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Stress-strain Characteristics of Reactive Powder Concrete under Cyclic Loading

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ABSTRACT

Reactive powder concrete (RPC) is a type of ultra-high strength cement composite material. It has advanced mechanical properties and shows high ductility characteristics. Many researches have shown that normal and high strength concrete fails under cyclic stresses at load level below its static capacity. In the present study, the mix design guidelines to produce high strength RPC is provided. RPC with compressive strength of 120, 130 and 140MPa was produced. The mechanical properties are obtained for hardened concrete. The present study focuses on the investigation of reactive powder concrete under uniaxial compressive cyclic loading. The investigation was carried out on cubical and cylindrical specimens. The behaviour of RPC under cylic loads is studied by obtaining the stress-strain characteristics under monotonic loading and cyclic loading. Three main types of tests were performed. Stress-strain envelope curve, common point curve and stability point curves were established under repeated load cycles. The limiting stress values required for design are provided. It was concluded that peak stress of the stability point curve could be regarded as the maximum permissible stress. A nonlinear analytical expression was proposed for the normalized stresses and strain which shows a precise fit with the experimental data. The expression will assist in predicting the cyclic response of concrete required for constructional applications.

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1. INTRODUCTION

High rise buildings, long-span bridges, tall statues of national and spiritual leaders become nation's pride, in turn creating a landmark and development of tourism. In actual operating conditions, most structures undergo variable loads. The structures are susceptible to earthquake, wind, blast and impact loads. Hence their design is mainly governed by repetitive loads rather than consideration of just gravity loads. The change with the time in the character of such loads can take a variety of forms i.e., deterministic changes, periodic and non-periodic changes which leads to complex failure mechanisms in structures. These can be expressed in terms of theory of probabilities. Thus, it is necessary to know the nature of failure, behaviour and performance of concrete under cyclic loads. Advanced analyzing methods are required for complex structures. A realistic analysis could be possible by finite element analysis using computerized programs and it requires constitutive laws of material to be used in the construction.

1. 1. Investigation on Cyclic Loads

a. Plain Cement Concrete

The first research on compressive and tensile cyclic loads was carried out by Considere and De Joly on mortar specimens in 1898. The repeated loads were applied at a frequency of 0.07Hz. Fatigue strengths recorded were 55% of static strengths [1]. Investigations of cyclic stresses on concrete were initiated by Van Ornum in 1903, with strengths in a range of 8.4-11MPa. Subsequent experiments on low strength concrete (14-32MPa) led to develop an understating of performance under compressive cyclic loading. The fatigue strengths observed were 45-60% of static strength at a repeated loading frequency of

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6.33Hz [2]. In later years the fineness and quality of portland cement were improved which led to the production of high strength concretes. Kern and Mehmel [3] studied the effect of concrete strains under cyclic loads. Sample strengths varied from 42-60 MPa. As a result, endurance (Wohler) curves were plotted which are a function of number of cycles vs maximal prismatic stress. Khadiranaikar [4] extended the investigation with high-performance concrete. The concrete with strengths 65, 85 and 102MPa was tested under uniaxial compressive repeated loading. Curves in the forms of envelope points, common points and stability points were plotted. Analytical equations were proposed to fit the experimental data. An analytical expression was provided for normalized curves. It is shown in equation 1.

$$\sigma = \varepsilon^{\beta} Exp\left[\left(1-\frac{\varepsilon}{\alpha}\right)\varepsilon\right] \quad (1)$$

where, σ, ε = Normalized stress and strain ratios respectively. α, β are equation parameters. The results concluded that peak stresses at common point and stability point were 0.85 and 0.75 of envelope stresses, respectively. The similar work was carried out by Aslam et al. [5] on geopolymer concrete of strengths 40-60MPa. Further equations for recycled aggregate concrete were proposed by Hu et.al [6] for numerical simulation of columns and frames subjected to cyclic loads.

b. Reinforced Cement Concrete

Study on plain concrete was insufficient for applications in recent years, where reinforced concrete was used for the construction of many structures. Hence, stress-strain models were proposed by various researchers for loading and unloading paths of confined concrete. The expressions obtained suggested that the reloading path varies in the form of cubic function [7-10]. An approach towards finite element modelling was made by Kwan and. Billington [11]. Different models were evaluated in predicting the cyclic behaviour of reinforced structural concrete. Further reinforced concrete tied columns were modelled by Lukkunaprasit and Thepmangkorn [12]. These were evaluated with experimental values by varying shapes and studying the hysteretic response under different loading cycles. Cyclic stress-strain study was done by Sadrnejad and Khosroshahi [13] with the help of simulation models for reinforced concrete (RC) under uniaxial, biaxial and triaxial compressive and tensile loads. The results indicated that the simulation models were capable of predicting the concrete behaviour under any stress path considered [13]. A theoretical analysis using various expressions was done to examine the RC bridge constructed in Iran. Azadpour and Maghsoudi [14] proposed a finite element model using ANSYS to compare the results of field analysis, which were obtained from preinstalled structural health monitoring (SHM) systems. The strains at several points on the bridge were measured using strain gauges. The strains obtained from theoretical analysis and the ANSYS model were compared with field reading. Theoretical equations provided a strain of 60-70% of field values. Whereas ANSYS model results were close to field analysis and were in the range of 80-90% of field values [14]. Research on loading history and number of cycles on fixed end RC beams and infill masonry was done. Results yielded hysteretic curves. Strut and tie models (STM) were proposed to evaluate the mode of failure and loading capacity of members [15,16]. The most recent study on RC portal frames subjected to lateral and cyclic loads was done by Gunasekaran and Choudhury [17]. The results were plotted in the form of hysteretic curves. It was observed that initiation of cracks took place at 30% of failure load. The ultimate lateral load causing failure was observed to be 62kN [17].

1. 2. Investigation on Reactive Powder Concrete

In latter part of 20th century Ultra-High-Strength Concrete (UHSC) is being employed in many important structures. Reactive-Powder-Concrete (RPC) is one, which is advanced among the group of UHSC. RPC can fulfil required characteristics of structural concrete, such as high durability, ultra-high-strength, high workability and high toughness, compared to plain concrete. RPC can take more loads, for a long-life span. Sherbroke pedestrian bridge in Canada is the first bridge constructed using RPC in 1997. It has a span of 60m. RPC of grade 200MPa was used for the construction. Seonyu footbridge in Korea with a span of 120m and Sakata Mirai bridge in Japan with a span of 50m were also constructed using RPC in 2002. RPC has also been utilized in construction of many bridges and pathways in USA, New Zealand, Australia, Austria and other parts of the world. It also has applications in the field of missile silos, energy dissipaters, airport and highway pavements and bridge piers etc.

RPC was first developed by Richard and Cheyrezy [18] using principles of homogeneity, ductility, and optimum packing. Mechanical properties of RPC were studied by Coppola et al. [19]. RPC of 200 MPa strength was produced by combinations of ambient, pressure and steam curing up to 90º – 160º C. Kumar and Gururaj [20] investigated RPC by replacing cement with metakaolin and alccofine with various proportions. They found that 51% of cement, 26% of alccofine and 15% of metakaolin will give higher strength, of up to 110MPa, among the various proportions. Elson and Sarika [21] studied many trial mixes of RPC by varying different raw materials and the highest strength of 130MPa was obtained. Optimum values of constituent materials for desired strength were obtained. The results indicated that ordinary portland cement of 1000kg/m^3, silica fume-22.25%, quartz powder-25.2%, W/B ratio-0.2 and steel fibres of 3.06%, is required to produce RPC of 130MPa Strength. Mingze et. al. [22] studied RPC under fatigue at various amplitudes. Cylindrical specimen was subjected to load (65-95% of ultimate strength) with the frequency of 3cycles/s with multi-level amplitude. They found that difference in the size of the specimen is less significant on residual strain in fatigue and relation between deformation and number of cycles was proposed. Muranal and Khadiranaikar [23] produced RPC of 180MPastrength. They studied the durability aspects of RPC under acid attacks and chloride ion permeability. The study concluded that the weight loss and reduction in strengths were very less compared to normal strength and high strength concretes. A very low to negligible amounts of chloride ions were passed through the specimens. RPC shows higher resistance under high concentrations of acids [23]. A study on mechanical properties of RPC was done by Madhkhan and Saeidian [24]. Glass fibres by volume of 1.5 - 2% were added. Normal curing yielded 90-100 MPa compressive strength. RPC with 110 - 140 MPa strengths were obtained with autoclave curing and accelerated ageing methods [24].

1. 3. Objectives

It is observed that many investigations have been carried to evaluate the behaviour of cement mortars, low - high strength plain and reinforced concretes under repeated loads. Mathematical models and analytical equations are obtained from such investigations to predict the behaviour of concrete under different stress paths. However, there is no significant data available on RPC to predict its nature under cyclic loads. Much of the investigations have been carried out to produce RPC with high strengths. But there are no standard guidelines available for mix designs. Hence an effort is made in this research to produce RPC high strengths and study its nature under cyclic loads. Following objectives have been set.

i. To produce three grades of RPC with strengths 120MPa, 130MPa and 140MPa.
ii. To study the behaviour of RPC under monotonic load curves and cyclic load curves.
iii. To study the stresses and strains under envelope curve points, common points and stability points.
iv. To propose a single analytical equation for the normalized stress and strains.

The study will provide the optimum mix proportions to produce ultra-high strength RPC. It will also provide limiting stress values required for the designs. The analytical equation will help in predicting the behaviour of RPC under cyclic stresses. This will help the researchers and constructional engineers to use the material to its full potential.

2. MATERIALS

From the literature, it is observed that high-grade ordinary portland cement (OPC) is recommended to produce higher strengths of concrete. In present research OPC-53 grade, Ultratech cement is used. The density and fineness are 3120 kg/m^3 and 3390 cm^2/g, respectively. It confirms to IS: 4032-1985 [26]. Silica fume - 920D is obtained from ELKEM MICROSILICA® that confirms to IS: 15388-2003 [27] and ASTM C1240 [28].

In RPC, coarse aggregates are completely eliminated. Only high purity silica sand is used. It is obtained from AU(P) LTD. Mukka, Mangalore. It is yellowish-white in colour and particle size in the range of 90 μm to 600 μm. The quartz flour is brought from Raviraj Mineral Industries, Bangalore. The particle size is in the range of 10 μm to 40 μm with a specific gravity of 2.6. Quartz flour improves density and hydration process. Water to binder (w/b) ratio is very low in RPC compared to normal concrete. Hence high-range water reducing agent is used with w/b ratio of 0.2. Master Glenium product from BASF of series SKY-8233 is used as superplasticizer in the present work, which is certified from ATM C494 and IS2645-2003 [29].

3. EXPERIMENTAL PROGRAM

3. 1. Production of RPC

a. Mix Procedure and Curing:

A Pan mixture of capacity 200 litres and mixing speed of 140 – 280 RPM is used for mixing raw materials. The speed of pan mixer was set to 150 RPM. The dry mixing of cement, silica fume, sand and quartz powder was done for 2 minutes. Later, 50% by volume of water was added along with superplasticizer and mixed for 5 minutes. The remaining amount of water and superplasticizer is then added to the wet mix. The constituents are mixed for 18±2 minutes to get a wet workable mix. The mix procedure adopted was similar and improvised to the procedure recommended by Parameshwar and Subhash [25]. The flowable mix obtained is shown in Figure 1. The mix is then poured into cubical and cylindrical moulds. Cube specimens are 100×100×100mm and cylindrical specimens are of 70mm diameter and 140mm height as shown in Figure 2. The samples were allowed to set and then immersed in a tank full of clean water. Normal curing was done up to 28 days as per IS 516-1959 [30].

b. Optimum Mix proportions:

At present, there are no standard guidelines available to produce RPC. Hence many trial mixes have been carried out. Above mentioned procedure is applied and

Figure 1. Wet mix of RPC

Figure 2. Samples of RPC

optimum composition is obtained for the constituent materials. The details of mix proportions are given in Table 1.

3. 2. Monotonic Load Tests A servo-controlled compression testing machine, of capacity 3000kN, was used to obtain compressive strengths. The load was applied at a rate of 0.5 kN/s till the complete failure of sample takes place. The loads (in kN) and deformation (in mm) are noted down. The corresponding stress and strain values are calculated. The test procedure is shown in Figure 3.

3. 3. Cyclic Load Tests An actuator of 500 kN capacity was used to apply cyclic loads. The load was increased at the rate of 20N/s. A compressometer with a load cell was used to record load values in kN. Circumferential extensometer and LVDT's were attached to specimens to record resultant deformation/displacement in terms of mm. The obtained data are processed in a data acquisition system. Further corresponding stress-strain values are calculated. The test setup is shown in Figure 4.

TABLE 1. Mix proportions of RPC

Sl. No.	Material	M1 (120 MPa)	M2 (130 MPa)	M3 (140 MPa)	Units
1	Cement	900	900	900	Kg/m^3
2	Silica Fume	90	108	135	Kg/m^3
3	Sand	977.32	932.92	911.65	Kg/m^3
4	Quartz Powder	135	90	45	Kg/m^3
5	Sper plasticizer	22.5	18	18	Kg/m^3
6	Water	0.21	0.2	0.19	-

Figure 3. Strength Test on RPC

Displacement controlled cyclic load tests have been carried out in the actuator. It was possible to regulate load history by monitoring strain in each cycle. In the ascending zone of the stress-strain curve, the loads are increased gradually up to pre-established intervals of strain and then loads are released to form the descending zone. This completes one cycle. Once the material is failed at ultimate load, stress-strain curve tends to drop. Then, the releasing of load is done when the stress values are observed to decrease than the peak stress values of respective cycles. The same procedure is applied for all three grades of concrete and cyclic load curves are plotted.

The stability points test was carried out for each individual cycle obtained from cyclic load tests. The unloading was done when the reloading curve intersects with unloading curve of previous cycle. The stress values are seen to decrease and get stabilized at certain strain values. A closed hysteresis loop is formed.

Figure 4. Cyclic Load Test

These values of lower bound stresses and strains are noted down. The curves are plotted by joining all the stress-strain points which forms a stability point curve.

4. RESULTS AND DISCUSSIONS

Three grades of RPC i.e., M1, M2 and M3 with compressive strengths 120 MPa, 130 MPa and 140MPa are produced for the present research. The number of loading cycles and stress levels are the major factors affecting the behaviour of RPC under cyclic loading. The effect of cyclic loading can be categorized as follows:

- High-stress levels with a low number of cycles.
- Low-stress levels with a high number of cycles.

In the former category, incremental deformations are observed which leads to formation of plastic strains and micro-cracks resulting in failure of structure. Hence present study focuses on such investigation.

4. 1. Monotonic Load Curve Incremental uniaxial monotonic loads are applied on the cylindrical specimens until the complete failure of specimen is observed. The peak stress and strain values for each mix are noted down.

Monotonic loading curves plotted for all the mixes are shown in Figure 5. The curves are in a linear state until 85% of peak stress value. The material is in perfectly elastic state. Further, an increase in the load changes the slope of the curve. It is due to the fact that initial cracks were formed when the stress values cross 85% of the ultimate stress values. The material enters into an elasto plastic state. The specimens continue to take the loads but shows higher deformation. At ultimate load, major cracks are formed and material loses all of its elastic properties and enters into a plastic state. The effective load carrying capacity of the specimens is lost. Further increase in loading induces additional strains and stress values are gradually decreased until the specimen fails completely.

From Figure 5 it is observed that the curve drops steeply after peak stresses. The failure is observed to be sudden and bursting in nature. This indicates the brittle nature of RPC. The peak stress and strain value obtained by monotonic loading are shown in Table 2.

4. 2. Cyclic Load Curves The displacement/ strain intervals are fixed. In ascending part of the curve, load values are increased up to predetermined strain interval and then the loads are released until the strain is stabilized up to certain lower bound values, which forms the descending part. This closed hysteresis loop forms one cycle. The process is repeated up to peak load/ stress values. At peak value of stress initiation of cracks takes place and the material loses its effective load carrying capacity. In proceeding cycles releasing of load is done when the reloading curve starts to descend. This process is continued until complete failure of specimen takes place. The points of strain and corresponding stress values are plotted in the form of cycles as shown in Figures 6-8 for M1, M2 and M3, respectively.

Figure 6 shows a comparison model [6] of normal strength concrete (NSC). The strength of concrete was 25MPa. From the figure, it was observed that stresses under cyclic loading are more than monotonic load stresses. The skeleton curve also known as envelope curve does not coincide with the monotonic load curve. The specimen failed after 10th cycle. The maximum strain corresponding to peak stress values was observed to be 0.002. The strain at complete failure is observed to be 0.010. It shows the ductile nature of normal concrete.

TABLE 2. Peak Monotonic Load Stress-Strains

Mix	Stress (MPa)	Strain
M1	118.19	0.003192
M2	128. 55	0.003208
M3	137.25	0.003219

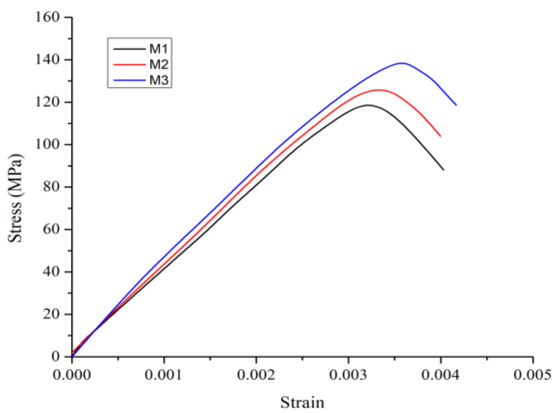

Figure 5. Monotonic Load Curves

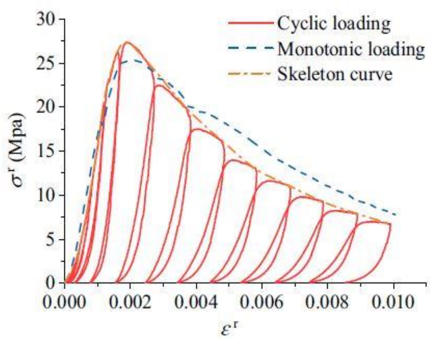

Figure 6. Comparison Model for NSC [6]

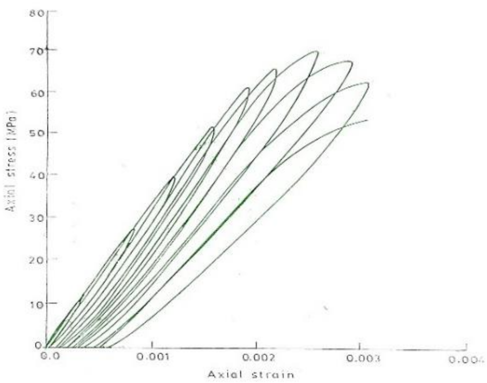

Figure 7. Comparison Model for HSC [4]

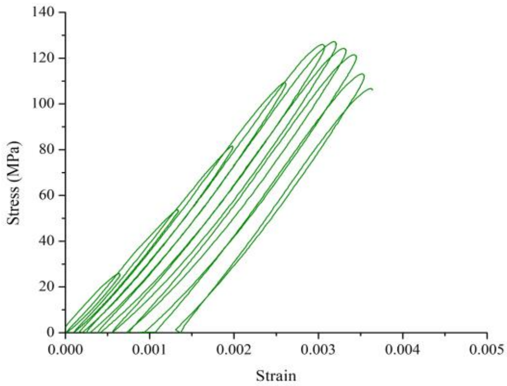

Figure 9. Cyclic Load Curves for M2

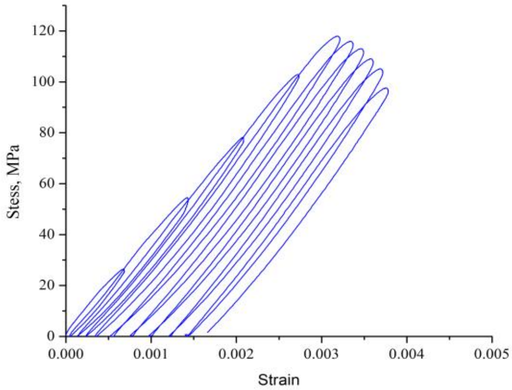

Figure 8. Cyclic Load Curves for M1

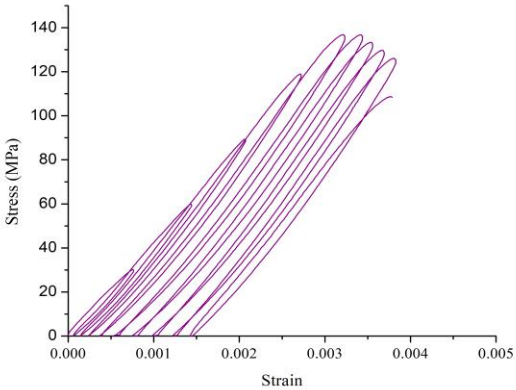

Figure 10. Cyclic Load Curves for M3

Figure 7 shows comparison models of high strength concrete (HSC). The strength of concrete was 85MPa. The results concluded that the envelope curve coincides with the monotonic load curve. The specimen failed after 11th cycle. The maximum strain corresponding to peak stress values were observed to be 0.0025. The strain at complete failure is observed to be 0.0030. It indicates that high strength concrete shows brittle nature of failure.

The results of the present study, the points of strain and corresponding stress values, are plotted in the form of cycles as shown in Figures 8-10 for M1, M2 and M3, respectively. It was observed that specimens for M1, M2 and M3 failed after 11th, 10th and 9th cycles respectively. This indicates that, as the grade of concrete increased, the resistance towards plastic stresses reduced for post-peak behaviour. The specimens tend to fail earlier than the lower grade concrete. However, RPC shows higher strain values i.e., 0.0031, at peak stress values than compared to NSC and HSC. This indicates that RPC shows better performance when subjected to higher stress values and also it can withstand more deformations. The strain at complete failure is observed to be 0.0035 which is again more than HSC. The RPC also shows the brittle nature of failure.

4. 3. Envelope Curve The envelope curve is plotted by superimposing the peak stress-strain points of each cycle obtained in cyclic load curves.

The envelope curve for M1 is plotted in Figure 11. It is observed that the envelope curve coincides with monotonic curve. Similar nature is observed for M2 and M3, respectively. The mean stress and strain values obtained are shown in the following Table 3.

4. 4. Common Point Curve The common point was initially defined as a folding point by Khadiranaikar [4] as the curve started folding after the intersection of the reloading portion of curve on loading portion of previous cycle. Thus, a common point curve is obtained by joining the loci of points where reloading curve intersects with unloading curve of previous cycle. The material remains in an elasto-plastic state. The common points for M1 are shown in Figure 12.

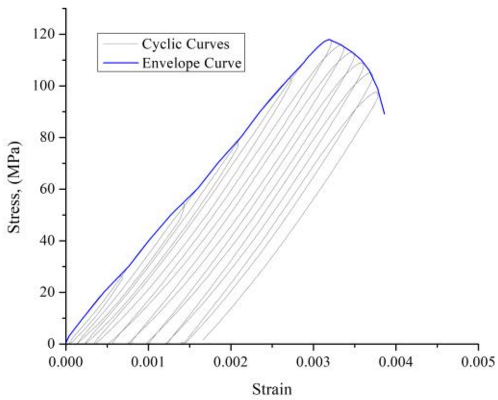

Figure 11. Envelope Curve for M1

TABLE 3. Peak Envelope Stress-Strains.

Mix	Env. Stress (MPa)	Env. Strain
M1	117.9893	0.003189
M2	127.2547	0.003197
M3	136.8497	0.003210

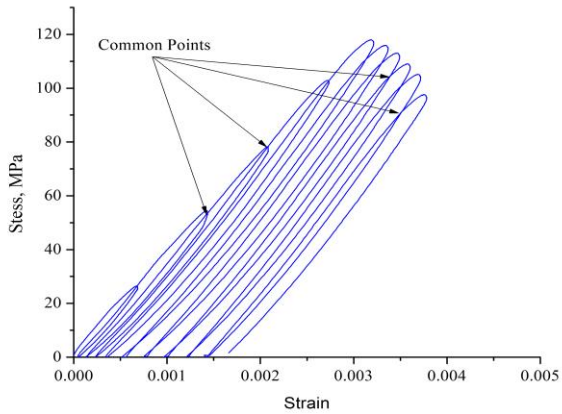

Figure 12. Common points for M1

A common point for RPC contributes much to structural design, as load beyond this limit results in remnant deformation, hence it sets an upper limit for the material to be used under cyclic loading. The mean peak stresses obtained from experiments are shown in Table 4.

TABLE 4. Peak Common Point Stress-Strains.

Mix	Stress (MPa)	Strain
M1	110.8901	0.003048
M2	119.8338	0.003137
M3	127.9705	0.003166

4. 5. Stability Point Curve Peak stress-strain values at common points of each curve are noted down. The stresses above common points will lead to additional strains, while stresses below these values will give no additional strains and it is observed that stress-strain curve will go into a closed hysteresis loop. These points are called stability points and the loci of points as stability point curves. These points are also considered as minimum stress levels.

The stability points test curves obtained from present investigation are shown in Figures 13-15. From the figures, it is observed that the number of cycles within the loop increases with an increase in stress value to reach a stability point. When stress values reach to maximum, an initial crack is induced. The strain in the specimen is increased with the stress values being nearly the same. The slope of the curve is changed after a certain number of cycles which indicates that the specimen has failed, yet it continues to take the load and further increase in the stress levels will lead to complete failure. The factor of safety specified in IS codes is 1.5 which is suitable for normal and high strength concretes. The present investigation provides a factor of safety of 1.35**.** Maximum stability point stress observed for M1, M2 and M3 are shown in Table 5.

4. 6. Analytical Curves The stress-strain values obtained from all the three curves are normalized with peak stress (σ_p) and peak strain (ε_p). When a linear regression model contains only one independent variable, it is referred as a simple regression model. In the present study, modelling is done between normalized stress as a dependent variable with respect to a single independent variable i.e., normalized strain. The present investigation is based on the principle of least squares. The difference between experimental observations and fitted curve in the scatter diagram are minimized, by the orthogonal regression method, to get intercepts and slope parameters. The curve is fitted by

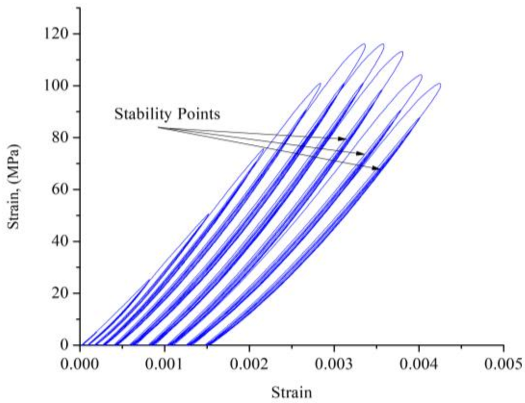

Figure 13. Stability Points test for M1

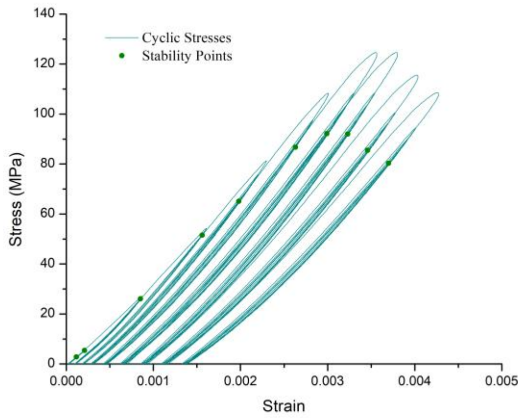

Figure 14. Stability Points test for M2

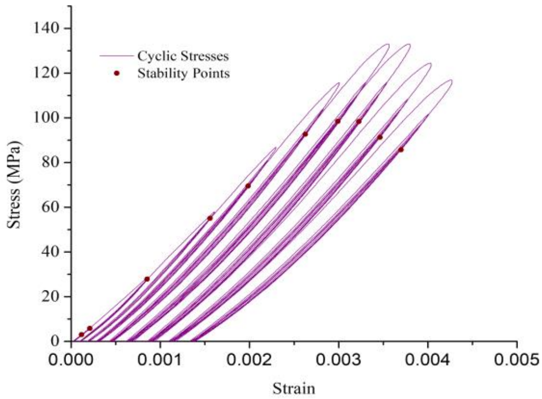

Figure 15. Stability Points test for M3

TABLE 5. Peak Stability Point Stress-Strains.

Mix	Stress (MPa)	Strain
M1	85.8386	0.002823
M2	92.1582	0.002991
M3	98.4249	0.003027

using MATLAB. The analytical expression obtained is in the Fourier form with a fitting degree of one. The proposed expression is shown below.

$$f(\sigma) = C_0 + C_1 \cos(\alpha\varepsilon) + C_2 \sin(\alpha\varepsilon) \quad (2)$$

where, σ, Ɛ are Normalized stress and strain ratios respectively, C_0 is an intercept parameter and, C_1, C_2, α are equation constants representing slope parameters.

The values of constants generated for each curve are presented in Table 6. The obtained mean values of strains are 0.003189, 0.003197 and 0.0003210 with a standard deviation of 3.41×10^{-5}, 4.62×10^{-5} and 5.91×10^{-5} for M1, M2 and M3 mixes, respectively. The obtained mean peak stress values are 117.99 MPa, 127.26MPa and 136.85MPa with a standard deviation of 2.18MPa, 2.67MPa and 2.98MPa for M1, M2 and M3 mixes, respectively. The proportion of variance is expressed as a statistical measure R-squared (R_C) for each type of cyclic curve. It is shown in Table 6 for all the grades RPC. From the above-proposed equation, the average variance was found to be 0.981.

The normalized curves for all three mixes are shown in Figures 16-27. It is observed that the analytical curve shows a perfect fit for all the experimental points considered. From the Figures 16 to 27, it is noted that the analytical envelope curve is linear in the initial portion up to 80% of normalized stress peak. Later it is observed to be parabolic in nature. The normalized common point curve follows the same path as normalized envelope curve with lesser stress values. It exhibits curvilinear behaviour in the initial portion as shown in Figures 19 to 21. The average maximum normalized peak stress corresponding to common points

TABLE 6. Values of Equation Constants

Curves	RPC Mix	Constants				
		C0	C1	C2	α	Rc
Envelope Point	M1	0.4512	-0.4162	0.2214	2.550	0.9883
	M2	0.4594	-0.4301	0.2450	2.741	0.9864
	M3	0.4709	-0.4328	0.1961	2.560	0.9856
Common Point	M1	0.4801	-0.4020	0.0260	3.192	0.9694
	M2	0.4563	-0.4067	0.0861	2.998	0.9609
	M3	0.4851	-0.4008	0.0475	3.041	0.9745
Stability Point	M1	0.3221	-0.3125	0.1967	2.848	0.9822
	M2	0.2974	-0.2886	0.2428	2.506	0.9897
	M3	0.3018	-0.2968	0.2018	2.659	0.9905

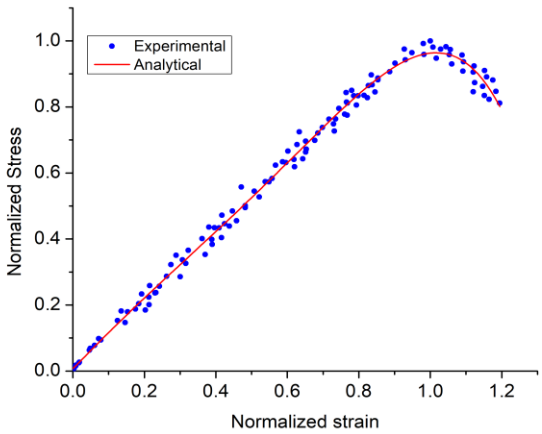

Figure 16. Normalized Envelope Curve for M1

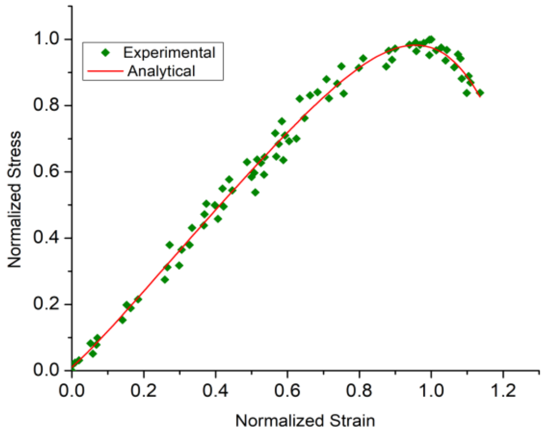

Figure 17. Normalized Envelope Curve for M2

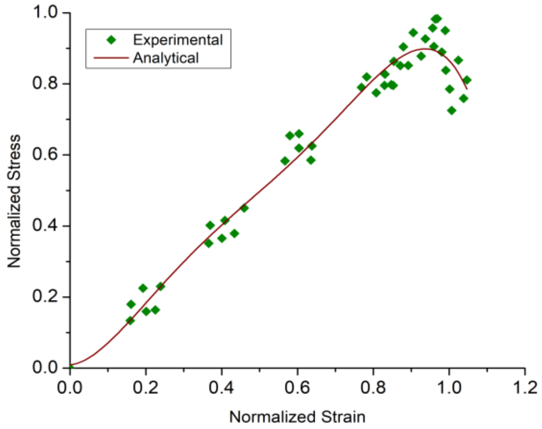

Figure 20. Normalized Common Point Curve for M2

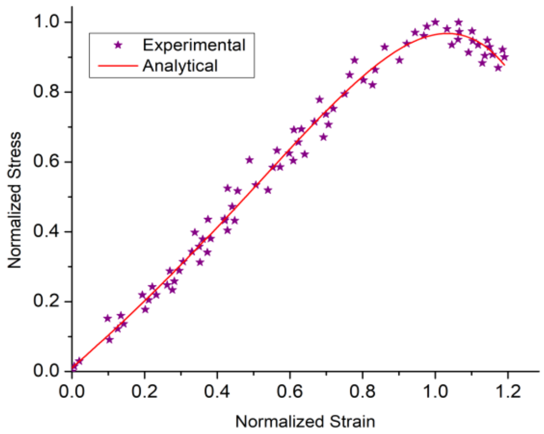

Figure 18. Normalized Envelope Curve for M3

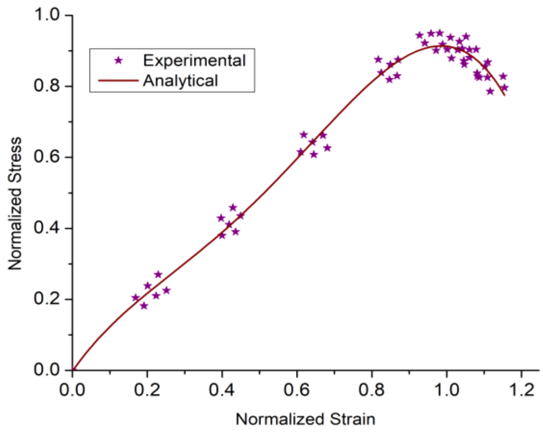

Figure 21. Normalized Common Point Curve for M3

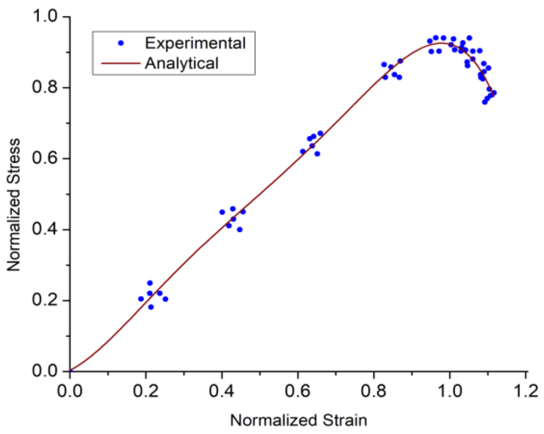

Figure 19. Normalized Common Point Curve for M1

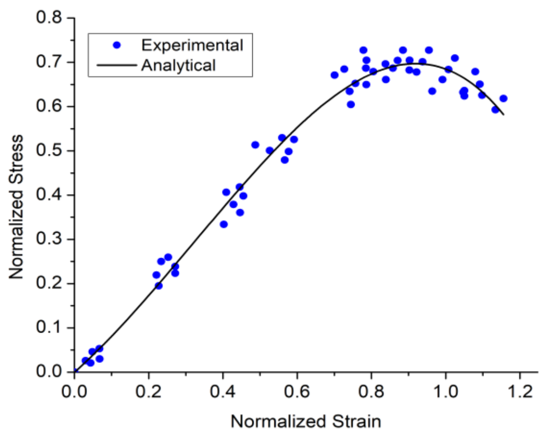

Figure 22. Normalized Stability Point Curve for M1

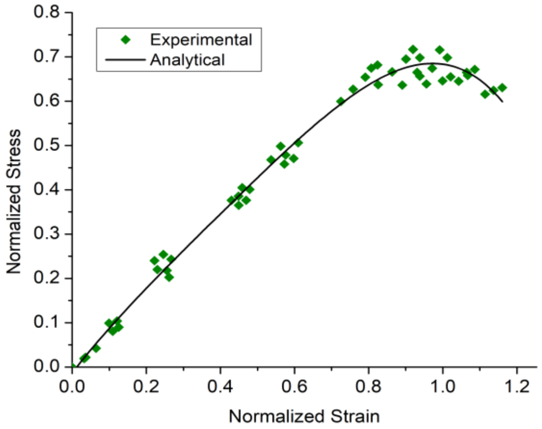

Figure 23. Normalized Stability Point Curve for M2

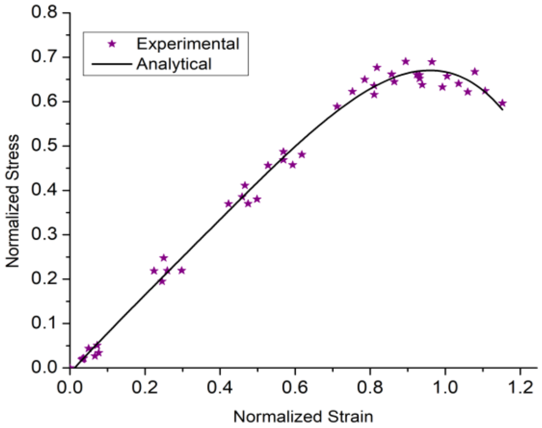

Figure 24. Normalized Stability Point Curve for M3

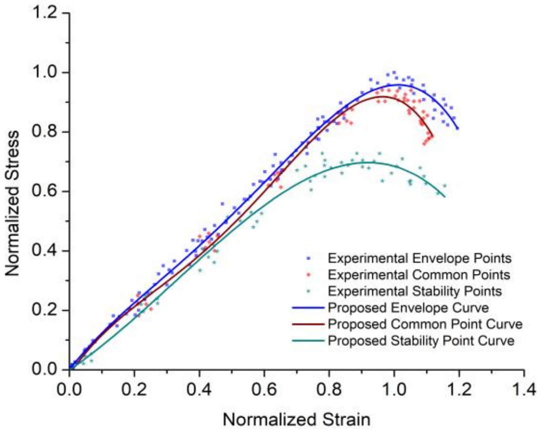

Figure 25. Combined Normalized Curves for M1

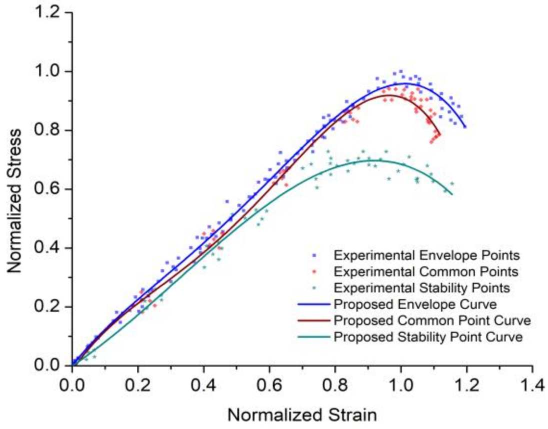

Figure 26. Combined Normalized Curves for M2

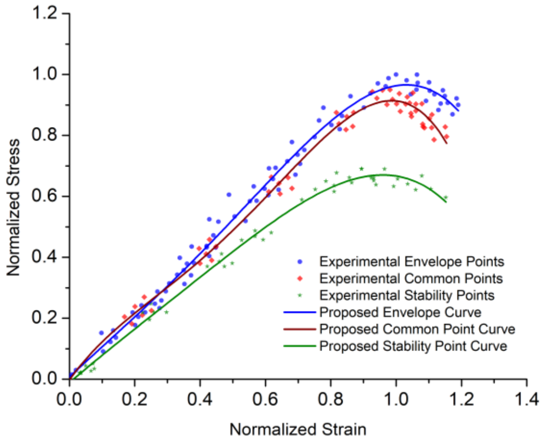

Figure 27. Combined Normalized Curves for M3

is observed to be 0.948 for all the grades of RPC. The normalized stability point curve is linear in nature as shown in Figures 22 up to 24. It provides the limits of plastic stress values beyond which failure of specimen due to plastic strain accumulation is observed. The average maximum normalized stability points stress observed is 0.728.

5. CONCLUSIONS

Reactive powder concrete is a new generation ultra-high-strength cement composite material. There are no specific guidelines available for the procedure of mix design. The present investigation aims to produce high strength RPC and to study its behaviour under cyclic loads. The conclusions drawn from the present research are as follows:

1. The procedure and mix proportions for producing ultra-high strength RPC with different constituent materials is obtained. RPC with 120MPa, 130MPa and 140MPa compressive strengths have been achieved.
2. Stress-strain characteristics of RPC under cyclic loads is compared with normal strength concrete (NSC) and high strength concrete (HSC). Higher strain values were observed at higher stress ranges.
3. The behaviour of RPC under cyclic loads is studied by plotting stress-strain monotonic curve, envelope points curve, common points curve and stability points curve.
4. It is observed that descending part of the monotonic stress-strain curve, after peak loading, falls drastically and shows the brittle nature of failure in RPC.
5. The envelope curve for all grades of concrete is similar and identical to monotonic stress-strain curve. It was also shown that envelope curve coincides with monotonic load curve at peak stresses.
6. The common point curve was established, which can be used as upper-stress limit in the design of RPC structures. It was observed that mean common point stresses are 90 - 94% of peak stress.
7. Lower strength concrete exhibited a lower stress ratio for the stability point curve. Stress values obtained in stability point curve indicate that stability point stress level is in the range of 70 - 75% of that of peak stress values before the failure of specimen.
8. The failure of specimen was initiated due to the formation of cracks at load cycles with peak stresses greater than the peak stress of stability points.
9. It was observed that both unloading and reloading curves of a cycle never intersected any other unloading and reloading curves of previous cycles respectively. It shows that in each cycle there is a residual strain. The average residual strain observed was 5×10^{-4}.
10. An analytical expression was proposed to predict the behaviour of RPC under uniaxial compressive cyclic loads. The expression exhibits a precise fit for all the grades of concrete considered.

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Persian Abstract

چکیده

بتن پودری واکنشی (RPC)نوعی ماده کامپوزیت سیمانی با مقاومت فوق العاده بالا است. خواص مکانیکی پیشرفته ای دارد و ویژگی های شکل پذیری بالایی را نشان می دهد. بسیاری از تحقیقات نشان داده اند که بتن معمولی و با مقاومت بالا تحت تنش های چرخه ای در سطح بار کمتر از ظرفیت استاتیکی خود دچار شکست می شود. در مطالعه حاضر، دستورالعمل طراحی مخلوط برای تولید RPC با مقاومت بالا ارائه شده است. RPC با مقاومت فشاری ۱۲۰، ۱۳۰ و ۱۴۰ مگاپاسکال تولید شد. خواص مکانیکی برای بتن سخت شده به دست می آید. مطالعه حاضر بر بررسی بتن پودری راکتیو تحت بارگذاری چرخه ای فشاری تک محوری تمرکز دارد. بررسی بر روی نمونه های مکعبی و استوانه ای انجام شد. رفتار RPC تحت بارهای سیلیکی با به دست آوردن ویژگی های تنش-کرنش تحت بارگذاری یکنواخت و بارگذاری چرخه ای مورد مطالعه قرار می گیرد. سه نوع اصلی آزمایش انجام شد. منحنی پوشش تنش-کرنش، منحنی نقطه مشترک و منحنی نقطه پایداری تحت سیکل های بار مکرر ایجاد شد. مقادیر تنش محدود کننده مورد نیاز برای طراحی ارائه شده است. نتیجه گیری شد که تنش اوج منحنی نقطه پایداری را می توان به عنوان حداکثر تنش مجاز در نظر گرفت. یک بیان تحلیلی غیرخطی برای تنش‌ها و کرنش‌های نرمال‌شده پیشنهاد شد که تناسب دقیقی با داده‌های تجربی نشان می‌دهد. این عبارت به پیش بینی پاسخ چرخه ای بتن مورد نیاز برای کاربردهای ساختمانی کمک می کند.