven cure at 180 °C for 2 days; and the highest flexural resistance was found as 8.37 MPa for the same combined cure type.

***Keywords*—**Rigid pavement, reactive powder concrete, combined cure, pressure test, flexural test.

I. Introduction

HIGHWAY pavements are generally classified into two groups as flexible pavements (asphalt roads) and rigid pavements (concrete roads) [1]. Today, construction of rigid pavements is becoming widespread in Turkey in the areas such as runways and similar constructions in airports, loading and unloading areas and car parks in the terminals and partly in urban roads. Considering the ever increasing number of commercial vehicles, concrete pavements are expected to spread as road pavements in the future [2]. Generally, rigid pavement is obligatory for the road with over 60-75x10^6 standard axle load number of 8,2 tons within a 20 years of project life, and for the airports with over 5000 departures of air liners [3]. Today, several paving type has been used in the field such as self-compacting concrete pavement, roller-compacted concrete pavement, pre-stressed concrete, unreinforced jointed concrete, and reinforced jointless concrete pavements. Recently, several studies on RPC pointed out that their pressure and flexural strength are very high. It is possible to construct rigid pavement concretes as RPC.

In the studies on concrete, high mechanical performance has been aimed with the materials containing cement. As a result of these studies, High Strength Concretes (HSC), Very High Strength Concretes (VHSC) and Ultra High Performance Concretes (UHPC) have been obtained [4], [5]. By adding fiber and applying special cures other than the traditional ones, UHPC have been produced. RPC belongs to this class. RPC takes its name after the materials and pozzolanic activity in the production. The word powder denotes that the material constituting RPC are of powder grain size, reactivity denotes that pozzolanic activity is repeated with hot cure process and concrete denotes that it is of cement matrix like other concretes [6]. RPC is a high strength composite material produced as a result of blending the mixture of cement with low water/cement ratio and silica fume with finely crushed quartz powder by using a super plasticiser [7]. In terms of mechanical strength, RPC has 2-4 times more resistance compared to HSC. RPC is a composite material with superior mechanical and physical properties, perfect ductility and very low permeability based on UHPC [8]. Yi et al. performed pressure resistance, tensile strength, Elastic Module and bending resistance tests. Their results pointed out that RPC showed better resistance compared to normal strength concrete [9].

Tam et al. examined the contraction and water permeability of RPC. As a result, they found out that while water/cement ratio decreased, water permeability of RPC also decreased [10]. RPC is an UHPC with low w/c ratio, high ratio of binders and powder, and ductility improvements with short-cropped wires [11]. Although RPC is a good alternative to HSCs, it has the potential to compete with steel in the construction sector. No reinforcement is necessary for the compensating the bending force that is directly affecting the material due to ductile fracture mechanism of RPC. The decrease in the dead loads, due to reducing structural members and thin sections of increased power holding capability, leads to a decrease in the earthquake forces on the structure and also an increase in the earthquake resistance of the structure. Fine sand in the RPC, instead of coarse aggregate in normal concrete, plays the role of thin aggregate in Portland concrete and cement in silica fume [12]. Water/binder ratio in RPC is as low as 0.15 level [13].

Materials used in RPC generally comprise of cement, silica fume, quartz sand and quartz powder with high strength, steel fibre, water and super plasticiser [2]. The contact surface between cement paste and aggregate grains is the weakest link in concrete. It is very important for improving the stability of fresh concrete by increasing the density using ultra-thin grains such as silica fume and thus decreasing the gaps. By this way, durability improves and resistance increases. Silica fume grains used in RPC production fill the gap between the bigger cement grains and thus make the concrete denser and more resistant by entering into pozzolanic reaction during cement

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hydration [14], [15]. Since silica fume has very thin particles and high reactivity, they are used with super plasticisers for producing VHSC (≥100 MPa) or concrete with high strength at early ages [16]. While aggregate gradation can be chosen in RPC production with the aim of strict grain placement, discrete granulometry is recommended in terms of workability. In the RPC design, it is seen that aggregate volume is generally between 30% and 50%, maximum grain diameters are usually below 1 mm, but there are cases exceeding 3 mm [17], [18].

Altoubat et al. stated that bending capability of concrete roads would increase with the addition of fragmented macro fiber to unreinforced concrete [19]. Ji et al. examined the effect of steel fibre content and water/binder ratio on RPC cracking resistance. As a result, they pointed out that steel fibre content had an important effect on RPC cracking resistance [20]. Steel, glass and polypropylene fiber are added to the concrete in order to improve the mechanical properties such as tensile and impact strength. Fibers used in concretes increase the tensile strength and flexural strength [21]. Zheng et al. stated that compressive and tensile strength of the concrete were increased by using steel fibre of 2% volume content [22]. Additives are materials other than water, cement, aggregate and fibre that are added to the concrete or mortar during or right before mixing. With the dissipation effect of super plasticiser additive, molecules of the additive are pulled by cement particles and bound around the cement during mixing. This formation increases the negative charges on the surfaces of cement particles and causes electrostatic repulsion. Powerful dissipation of cement particles is the result of this. Despite low water content, workability of the concrete considerably increases [23], [24]. One of the most important steps of concrete production is the curing of the concrete and the procedures finalising this process.

In a general sense, curing is the method and applications to further the cement hydration with the aim of gaining the concrete more strength. This is the process of filling the gaps full with water on the cement paste with the products of cement hydration to the maximum. Since the reaction speeds of cement components are different, the whole cement can't set at the beginning. Components of cement that do not set quickly are more in percentage terms than the components that set quickly. Therefore, the increase in the concrete resistance continues for almost 25-30 days and even for months and years [14]. Topçu and Karakurt applied cure under 2,5 MPa axial pressure on the RPC mixture they prepared until it set after pouring it in moulds. Then, they applied water cure at 90 °C for 7 days and steam cure at 250 °C for 7 days to the samples, and at the end of this curing process they tested samples' compressive and flexural strength. As a result, they obtained 253,2 MPa compressive and 63,67 MPa flexural resistance the maximum [25]. Yazıcı applied three different curing methods (standard water cure, autoclave cure and steam cure) on the RPC samples. Standard cure was applied in water at 20 ºC for 28 days, autoclave cure was applied at 210 ºC under 2,0 MPa steam pressure as three different periods for 8, 16 24 h, and steam cure was applied at 90 ºC with no pressure as two different periods for 6 and 12 days. As a result of the tests, compressive strength of these mixtures was found out as above 170 MPa [26]. Yazıcı et al. investigated the effect of curing methods on the mechanical performance of RPC. In that study, the mechanical properties of RPC with 0,18 w/c ratio and 3% steel fibre in volume under different curing methods were examined. Compressive strength was obtained as 163 MPa with 2 days of water cure, as 202 MPa with 28 days of water cure, as 255 MPa with 3 days of steam cure at 100 ºC and as 273 MPa with 8 hours of autoclave cure at 210 ºC under 2 MPa pressure. Moreover, flexural strength reaching 40 MPa were obtained. According to the study results, steam and autoclave cures not only increased the resistance gaining speed, but also increased the pressure resistances in a few days above the values obtained by 28 days of water cure. They stated the reason for this as the support by the quartz powder that was used as aggregate to the hydration with heat treatment [27]. Şahinoğlu stated that autoclave curing period in RPC production should be at least 2 hours [28]. The aim of the heat treatment of the concrete is to increase the hydration speed and thus decrease the setting and hardening period. Besides water cure (standard) of the setting concrete, resistance can be gained in a shorter time with different curing methods. These kinds of cures that facilitate the resistance gaining are generally categorised as heat treatments [14]. One of the heating treatments is combined cure.

Combined cure is the consecutive application of different cures. If a sample is taken to drying oven cure at 200 ºC after the standard water cure at 20 ºC for 7 days without giving a break, this is a combined curing. Moreover, if a sample is taken firstly to standard water cure at 20 ºC for 7 days and to hot water cure at 90 ºC and to drying oven cure at 200 ºC without giving a break, this is also a combined curing. There is no standard in the literature for combined cures. It can be said that concrete pressure and flexural strength can be possibly increased by applying different combined cure types.

The aim of the study was to determine the most appropriate combined cure type. Pressure and flexural strength was used as selection criteria.

II. Material and Method

A. Material

In this study, CEM II / A-M (P-L) 42,5 R type cement in accordance with TS EN 197–1 standard were used in all concrete mixtures. Physical and chemical properties of silica fume are shown in Table I.

Physical properties of quartz sand were shown in Table II.

Physical and chemical properties of quartz powder were shown in Table III.

Polycar-300 was used as super plasticiser. The properties of super plasticiser Polycar-300 provided by the producing company was given in Table IV.

For C30/37 control sample, crushed limestone aggregate was used in the mixture. Drinkable city water supply was used in the experiments.

TABLE I
PHYSICAL AND CHEMICAL PROPERTIES OF SILICA FUME

Chemical Properties	
Material	**Quantity (%)**
SiO_2	94,17
Al_2O_3	0,70
Fe_2O_3	0,43
CaO	0,67
MgO	1,23
SO_3	0,57
>45 μm	0,79
Loss on ignition	0,77
Unit volume (gr/cm^3)	0,45
Specific weight	2,25
Specific surface (cm^2/gr)	200000

TABLE II
PHYSICAL PROPERTIES OF QUARTZ SAND

Property	0.15–0,6 mm Quartz Sand
Unit volume (gr/cm^3)	1,60
Specific weight	2,68
Specific surface (cm^2/gr)	150

TABLE III
PHYSICAL AND CHEMICAL PROPERTIES OF QUARTZ POWDER

Component	Quartz Powder %
SiO_2	99,20
Al_2O_3	0,5
Fe_2O_3	0,03
TiO_2	0,02
Density (gr/cm^3)	1,34
Specific weight	2,70

TABLE IV
PROPERTIES OF SUPER PLASTICISER POLYCAR-300

Property	Values
Appearance	Liquid
Density	1,1 kg/L
pH	4.00–5.50
Chloride content	< % 0,1 (TS EN 480–10)

B. Method

The quantity values of the materials used in C30/37 concrete production were given as kg in Table V.

C30/37 sample moulds were 150x150x150 mm and 50x50x300 mm for compressive and flexural samples, respectively. Samples were placed in the moulds by lumping. Samples were removed from the moulds after 24 h. Then, they were taken into standard water curing pool at 20 °C as three for each for 28 days.

There was no found any national or international standard for the design of RPC, yet. Different mixture theories were used for the ratios of granular materials to form a firm structure [6]. These theories have been derived from Mooney's suspension viscosity model [6], [29]. Generally, used mixtures from different mixture designs were obtained by utilizing Mooney's model that was shown for one unit in Table VI [30]. In all mixtures with RPC in this study, Mooney's ratios were taken into account.

TABLE V
C30/37 CONCRETE MIXTURE RATIOS

Materials	Quantity (kg/m^3)
Cement	450
0-4 mm (Crushed Limestone)	799
4-8 mm (Crushed Limestone)	385
8-16 mm (Crushed Limestone)	565
Water	189
TOTAL	2388

TABLE VI
MIXTURE RATIOS OF TYPICAL RPC 200 AND RPC 800 CONCRETES ACCORDING TO CEMENT [30]

Materials	RPC200				RPC800	
	Fiberless		Fiber		Silica Aggregates	Steel Aggregates
Portland Cement	1	1	1	1	1	1
Silica Fume	0,25	0,23	0,25	0,23	0,23	0,23
Sand (150–600 μm)	1,1	1,1	1,1	1,1	0,5	-
Crushed Quartz (d_{50} = 10 μm)	-	0,39	-	0,39	0,39	0,39
Super Plasticiser	0,016	0,019	0,016	0,019	0,019	0,019
Steel fiber (L=12 mm)	-	-	0,175	0,175	-	-
Steel fiber (L=3 mm)	-	-	-	-	0,63	0,63
Steel Aggregates (< 800 μm)	-	-	-	-	-	1,49
Water	0,15	0,17	0,17	0,19	0,19	0,19

TABLE VII
FIBRELESS RPC MIXTURE RATIOS

Materials	Quantity (kg/m^3)
Cement	821
Silica Fume	189
Quartz Sand (0,15-0,6 mm)	902
Quartz Powder (0-0,045 mm)	320
Super Plasticiser (Polycar 300)	16
Water	140
TOTAL	2388

No-fiber RPC mixture ratios used in the experiments are shown in Table VII.

Fiberless RPC sample moulds were 50x50x50 mm and 50x50x300 mm for compressive and flexural samples, respectively. No compression pressure was applied to the fiberless RPC samples poured in the moulds during the setting period. Samples were placed in the moulds by lumping. Samples were removed from the moulds after 24 h. Then, they were taken into standard water and combined curing pool at 20 °C for 28 days. Compressive and flexural strength tests were performed on the samples after standard water and combined curing. TS EN 12390-3:2010 standard was applied in compressive test and TS EN 12390-5:2010 standard was applied in flexural test.

9 different types of combined cure trials were made in order to obtain the most suitable combined cure, as shown in Table VIII. Combined cure tests were applied at different temperatures for different periods in the study. As a result of the study, combined cure with the highest compressive strength was obtained.

TABLE VIII
COMBINED CURE APPLICATION IN THE RPC PRODUCTION

Temperature-Period-Cure	Type of Cure
Water Bath at 90 °C for 3 Days - Drying Oven at 180 °C for 1 Day	Combined
Water Bath at 90 °C for 3 Days - Drying Oven at 180 °C for 2 Days	Combined
Water Bath at 90 °C for 3 Days - Drying Oven at 180 °C for 3 Days	Combined
Standard Water Cure at 20 °C for 7 Days - Drying Oven at 180 °C for 1 Day	Combined
Standard Water Cure at 20 °C for 7 Days - Drying Oven at 180 °C for 2 Days	Combined
Standard Water Cure at 20 °C for 7 Days - Drying Oven at 180 °C for 3 Days	Combined
Standard Water Cure at 20 °C for 7 Days - Water Bath at 90 °C for 2 Days - Drying Oven at 180 °C for 1 Day	Combined
Standard Water Cure at 20 °C for 7 Days - Water Bath at 90 °C for 2 Days - Drying Oven at 180 °C for 2 Days	Combined
Standard Water Cure at 20 °C for 7 Days - Water Bath at 90 °C for 2 Days - Drying Oven at 180 °C for 3 Days	Combined

III. RESULTS AND DISCUSSION

TABLE IX
FIBRELESS RPC DIFFERENT COMBINED CURE PRESSURE TEST RESULTS

Cure Type no	Combined Cure Types	Average Compressive Strength (MPa)
1	Water Bath (WB) Cure at 90 °C for 3 Days - Drying Oven Cure at 180 °C for 1 Day	116
2	Water Bath (WB) Cure at 90 °C for 3 Days - Drying Oven Cure at 180 °C for 2 Days	117
3	Water Bath (WB) Cure at 90 °C for 3 Days - Drying Oven Cure at 180 °C for 3 Days	109
4	Water Cure at 20 °C for 7 Days - Drying Oven Cure at 180 °C for 1 Day	108
5	Water Cure at 20 °C for 7 Days - Drying Oven Cure at 180 °C for 2 Days	109
6	Water Cure at 20 °C for 7 Days - Drying Oven Cure at 180 °C for 3 Days	89
7	Water Cure at 20 °C for 7 Days - WB Cure at 90 °C for 2 Days - Drying Oven Cure at 180 °C for 1 Day	115
8	Water Cure at 20 °C for 7 Days - WB Cure at 90 °C for 2 Days - Drying Oven Cure at 180 °C for 2 Days	**123**
9	Water Cure at 20 °C for 7 Days - WB Cure at 90 °C for 2 Days - Drying Oven Cure at 180 °C for 3 Days	108

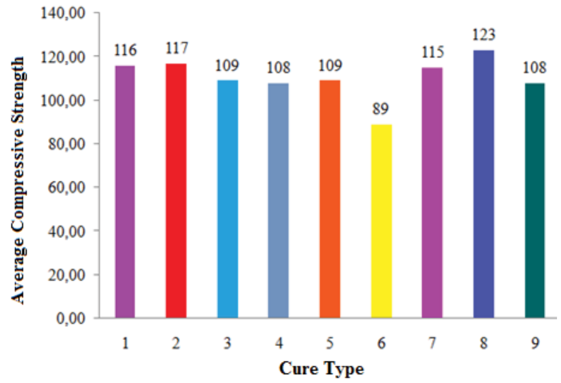

Fig. 1 Average Compressive Strength According to the Cure Types (MPa)

Combined cure tests were applied at different temperatures for different periods in the study. 9 different types of combined cure trials were made in order to obtain the most suitable combined cure. As a result of the study, combined cure with the highest compressive strength was obtained.

As seen in Table IX, the highest pressure resistance was obtained with 123 MPa in the combined cure of standard water cure at 20 °C for 7 days - water bath at 90 °C for 2 days - drying oven at 180 °C for 2 days. Test results for determining the most suitable combined cure were shown in Table IX.

Average compressive strength was shown according to cure types in Fig. 1.

As shown in Table IX, combined cure with the highest compressive strength was obtained with consecutive water cure at 20 °C for 7 days - water bath cure at 90 °C for 2 days - drying oven cure at 180 °C for 2 days. As seen in Table IX, among the different cure types, the highest pressure resistance of fiberless RPC is 123 MPa after the application of water cure at 20 °C for 7 days - water bath cure at 90 °C for 2 days - drying oven cure at 180 °C for 2 days. It can be said that concrete compressive and flexural strength can be possibly increased by applying different combined cure types. Compressive and flexural test results for C30/37 fiberless RPC are given in Table X.

Compressive and flexural strength of fiberless RPC after 28-day standard water cure and optimum combined cure were shown in Fig. 2.

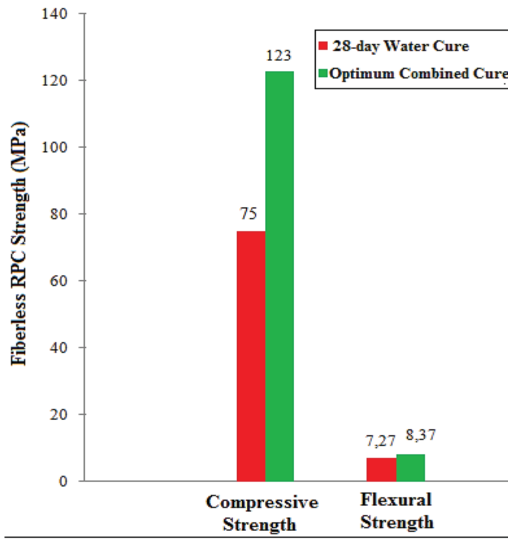

Fig. 2 Compressive and Flexural Strength of Fiberless RPC

TABLE X
COMPRESSIVE AND FLEXURAL TEST RESULTS

Concrete Type	Average Compressive Strength (MPa)		Average Flexural Strength (MPa)	
	28-day Water Cure	Combined Cure	28-day Water Cure	Combined Cure
C30/37	37	-	4.55	-
Fiberless RPC	75	123	7,27	8,37

IV. Conclusions

- Water/binder ratio of fiberless RPC in the study was 0,15 in average. Since the maximum water/binder ratio was determined as 0.40-0.45 in the specifications for rigid pavement, fiberless RPC type can be used for rigid pavements.
- The highest compressive strength of fiberless RPC was found as 123 MPa with water cure at 20 ºC for 7 days – hot water cure at 90 ºC for 2 days - drying oven cure at 180 ºC for 2 days; and the highest flexural strength was found as 8,37 MPa for the same combined cure type. Since the minimum compressive strength was determined as 28 MPa and the minimum flexural strength as 4,5 MPa in the specification for rigid pavement ratios, fiberless RPC type can be used for rigid paving.
- When the compressive and flexural strength in the rigid pavement with fiberless RPC and in other constructions are higher than normal concretes, material and cost saving is possible by constructing all construction elements in smaller sizes.
- As a result of the study, the combined cure type with the highest compressive strength was obtained with consecutive water cure at 20 ºC for 7 days – hot water cure at 90 ºC for 2 days - drying oven cure at 180 ºC for 2 days. It can be said that compressive and flexural strength can be possibly increased by applying different combined cure types.

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