CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary of Research

This research presents a comprehensive investigation of the mechanical properties of nanosilica reactive powder concrete (NSRPC) as well as determining the cracking and ultimate shear capacities of beams made from such concrete which are referred to as NSRPC beams. The investigation is of four Parts:

1. Experimental study on control specimens (Cylinders and prisms) of different mixes of NSRPC to assess their mechanical properties including compressive strength f'_{cf}, splitting tensile strength f_{spf}, modulus of rupture f_{rf} and modulus of elasticity E_{cf}.
2. Carrying out experimental tests on sixteen, two point loaded , simply supported, singly reinforced, rectangular, NSRPC beams designed to fail in shear to determine the effect of important parameters on their shear behavior. The beams were all of same dimensions and the studied parameters were:

a. Material parameters: Including varying the percentage of nanosilica content NS, percentage of silica fume content (SF), percentage of the volumetric ratio of steel fibers (V_f) as well as the effect of the dual absence of NS and V_f from the mix.

b. Beams parameters: Including varying the ratio of longitudinal steel bars (ρ), the shear span to effective depth ratio (a/d) and the use of steel stirrups in the beam.

To allow investigating the effect of each parameter independently , a reference NSRPC beam having NS= 3%, SF=15%, V*f*=2, ρ=0.0742, a/d=3.5 and no steel stirrups was considered and the effect of each parameter was studied separately by varying this parameter while keeping all the remaining parameters constant equal to those of the refrence beam.

Structural characteristics such as the cracking shear force V_{cr}, ultimate shear capacity Vu, the associated mid–span vertical deflections Δ_{cr} and Δ_o , the ductility ratio $\Psi = =\Delta_o/\Delta_{cr}$, maximum crack width W_{max} , maximum longitudinal tensile strain ε_{Lmax}, maximum diagonal tensile strain ε_{Dmax} as well as mode of failure and crack patterns were all investigated and carefully discussed.

3. Carrying out finite element analysis FEA (Through the use of ANSYS computer programme, version 11) to determine numerically all the mentioned structural characteristics. The accuracy of the theoretical FEA was assessed by comparison of results with the experimental findings.
4. Carrying regression analyses for the experimental results to establish empirical equations for estimating the compressive strength f'_{cf} , splitting tensile strength f'_{spf}, modulus of rupture f'_{rf} for NSRPC. In addition, an empirical equation was also established for the prediction of the ultimate shear capacity Vu of NSRPC beams which was compared with various design approaches.

7.2 Conclusions

From this research work, the following conclusions are drawn:

7.2.1 Mechanical properties of NSRPC

1.Results show that there is a significant improvement in the mechanical properties of NSRPC due to the addition of nanosilica and steel fibers. Increasing nanosilica content NS from zero to 3% increased f'_{cf} by 31.3% , f_{spf} by 45.3% , f_{rf} by 50% and E_{cf} by13.4%. Increasing silica fume content SF from 5% to 15% increased f'_{cf} by 21.1% , f_{spf} by 7.8% , f_{rf} by 12.2% and E_{cf} by 5.4%. Increasing the volumetric ratio of steel fibers Vf from zero to

2% resulted in a pronounced and remarkable enhancement in the mechanical properties of NSRPC, such that f'_{cf} increased by 60.8% , f_{spf} increased by 242.5%, f_{rf} increased by 275% and E_{cf} increased by 24.4%.The tests on control specimens revealed that when both nanosilica and steel fibers were absent from the mix, the mechanical properties of the hardened concrete were decreased dramatically, such that: f'_{cf} decreased by 52.4%, f_{spf} decreased by 78.8%, f_{rf} decreased by 81.1% and E_{cf} decreased by 28.8%.

2-NSRPC mixes containing nanosilica 3% and steel fibers of ratio 2% showed 110% higher compressive strength (f'_{cf}), than that corresponding to dual absence of nanosilica and steel fiber. Dual absence of nanosilica and steel fibers in NSRPC resulted in a brittle material which fail suddenly and violently. Noting that the addition of nanosilica and steel fibers in NSRPC mixes changes their brittle mode of failure when hardened into a more ductile one and improves the concrete ductility, post cracking and load carrying capacity. Nanosilica addition results in more closely spaced cracks, reduces the crack width.

3- It was found that the addition of nanosilica and steel fibers to NSRPC mixes resulted in a higher improvement of splitting tensile strength than of compressive strength.

4- More than (100)mixes were tested, the optimum mix having 3% NS , 15% SF and 2% Vf. It must be pointed out here that an extra mix having NS=4% was also tried in this research program but, in comparison with the 3% NS mix, it gave weaker properties of the hardened concrete. Therefore it was concluded that a percentage of NS content greater than 3% in the mix would not be beneficial for improvement of concrete strength and economically undesirable and thus it was rejected. It is also of interest to not here that two extra mixes having SF=20% and 25% were also tried but gave weaker strength results of the hardened concrete than the mix of

SF=15%. If a higher percentage of V_f was used, mixing problems would arise as a result of the substantial immediate loss of workability of the mix and non-uniform distribution of fibers due to the effect of fibers balling which would require great efforts and relatively long vibration time to manufacture a beam.

7.2.2 Shear Capacity and Structural Performance of NSRPC beams

a- Effect of varying material parameters

1-Increasing nanosilica content NS from zero to 3% resulted in the following percentages of variation in the structural properties of the tested NSRPC beams;

- ❖ Diagonal cracking shear force V_{cr} (hence cracking load P_{cr}) increased by 35.7% .
- ❖ Ultimate shear capacity V_u(hence ultimate load P_u) increased by 25.1%.
- ❖ Deflection Δ_o (corresponding to ultimate load) decreased by 15.2%.
- ❖ Ductility ratio Ψ decreased by 26.1%.

Therefore increasing NS made the beam stronger but more brittle.

2- Increasing silica fume content SF from 5% to 15% resulted in the following percentages of variation in the structural properties of the tested NSRPC beams;

- ❖ Diagonal cracking shear force Vcr (hence cracking load P_{cr}) increased by 18.8 %.
- ❖ Ultimate shear capacity Vu (hence ultimate load P_u) increased by 10.7%.
- ❖ Deflection Δ_o (corresponding to ultimate load) decreased by 10.9% .
- ❖ Ductility ratio Ψ decreased by 30.6%.

Therefore increasing SF made the beam stronger but more brittle.

3- Increasing steel fibers volumetric ratio V_f from zero to 2% resulted in the following percentages of variation in the structural properties of the tested NSRPC beams;

- ❖ Diagonal cracking shear force V_{cr} (hence cracking load P_{cr}) increased by 72.7%.
- ❖ Ultimate shear capacity V_u (hence ultimate load P_u) increased by 198.9%.
- ❖ Deflection Δ_o(corresponding to ultimate load) increased by 115.8%.
- ❖ Ductility ratio Ψ increased by 112.5%.

Therefore increasing V_f made the beam stronger and more ductile.

4-the dual absence of nanosilica and steel fibers from the concrete of the tested NSRPC beams resulted in the following percentages of variation in their structural properties;

- ❖ Diagonal cracking shear force Vcr (hence cracking load Pcr) reduced by 47.4%
- ❖ Ultimate shear capacity Vu (hence ultimate load Pu) reduced by 74%.
- ❖ Deflection Δ_o (corresponding to ultimate load) decreased by 51.2%
- ❖ Ductility ratio Ψ decreased by 61.8%

Therefore the absence of NS and V_f from the concrete made the beam weaker and highly brittle.

5- The inclusion of nanosilica with steel fibers in NSRPC beams results in enhanced stiffness, reduced crack width and reduced rate of crack propagation. At failure, the NSRPC beams behave in a ductile manner as compared with the dual absence nanosilica and steel fibers beam.

b- <u>Effect of varying beam parameters</u>

1- Increasing the longitudinal steal ratio ρ from 0.0742 to 0.0911 resulted in the following percentages of variation in the structural properties of the tested NSRPC beams;

- Diagonal cracking shear force V_{cr} (hence cracking load P_{cr}) increased by 26.3%.
- Ultimate shear capacity V_u (hence ultimate load P_u) increased by 21.9.
- Deflection Δ_o (corresponding to ultimate load) decreased by12.2 %.
- Ductility ratio Ψ decreased by 17.6%.

Therefore it can be concluded that the contribution of the longitudinal steel bars in flexural strength is much higher than its contribution in shear resistance.

2-Decreasing the shear span to effective depth ratio a/d from 3.5 to 2.5 resulted in the following percentages of variation in the structural properties of the tested NSRPC beams;

- Diagonal cracking shear force V_{cr} (hence cracking load P_{cr}) increased by 15.8% (for the case Vf = 2%)and 12.5% (for the case Vf= 1%).
- Ultimate shear capacity V_u (hence ultimate load P_u) increased by 54.6% (for the case V_f = 2%) and 48.6% (for the case V_f =1%).
- Deflection Δ_o (corresponding to ultimate load) increased by 8.9% (for the case V_f =2%) and 22.2% (for the case V_f = 1%).
- Ductility ratio Ψ increased by 161.8% (for the case V_f=2%) and 123.1% (for the case V_f=1%).

Therefore it can be concluded that decreasing a/d ratio caused smaller bending moment to develop in the beam and this made the beam to resist higher ultimate load.

3-The use of steel stirrups in a NSRPC beam of the present research (with amounts ϕ6mm@ 85mmc/c in the two shear spans of the beam) resulted in the following percentages of variation in its structural performance;

- Diagonal cracking shear force V_{cr} (hence cracking load P_{cr}) increased by 9.1% .
- Ultimate shear capacity V_u (hence ultimate load P_u) increased by 94.4%

- Deflection Δ_o (corresponding to ultimate load) increased by 61.4%.
- Ductility ratio Ψ increased by 106.3%

Comparison between the percentage increase in V_{cr} and V_u resulted from the use of steel stirrups indicates that steel stirrups can only work effectively after the formation of a diagonal shear crack. Obviously steel stirrups help in giving the beam greater shear resistance and reduce crack width at all stages of loading and also at the onset of failure.

7.2.3 Finite Element Modeling

The structural performance of the sixteen NSRPC beams tested in this research was analyzed numerically using a powerful nonlinear finite element method package (ANSYS V.11).The cracking shear force, ultimate shear capacity, cracks propagation, longitudinal strains as well as load- deflection curves were all found reasonably predicted by ANSYS computer program. The finite element modeling was set of take into account all the investigated "material" and "beam" parameters.

7.2.4 Proposed Empirical Equations

The statistical analysis program SPSS version 18 was used to carry out regression analyses of the experimental results obtained from testing sixteen NSRPC beams. Accordingly empirical equations were established for the prediction of "compressive strength f'_{cf} , splitting tensile strength f'_{spf} modulus of rupture f'_{rf} " of NSRPC as well as the ultimate shear capacity Vu" of NSRPC beams. These empirical equations were found in good correlation with the test results and with some existing methods.

7.3 Recommendations for Future Research

To obtain a better understanding and future improvement in the subject of using nanosilica as an additive material in manufacturing structural concrete members, the following suggestions for future research may be considered:

1- Experimental and theoretical investigation of the flexural behavior of NSRPC beams.
2- A study of the behavior of NSRPC beams under the combined effect of bending, shear and torsion.
3- Experimental and theoretical investigation of the shear behavior of non – prismatic NSRPC beams and corbles.
4- Flexural and shear behavior of continuous NSRPC beams.
5- Shear strength of deep NSRPC beams with and without opening.
6- Structural performance of NSRPC beams subjected to dynamic loading such as impact, repeated or reversal loading. Also a study of their performance under the action of moving loads or vibration.